FULL SCALE FORM-FINDING : INTRODUCING FABRIC MATERIALITY IN THE FABRICATION OF ARCHITECURAL FRP

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ABSTRACT

FRP's (fiber reinforced polymers) unique material properties have led to its wide application across industries in the past decades. 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 mould. The paper describes an initial proposal for an alternative fabrication process for architectural FRP elements that relies on fabric-materiality. Self-organisation and textile manipulations embedded in the suggested fabrication process suggest a mould free process, combining form finding and garment making techniques, to allow for complex morphologies, surface articulation and variation, being essential in contemporary architectural practices. The paper describes the fabrication process through physical experiments, as well as its design process and potential architectural applications through digital experiments.

1 INTRODUCTION

Since the initial introduction of polymer composites in the aviation industry in WW2, its use has spread to almost every industrial field, from naval to automotive, infrastructure and design. In the architectural field, polymer composites, in the form of FRP, were first introduced in the late 1960s. After several years of experimental applications in a number of seminal architectural projects[1] of medium-scale, followed two decades of relative abandonment of the material. It is only in the late 90's that FRP re-emerged, influenced by the introduction of computation in architecture [**Error! Reference source not found.**]. A growing interest in FRP is noticeable in the past five to ten years, as FRP increasingly appears in architectural applications, both in experimental and academic contexts as well as in commercial and industrial projects.

FRPs present unique properties of extreme strength, durability and low density, coupled with varied surface finishes. Despite the opportunities offered by the material, its application for architecture raises significant issues. Contemporary architectural practices, such as complexity of form, surface articulation and differentiation, act as barriers for wider implementation of FRP in architecture. The total reliance on moulds in its standard fabrication processes together with the large scale and uniqueness of the architectural object, restrict potential architectural applications.

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[1] Seminal architectural experiments such as Matti Suuronen's Futuro House, Buckminster Fuller's Fly's Eye Dome and Renzo Piano's pavilion for the Milan 1967 Trienale made creative and innovative use of FRP for architectural application.

A similar challenge presented by the moulding of complex architectural forms is experienced in the field of concrete casting. Textile-based moulding systems are developed for concrete casting as fabric formwork; relying on the material attributes of textile as a form active structure, membrane casting allows the freedom from moulds and suggests double curved morphologies [**Error! Reference source not found.**]. While FRP is mostly a fabric-based material, its standard fabrication processes do not rely on its inherent textile attributes.

The paper presents an initial proposal for an alternative fabrication process for architectural FRP elements, relying on fabric-materiality: its attributes of self-organisation, flexibility and pliability. The new process eliminates the need for moulds and facilitates affordable geometrical variation. It adapts techniques of form finding and garment making, as features for the control of the fabric's self-organisation and its manipulation, to achieve the final form.

The paper describes the principles of the suggested fabrication process and its design tool, via examples of initial digital and physical experiments. Envisaged architectural applications are demonstrated by two digital design experiments, as case studies.

2 FRP AND ARCHITECTURE

The use of FRP in the construction industry is well established, for varied purposes and by different application modes [2]; in architecture FRP has been used mainly for large undertakings where formal complexity and surface finish were essential for the design[2]. Two generic modes of applications can be delineated for employing FRP in the fabrication of architectural elements. The first mode sub-divides the whole element into a number of large segments (e.g. the Chanel Pavilion, by Zaha Hadid[3]), while the second mode divides the whole element into a large number of small components - either identical, repetitive or diversified – that together form one system (e.g. the facade of the SMFOMA expansion, to be completed in 2016[4]).

Despite the adaptive materiality of FRP that suits perfectly the contemporary continuous folding surfaces and the free form "blob" architecture [4], there are still outstanding gaps in the ability of FRP to respond to some emerging challenges in a sustainable and reasonable way. Both modes of architectural FRP applications, as a segmented integral element and as a component system, face substantial barriers. Main reasons are related to typical FRP fabrication processes that apply to architectural structures, mainly relying on moulds [5]. The typically large architectural scale, together with contemporary architectural practices such as complex shapes, surface articulation and the variation of form, highlight the limitation posed by the necessity to use moulds.

