

Alternative Fabrication Process for Free-Form FRP Architectural Elements Relying on Fabric Materiality Towards Freedom from Molds and Surface Articulation

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Abstract. FRP (fiber reinforced polymers) is a family of composite materials combining fibers and polymers to offer exceptional mechanical properties. Its unique material properties have led to its wide application across industries. Although we witness a growing interest in the material in the architectural field in recent years, a significant barrier to its application lies in the need for a mold. The paper describes a new alternative fabrication process for architectural FRP elements that relies on *fabric materiality*. It suggests a mold free process, combining form finding and garment making techniques, to allow for complex morphologies, surface articulation and variation. The paper describes both the fabrication process through physical experiments, as well as the design process through the use of two design software tools. It demonstrates the potential for sustainable variation of large component facade system.

Keywords: FRP, Fabrication, Architecture, Mold, Materiality, Variation

1 Introduction

A composite polymer is an engineered combination of fibers with a polymer matrix that makes it an extremely lightweight and strong material. The fiber reinforced polymers (FRP) family of materials combines fibers, such as glass fibers, carbon, and Kevlar, with polymers, such as epoxy, polyester, vinyl ester and nylon. As part of the ever-increasing quest for high-performance materials, the use of composite polymers has spread extensively in the past decades in numerous industries [1]. The main reason for its assimilation in industries such as the aviation, naval and automotive industries has to do with its high ratio of strength to weight and great durability [2-3].

Fabrication processes of FRP elements vary according to the type of industry and the characteristics of the final element. All conventional fabrication processes for FRP are based on molding. Among the most widely used molding techniques are contact molding, compression molding, vacuum molding, resin injection molding, and even injection molding with preregs or filament winding, each of which require the use of a certain type of mold [2]. The cost of fabricating an element is directly connected to the chosen molding technique, the scale and the formal complexity of the element/mold. Since architectural elements are usually rather large, this technical aspect of the fabrication process has significant implications.

The paper proposes an alternative fabrication process for architectural FRP elements, that relies on the fabric's materiality. The new process eliminates the need for molds and facilitates affordable geometrical variation. The paper presents an experimental fabrication process that is an integration of a full-scale form finding process together with textile manipulations that are borrowed from the world of garment making. The paper describes both the design and the fabrication methods, via examples of digital design experiments and physical experiments. Together, it demonstrates the potential architectural applications, both as whole structures of small-medium scale and as large cladding component systems.

2 FRP and Architecture

Polymer composites, in the form of FRP, were first introduced to the architectural field in the late 1960s. Seminal experimental projects, such as Matti Suuronen's Futuro House or Buckminster Fuller's Fly's Eye Dome, were the first to apply the family of composite polymers to medium-scale structures. After two decades of relative abandonment, the material reemerged in the late '90s, influenced by the introduction of computation in architecture [4]. In the past five to ten years, FRP increasingly appears in architectural applications, both in experimental contexts and in commercial and industrial projects. It has been used only in particular situations, in cases where a high ratio of strength to weight and material durability were of major importance, or for repetitive elements where a single mold could be used to manufacture a large number of elements, or for large undertakings where formal complexity and surface finish were essential for the design.

Two generic modes of applications can be delineated for employing FRP in the fabrication of architectural elements. The first mode divides the basic element into a small number of large segments (e.g. the Chanel Pavilion, by Zaha Hadid¹), while the second mode divides the large element into a large number of small components - either identical and repetitive, or diversified - which together form one system (e.g. the facade of the SMFOMA expansion, to be completed in 2016²).

Along with FRP's unique properties and the array of opportunities it brings, its application in the field of architecture faces some challenges. Both modes of architectural applications present substantial barriers due to the high cost of molds for each final element and the complexity of the assembly process. Contemporary architectural practices, such as the realization of complex freeform morphologies and the quest to improve performance through variation and differentiation, clearly highlight the limitation posed by the necessity to use molds, since such practices require numerous complex molds for each individual project.

Due to the size of large-scale architectural structures, the fabrication and manipulation of their molds turns out to be complex and highly expensive. While technically feasible, with the use of contemporary CNC technologies, the fabrication of molds for architectural elements which are unique and non-repetitive, non recyclable and hardly reusable, makes the use of FRP inefficient and costly [5-6].

¹ <http://www.zaha-hadid.com/architecture/chanel-art-pavilion> [10-1-2015]

² <http://snohetta.com/project/16-sfmoma-expansion> [1-12-2014]

3 Searching for Alternative Molding Systems

The investigation of molding techniques and formwork systems has greatly increased in the context of this decade's growing research interest in the challenge of realizing complex non-repetitive architectural forms. Two main directions are noted in this respect: making the molding system more efficient through reconfigurable molds (also referred to as moving molds), which enable the multiple usage of molding, and creating moldless form-making techniques that rely on form-active structures. Reconfigurable molds (e.g. ADAPA Adaptive Molds from Denmark, North Sails 3DL molding technique from the United States and FlexiMold from the Netherlands) rely on a complex mechanical system of moving pistons, connected directly to the CAD software; these are mainly used as an offsite casting process, whether for polymer composites or concrete materials [6]. Moldless form making techniques rely mainly on form-active surfaces, and are the product of the contemporary elaboration of simple systems, based on advanced modeling and simulation tools. Form-active structures redirect external forces primarily through the form of their material. Flexible fabric formwork systems make use of form-active structures as the molds for surface-active elements, such as shells. They relate to the long-time tradition of form-finding: a design/fabrication process in which form is not defined by the designer but rather generated by the definition of boundary conditions, and the self organization of the material under those. As such, flexible fabric formwork optimise naturally in response to given conditions since the material presents no resistance to compression and configures itself into optimal form when under tension. [7]. Fabric based molding systems exist in all types of form-active structures: under compression (such as air-formed concrete) or tension (such as fabric formwork).

Air Formed Structures, or Pneumatic Formwork, are membranes which are pressurised to temporarily support the reinforcement and the concrete mix until it is cured. The concrete may be placed outside or the inside the membrane. This type of fabrication process produces only synclastic morphologies, which is one of its greatest limitations. Pneumatic formwork is still used, with a renewed interest in the "Bini-shell system"³. On that basis, other inflatable formwork systems are currently being developed, like the "wedge system", in TU Vienna [8] and the "Concrete cloth shelters"⁴.

Membrane Casting (of Fabric Formwork) is the casting of wet concrete into a thin formwork membrane that deflects into a repertoire of precise tension geometries forming convex surfaces under the viscous pressure of the cast material. This produces naturally efficient structural curves of unprecedented sculptural forms of extremely light formwork and extraordinary surface finishes. Fabric formwork has been extensively researched, for the structural optimisation it offers, for the sustainable approach, minimising efforts invested in molds, and for the texture finish it gives to the elements⁵. Current advances in simulation and the integration of digital

³ The Bini-Shell system was originally invented in the 1960's by Dr. Dante Bini, who built 1,600 of them in 23 countries. <http://www.binishells.com/systems/systems.html>

⁴ <http://www.concretcanvas.com/>

⁵ An important center for the research on membrane casting is the CAST lab for fabric formwork at the University of Manitoba in Winnipeg, Canada
http://www.umanitoba.ca/cast_building/research/fabric_formwork/index.html.

tools drive potential applications further [9]. Their combination with of other forming systems within the process, expands the present somewhat limited repertoire of geometries and opens up future prospects [10].

Tensile membranes are being used for different alternative molding systems, most of it aimed at the creation of double curved concrete elements. The approximation of a target surface to be built, by the geometries afforded by the molding system is challenging [11]. The use of stretched fabric over flat rigid curvilinear frames as a mold for FRP elements is demonstrated in the canopy-like structures of "Pleated shell"⁶

Although complex and varied in its outcomes, it should be noted that the main limitation of these systems is that the final shape derives from the material's adaption to forces; thus, it is restricted to a specific family of morphologies. Pronk tackles the limited morphologies implied by such form-active molding by combination of different systems (pneumatics, cable nets and tensile membranes. [12]. Potential further expansion of the repertoire of shapes and structures is suggested by the combination of a FRP mold and a concrete cast elements, forming an anticlastic saddle surface [13].

4 Fabric Materiality in FRP Fabrication Process

.FRP is composed of fiber material, mostly in the form of woven textile. In its various standard fabrication processes it makes use of the capacity of textile to adapt to the given form of the mold, under pressure. The basic fabrication process consists of the layering of several fabrics over a mold, their impregnation with resin, and the curing of the whole under heat. The layering of material is designed based on the calculation of the various parameters concerning the fabric (such as weaving type, weight) , to enable a perfect drape over the mold, for maximal adherence to the shape with minimum wrinkles or encapsulated air. The resulting element does not reveal the *fabric materiality* of its textile component in its morphology, nor rely on it in its the fabrication process.