The tendency of contemporary architecture for complexity of forms, fluidity and geometrical freedom is growing since the mid 1990's, with a tight relation computational development of design and visualization tools. The materialization of such free-form curvilinear surfaces is the great challenge of digital fabrication in architecture [1]; uniqueness of the parts and their geometrical complexity are the main concerns for moulding-based fabrication processes, typical to FRP. Along with folding free form surfaces, digital tools for fabrication and parametric design have introduced the topics of variation and high degree of geometric control into architectural practice and discourse.

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[2] Zaha Hadid typically creates flowing complex curved surfaces in FRP, both for interior and exterior applications, for example Stuart Weizman stores (http://www.zaha-hadid.com/architecture/stuart-weitzman-flagship-store/) or the Nordpark railway stations (http://www.zaha-hadid.com/architecture/nordpark-railway-stations/)

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

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

Geometrical variations of the building's envelope achieve performative targets of the skin [6], becoming layered and irregular, consequently requiring a unique mould for each and every part. Performative requirements are coupled with contemporary aesthetics of renewed interest in ornamentation, in a growing number of articulated façade and intricate surfaces [7][8], powered by digital design tools.

Although technically feasible with the use of contemporary CNC and robotic technologies, complexity of the architectural form, articulation of surface and a high level of variation present a real challenge when materialised in FRP; the high cost and complexity implied by the fabrication of moulds for each part as well as high degree of manual labour required in its fabrication, limit its potential applications in the field [9]. Costly moulding processes of this kind are mainly applied to the fabrication of "one-off" elements of high value or to repetitive neo-classical catalogue-elements that are mass-produced[5]. Restricted architectural applications would naturally range from high-end projects of large overall budget to buildings and landmarks of historical value restoration projects[6]. Overall, the fabrication of moulds for architectural elements which are unique and non-repetitive, non recyclable and hardly reusable, makes the use of FRP inefficient and costly [10][11].

3 FABRIC-MATERIALITY IN FRP FABRICATION PROCESSES

The major constituent of FRP is fibre material, mostly in the form of structured textile. Standard FRP fabrication processes are based on the capacity of textile to adapt to the given form of the mould, under pressure. Various parameters of the fabric (such as fibre type, weaving type, weight) are taken into account by computational models to design the layering of material that will enable a perfect drape over the mould, for maximal adherence to the shape with minimum wrinkles or encapsulated air. However, the resulting element does not reveal the particular attributes of the textile of which it is made, its *fabric-materiality* not affecting its morphology, nor contributing to its the fabrication process.

Several experimental projects in recent years have tackled the issue of FRP form-making on the fibre level, developing techniques of direct fibre placing by robotic arms over two dimensional elements. Elaborate three dimensional double curved forms have been achieved without using complex three dimensional core moulds, but relying only on simple two-dimensional elements, robotic process and fibre materiality[7][9].

The experimental fabrication process suggested in this paper similarly relies on the materiality of the fibres, aiming to achieve formal complexity and discard the complex moulds as described above, but tackling it on the fabric level. Flexibility and capacity for self-organisation, as particular attributes of textiles, are regarded as *fabric-materiality*. Its integration in the fabrication process of architectural

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[5] http://www.fiberglassafi.com/

[6] For example Berkeley building at 420 Boylston st. in Boston, by Finegold Alexander Architects (http://faainc.com/projects/the-berkeley-building-420-boylston-st/) or the Terminal Tower in Cleveland, restored by Architectural Fiberglass (http://www.fiberglassafi.com/downloads/press/press-properties-0809.pdf)

[7] Fibre placement over two-dimensional elements achieving complex double curved elements is demonstrated in the two research pavilion by the Achim Menges of the ICD, (Institution for Computational Design in the Faculty of Architecture and Town Planning in Stuttgart), in close collaboration with Jan Knippers from the ITKE (the research pavilions of 2013-2014 and of 2012-2013,) http://icd.uni-stuttgart.de/?p=11187. The "C-lith" installation by Glenn Wilcox and Anca Trandafirescu at the Taubman College in Michigan share similar aims, using manual processes. https://taubmancollege.umich.edu/research/research-through-making/2014/c-lith-carbon-fibre-architecture [15-1-15]

FRP, as an alternative forming process, draws from form-finding practices as well as garment making techniques of fabric manipulation.