Several experimental projects in recent years have tackled the issue of FRP form-making, on the fiber level, developing direct fiber placing techniques (such as filament winding). The use of robotic arms for the direct placement of fibers (of glass and carbon) over simple two dimensional molds for the fabrication of complex double curved elements is demonstrated in two research pavilions by the ICD (Institution for Computational Design in the faculty of architecture and town planning in Stuttgart), by Achim Menges, in close collaboration with Jan Knippers from the ITKE (the research pavilions of 2013-2014⁷ and of 2012-2013⁸) [14]

⁶ "Pleated shell" an installation at Sci-Arc 2012, by Shajay Bhooshan of Zaha Hadid Architects, Josh Zabel of Kreysler & Associates, and a group of Sci-Arc students. Before they made it, they broke the mold. [compositesandarchitecture.com/?p=1089]. Retrieved from <http://compositesandarchitecture.com/?p=1089>

⁷ <http://icd.uni-stuttgart.de/?p=11187>

⁸ <http://icd.uni-stuttgart.de/?p=8807>

A similar aim for alternative fabrication of complex three dimensional components, by manual means of direct placing of fibers is demonstrated in the "C-Lith" installation⁹.

Aiming to achieve formal complexity and discard the core mold, as described above, the experimental fabrication process described in this paper also suggests an alternative form active fabrication processes for FRP, relying on *fabric materiality*. It focuses on the fabric characteristics of the fiber elements in composite FRP and its self-organizational properties. Using ideas from the body of research on form finding in architecture, and learning from fabric formwork methodologies, this study investigates ways to develop a design and fabrication method for the generation and fabrication of complex geometry architectural elements using FRP. Adapting textile attributes and manipulation techniques from the world of garment making, the suggested process seeks for the introduction of surface articulation and complex forms into the fabrication of FRP elements. It suggests the freedom from molds, by treating the FRP as hanging membrane, and proposes ways for local differentiation of the surface for performance, optimization and ornamentation.

Fabrics can bend in multiple directions, creating three dimensional forms with double curvature with large deformation under low stresses. A structural stability and a spatial organization of a greater order can be gained with low energy actions. Man has channeled the pliability of fabric and its self organization for the achievement of a desired structure since early days of human history for clothing fabrication, by manipulating fabrics in various ways. Simple manipulations such as stitching, gathering, pleating, furrowing and many more transformed flat fabrics into complex three dimensional structures in space.

The variety of manners by which form is obtained in textile is demonstrated in the garment-making discipline and can be placed under four main categories: the drape, being a fabric's property, pattern-making and fabric manipulations, being tailoring practices and "fully-fashioned", which is a fabric material construction.

Out of these four categories which constitute the *fabric materiality*, the experimental fabrication process described in this paper is making use of the drape and some fabric manipulation techniques, Pattern-making and fabric construction ('fully fashioned') are not in the scope of this experiment.

5 Alternative Fabrication Process in FRP

Developed from an earlier technique devised by Blonder [16], the method essentially involves hanging up a textile membrane (such as woven glass fiber or carbon fiber) impregnated with resin, then curing it and overturning the result, to obtain a shell-like structure (Fig.1). The shape obtained is defined by the drape, which can be manipulated by variations in the amount of material, insertion of lines of stiffness (such as the seam) and changes in its orientation. Fabric orientation is defined by the Grain - the orientation of the yarn within the fabric, running in three possible

9 C-Lith by Glenn Wilcox and Anca Trandafirescu at the Taubman College in Michigan, via the "Research Through Making" platform.
<https://taubmancollege.umich.edu/research/research-through-making/2014/c-lith-carbon-fiber-architecture> [15-1-15]

directions: lengthwise (the warp direction of the weave, has less stretch), crosswise (the weft direction of the weave, more stretchy than the lengthwise) and the bias, at 45° to both lengthwise and crosswise. (45° being "true bias", while all other angles between the two perpendicular grains defined as "simple bias"). The bias is the grain allowing the most stretch in fabrics; when a fabric is cut in the bias, shear resistance decreases, so that the flat surface deforms in-plane.

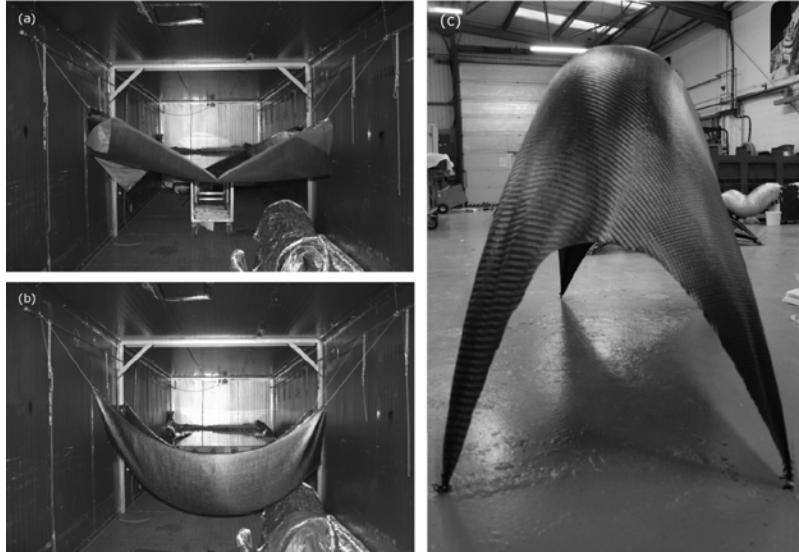


Fig. 1. Basic fabrication process Upper Left: (a) hanging. Lower Left: (b) curing. Right:(c) inverting. Prepreg Carbon 0/90 Twill, 600 gr/m²

On top of the described basic process, features and manipulations are introduced. The further elaboration of the basic assembly processes in garments is considered as *fabric manipulation*. These manipulations introduce local three dimensionality in the two dimensional fabric, altering its surface and organization in space. The extremely rich array of different traditions, techniques, methods and tools, can be classified through the process of their making: by needle, by pressure and by heat. Although described as separate practices, often times these are combined in craftsmanship, for the elaboration of a surface, or a garment. The features introduced in this experiment are borrowed both from the world of sail-making, like the corner reinforcement feature (Fig.2), as well as from the world of garment making, like the cuts and pleats (Fig.3). They potentially serve a range of performance purposes, such as structural or acoustical behavior, as well as serving for the articulation of the surface, for differentiation and functional ornamentation.

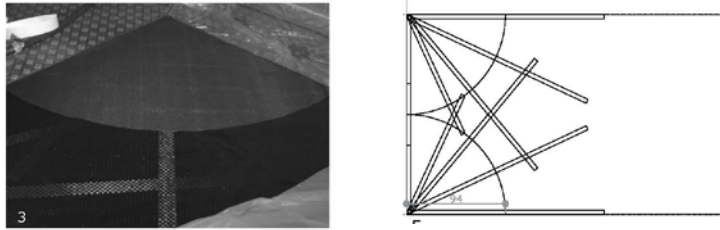


Fig. 2 (left) - Corner reinforcement by local additional layers of directional fibers. Pre-preg Carbon 0/90 Satin, 200 gr/m². (right) schematic layering pattern.



Fig. 3 - cuts and pleats for surface articulation. Pre-preg Carbon 0/90 Twill, 600 gr/m²

The proposed fabrication process consists of the following detailed stages :

- *Tailoring composite woven fabrics to the desired shape:* Fabrics can be of varying fibers, thickness or weaving pattern. Prototypes of the process were realized both in carbon fiber and in glass fiber fabrics, using both wet lay-up and dry lay-up processes (pre-pregs).
- *Layering fabric plies:* Layering can differ throughout the completed piece in the number of plies, the types of fabrics and the cut shapes
- *Placing features:* Various techniques and manipulations from the world of garment-making – such as cuts, stitches, pleats, pinches and ruffles – can be applied to locally manipulate the morphology.
- *Setting the anchoring points and hanging the membrane:* Fabric is hung from different anchoring points, at the specified heights. The phase of impregnating the fabric with resin will depend on the chosen resin system: wet lay-up systems (hand impregnation or spraying) will be applied just before hanging the membrane, while dry lay-up (pre-pregs) do not require an impregnation phase.
- *Curing:* The curing process is selected according to the chosen fabric and resin system.
- *Inverting the stiff cured structure:* Once the element is cured, it is stiff and can be inverted. Depending on the element's scale, this phase might

require machinery (cranes, lifts, etc.). Post-curing treatment of the inverted structure can include surface finishing such as sanding, coating and painting. The inverted structure will require further treatment for its placement and subsequent anchoring to the ground.