3.1 Self Organisation

Form finding refers to a design/fabrication process in which form is not defined by the designer but rather generated by the definition of boundary conditions of self-organising material systems [12]. In a dynamical and adaptive process, such systems acquire and maintain structure themselves, without external control [13]. Form finding instrumentalizes the self-organisational properties of materials, towards performance-oriented design [14]. The structured arrangement of fibres in space by mechanical interlocking in the form of textile, is at the basis of the capacity of the textile material-system to self organise in three dimensional space, in reaction to extrinsic forces, such as gravity. Relying on fabric's self-organisation capacities, complex forms can be achieved by form-finding techniques and without external guiding forces such as rigid moulds.

Form finding as a design tool is a long-time practice, with hanging chains models being the design tool of Antonio Gaudi's for his Basilica and Expiatory Church of the Holy Family ("Sagrada Familia") in Barcelona of the early 20th century, and for Frei Otto for his Mannheim Multihalle in 1975. Digital design concepts relate to the idea of form generation (as opposed to design) and form-finding, supported by computational tools of real-time physics simulation, gradually becoming more accessible as part of 3D software commonly used by architects (such as Kangaroo Physics (add-on for Grasshopper parametric platform in Rhinoceros 3D modelling software). While traditionally serving as a mean for the generation of the form, this capacity of self-organisation can be harnessed for the fabrication process itself of FRP when deployed through form-finding processes.

3.2 Fabric Manipulation

The basis of all textile manipulations, from the fabric's texture to the overall shape of the garment, is the induction of low-stresses for the creation of complex forms. By low energy actions over the fabric, which generate large deformations of double curvature, structural stability and a spatial organization of a greater order can be obtained. Manipulating fabrics in various ways, man has channelled, since early days of human history, the self-organisation of fabric and its pliability for the achievement of desired structures, for clothing and shelter. Simple manipulations such as stitching, gathering, pleating, furrowing and many more, transform flat fabrics into complex three-dimensional structures in space.

The variety of manners by which form is obtained in textile, demonstrated in the garment-making discipline, 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 of fabric-materiality related techniques, 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 beyond the scope of this paper).

4 FABRICation: AN ALTERNATIVE FABRICATION PROCESS IN FRP

FABRICation is proposal for a fabric-based material system in FRP; an experimental fabrication process for architectural FRP relying on fabric-materiality, developed from an earlier technique devised by Blonder [15]**Error! Reference source not found.**. It consists of fabric-materiality attributes of self-organisation and fabric manipulations. Global shape of the structure is generated by form finding, and surface articulation is obtained by fabric manipulation techniques. Being a form-found system, where form is defined by its fabrication process and material self-organisation, it requires a digital simulation tool for its design.

4.1 Global Shape By Form Finding

The global shape of the structure is obtained by form-finding techniques in full scale. From the various form-finding processes traditionally applied to textiles (pneumatics, tensile membranes, catenary membranes), hanging membranes were chosen as the basic fabrication feature. The fabrication process consists of hanging up a textile membrane (such as woven glass fibre or carbon fibre) impregnated with resin, then curing it and overturning the result, to obtain a shell-like structure (Figure 1). The shape obtained is defined by the drape, which can be manipulated by variations of material type (density and weight), by variations in the amount of material, by insertion of lines of stiffness (such as seams), by variation of weaving type[8] and by changes in its orientation[9]. The process is applicable for both manual wet lay-up and prepreg; experiments were realised in different fibre types (glass, carbon, basalt), together with different epoxy-based resin systems, using different curing modes (curing oven and ambient temperature) and by different fabrication processes (wet lay-up and prepregs). The fabrication process affects the resulting morphology of the element, as resin weight adds to gravitational force acting over the fabric, defining its catenary self-organised shape. Resin excess, typical to manual wet lay-up, results in deeper sagging of the fabric and more acute surface deformations (Figure 3).