A large prototype structure was realized, measuring 200(W) 1000 (L) 100(H) cm. (Fig. 4). It incorporated the following features: large opening, cuts, stitches, slots, pinch, pleats and corner reinforcements.



Fig.4: Large prototype incorporating various features. Pre-preg Carbon 0/90 Satin, 200 gr/m². 3 plies+corner reinforcement

6 Simulation Based Design Process

As the fabrication process is a full-scale form finding process, the form of the resulting element is the outcome of the self-organization of the material according to its properties, the boundary conditions and manipulations applied on it. Therefore, it cannot be designed directly as a simple 3D object, but requires a simulation engine for its design, that will emulate its fabrication process. Such simulation can be realized through several digital tools, of different type. While the full physical simulation of draped fabric is still a complex computational challenge [17-18], computer based form finding (real-time physics simulation) is gradually becoming more easily accessible, aided by tools such as Kangaroo Physics (add-on for Grasshopper parametric platform in Rhinoceros 3D modeling software). On a different angle, 3D modeling, animation, and rendering software, such as 3DStudio MAX, offer high definition cloth simulation tools. In the framework of such simulation tools, it is possible to calculate the behavior of a fabric under gravitational load and other external physical forces, and introduce changes in the boundary conditions (e.g., the position of anchors and height) that are directly reflected in the fabric's drape simulation. The required final form is the result of an iterative process in which the obtained shape is visualized through dynamic digital simulation.

During the current stage of the research, digital experiments were conducted through two types of simulation engines: real time physics by Kangaroo for Grasshopper Rhino, and cloth modifier in 3DStudio Max. As each of the engines

targets different types of markets, they differ in many aspects such as their logic of modeling, manipulation capabilities, detailing, accuracy, end result and ease of interface with other digital tools. As a parametric software tool that is oriented towards the architectural field, Kangaroo physics easily simulates the form finding process of hanging membranes in the digital realm under physical laws. Its model is based on damped springs connecting abstract particles, over which various physical forces are applied. The character and behavior of the fabric are defined through its springs characteristics, connecting the abstracted particle mesh of the fabric. Boundary conditions, such as anchor points, and external physical forces, such as gravity or wind, are easily defined and can be the dynamic result of different parameters internal or external to the grasshopper tool itself. The Cloth Modifier in 3DS Max is oriented towards realistic animation, and incorporates within it a modifier, which is based on a garment making logic (panels, seams, tear lines etc.). The character and behavior of the fabric can either be selected out of set of presets of fabric types, or can be defined through a table of parameters (such as bend, stretch, plasticity, density etc.), which consider the anisotropic character of woven fabric (by U/V definitions). Features such as holes, seams, tears and folds can be easily defined, through the "Garment maker" modifier, and other manipulations of the fabric can be defined by coupling to other dynamically animated objects in the scene. (See Fig. 5)

While Kangaroo Physics facilitates the optimization process of the global shape by draping and the variation of constraints in a parametric method, the Cloth modifier can embed fabric manipulation features in the simulation, for the surface articulation and differentiation. For both tools, the simulation process necessitates a process of calibration between the digital virtual realm and the fabric's physical materiality. It is material specific and requires the translation of physical material properties as parameters in the simplified digital simulation interface

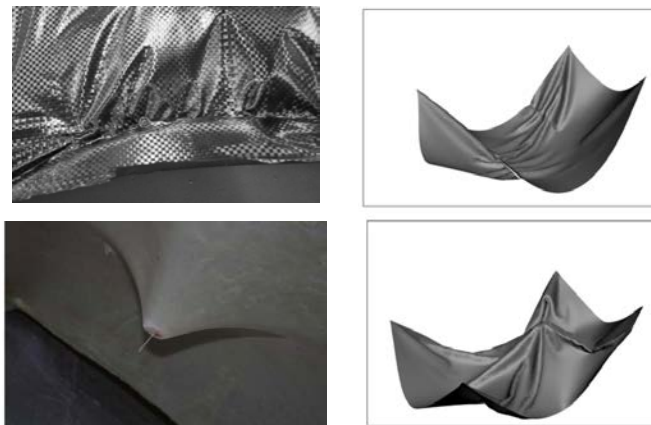


Fig. 5: Upper left: Stitch feature in physical model. Upper right: Stitch feature in digital model. Lower left: Pinch feature in physical model. Lower right: Pinch feature in digital model. All digital models were realized by Cloth modifier in 3DSMAX. Top physical model is realized in carbon fiber prepregs, bottom model is realized in wet lay-up fiberglass.

7 Potential Architectural Applications

The introduction of full-scale form finding as the fabrication process of FRP for architectural elements is mainly envisioned for two project types: The first type is small to medium structures of complex free form morphology, treated as one whole form. The second type is large cladding systems based on varied small-sized components of complex double curved geometry. Entire structures, in small to medium scale, can be rapidly erected in a process where structural optimization is naturally embedded in the fabrication process. It can enable the erection of structures where FRP serves both as structure and as skin. The formal language of such a structure would naturally derive from hanging membranes and their manipulation. The fabrication of such a structure would typically take place on site.

Cladding systems, can tolerate local variations, as they are comprised of components that can be differentiated. The difference in form does not imply the fabrication of a new mold, but only simple changes in boundary conditions and fabric manipulations, which are easily obtained. The fabrication of such components would typically take place off-site, and would be easily transported to site, like conventional facade elements.

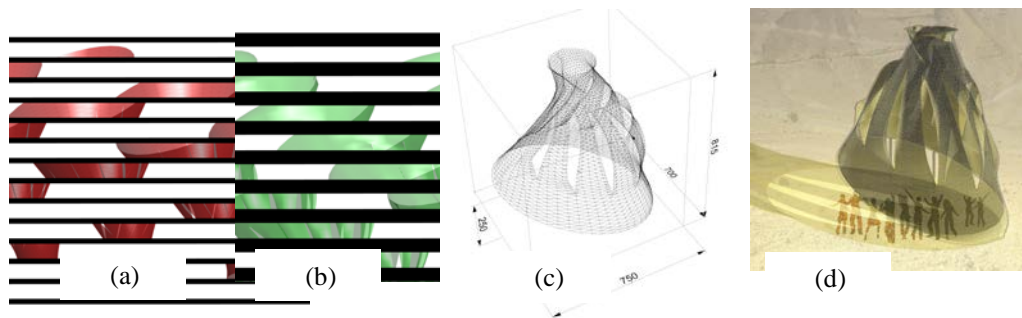


Fig. 6: A suggestion for a small-medium type structure, a pavilion based on two rings, hanging cloth tailored with slots (a) Digital model in initial state, tilted upper ring (b) Digital model in draped state, with a twist of the lower ring, after Grasshopper simulation (c) final mesh, flipped structure (d) Rendering

8 Case Study - A Differentiated Facade

The application of the suggested fabrication process for a component system is demonstrated through a digital experiment. A Kangaroo definition for Rhino Grasshopper was written, simulating the draping of different rectangular surfaces. The whole design is parametric, and could afford a large number of components. (Fig.6) To avoid long calculation times and for efficiency reasons the detailed demonstration is realized over an array of 6X4 panels.

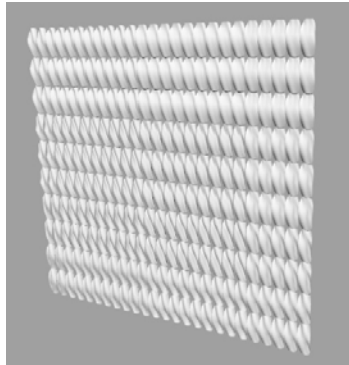


Fig. 7: A low-resolution simulation of a large amount of components, an array of 25X10 panels

All panels are of identical size, and have the following constraints applied on them :

- All panels are subdivided in identical resolution (10X10)
- All panels have same "fabric characteristics" (stiffness value of mesh springs)
- All panels are constrained in four corners (with an internal offset from the panel's size in rest length, for its drape)
- All panels are subjected to gravity

The fabrication process simulated in the grasshopper definition consists of the placing of four anchor points at the corner of the fabric panel, and the hanging of the membrane at a set distance between them (the offset). A simple "pinch" manipulation is applied over the fabric. In the definition, an anchor spring of one vertex is added within the panel's area. This additional anchor creates the Pinch feature demonstrated above (see Fig.5), in both physical and digital models. The parametric platform of grasshopper easily generates a different anchoring point for each panel. For the demonstration, two models were realized, differing only in the logic of generating the different anchoring points (see Fig.8).

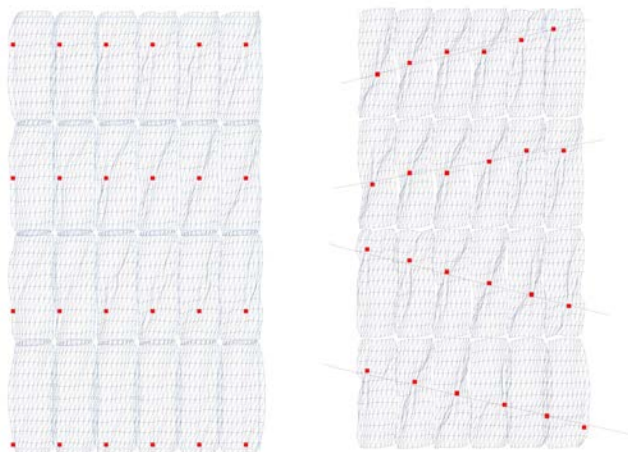


Fig 8: Left: model A with anchoring points distributed by an incremental series. Right: Model B, with anchoring points distributed according to attractor curves.

It is important to note that the fabrication of such a set of panels does not require a different mold for each panel, as it would be done in conventional FRP fabrication processes, but simply a different hanging point of the Pinch. Nevertheless, morphological difference between the panels is clearly noticeable. As the anchoring points at the perimeter of each of the panels are identical, the different surfaces can all be easily connected to a standardized building system, such as the building's facade, as demonstrated by the schematic cylinders in model A (See fig.9), connecting the panels and the back surface.

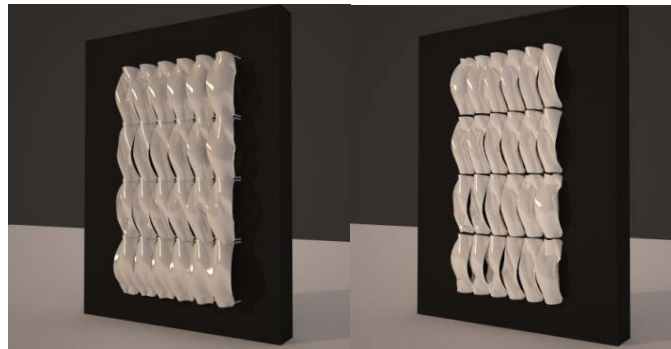


Fig.9: Left: model A with anchoring points distributed by an incremental series. Right: Model B, with anchoring points distributed according to attracting curves.

9 Conclusion and Further Research

The paper describes an alternative fabrication process of FRP architectural elements, based on the notion of fabric materiality. It suggests a mold free fabrication process that draws from the world of architectural form finding and garment making, to allow complex morphologies. The integration of fabric manipulation features articulates the surface and generates variation while suggesting sustainable large differentiated systems.

The suggested approach supports architectural applications for small-medium structures and large-scale component based cladding system. Previous stages of this research had demonstrated the feasibility of fabricating small-medium structure. This paper concentrated on the examination of the potential for the implementation of the suggested approach as a cladding system for a large-scale structure.

For both structure types, the surface of the elements could be articulated by fabric manipulations (stitches, folds, cuts, etc.) to obtain specific performance requirements such as ventilation, reduction of weight, flow of forces, acoustics, stability and insulation. These mechanisms should be further elaborated to form a tight link between the resulting performance and the surface articulation techniques. The design method has been tested while employing two different design software tools, each presenting different advantages and drawbacks. Further research is needed in this realm in order to be able to determine conclusive recommendations regarding the

optimal tool for this process. Future research should involve the examination of tools from related disciplines such as fashion design (e.g. Optitex¹⁰) or dedicated FRP laminate modelers (e.g. Patran¹¹). A simple flow of design and fabrication of differentiated FRP elements for architecture can be suggested, requiring additional physical experimentation and digital modeling research.

The freedom to generate variations and the release from the constraints of needing a mold, as suggested by the design and fabrication method described in this paper, has the potential to drive future architectural applications in FRP toward differentiation and responsible complexity of form.

¹⁰ <http://www.optitex.com/Pattern-Making-Suite> [20-1-2015]

¹¹ <http://www.mscsoftware.com/product/patran> [20-1-2015]

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