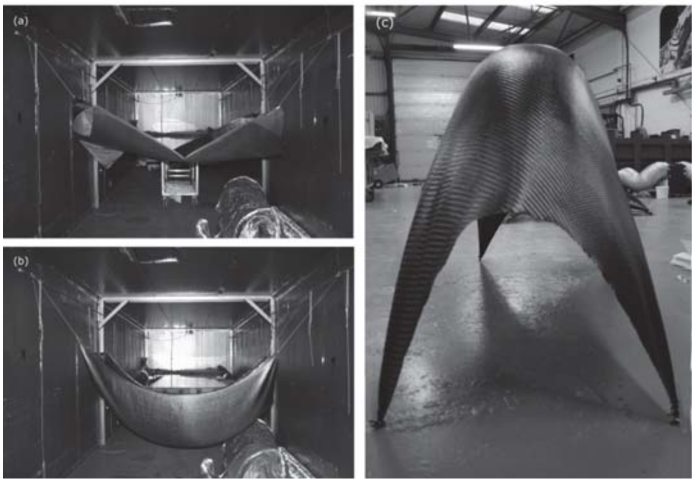

Figure 1: Basic fabrication process. Prepreg Carbon 0/90 Twill, 600 gr/m^2

Upper Left: hanging. Lower Left: curing. Right: inverting.

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[8] Variation of weaving types and fibre directions in fabrics for an optimal adherence to the mould's shape is well established in FRP fabrication processes, both in hand lay-up fabrication techniques and in digital analysis and simulation tools. The same principles apply to the drape of the fabric in self-organisation, satin weave being the most drapable of weaving types.

[9] Fabric orientation is defined by the Grain - the orientation of the yarn within the fabric, running in three possible directions: lengthwise (the warp direction of the weave, has less stretch), crosswise (the weft direction of the weave, more stretchy then the lengthwise) and the bias, at 45^o to both warp and weft (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.

4.2 Surface Articulation By Fabric Manipulations

Features and manipulations of the fabric are introduced as further elaboration of the global shape obtained by form finding. These manipulations introduce local three-dimensionality, altering the surface and its organisation in space. The features introduced in this experiment are borrowed both from the world of sail-making, like the corner reinforcement feature as well as from the world of garment making, like the cuts and pleats (Figure 2). They potentially serve a range of performance purposes, such as structural or acoustical behaviour, as well as serving for the articulation of the surface, for differentiation and functional ornamentation.

As the forms generated by the hanging cloth models behave structurally as surface-active structures, similar to classic shells, some similarities can be drawn in the form of strategies for local reinforcement. Similarly to concrete shells, features can be introduced for the elaboration of the edge condition, areas with highest stresses and level of deformations. Experiments were done with features such as splits, stitches, slots and foam-filled pocket (Figure 2), adding structural height or localcurvature, hence resulting in additional stiffness.

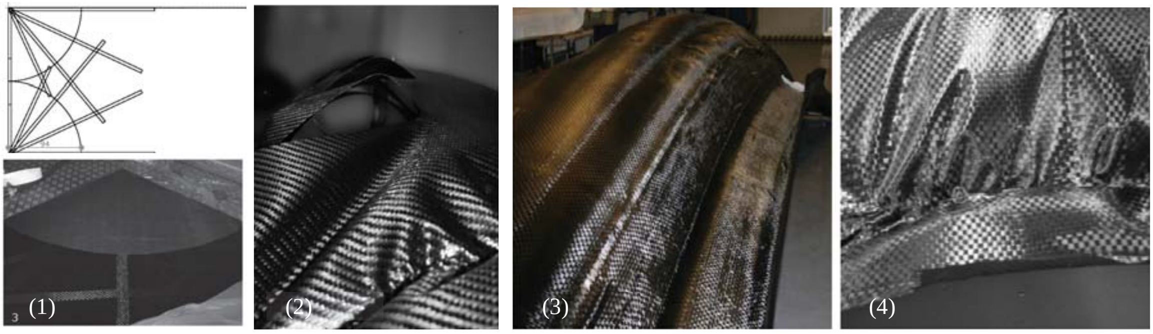


Figure 2 : Features and fabric manipulations for local reinforcements and surface articulation

(1) Corner reinforcement by layering of directional fibres. Pre-preg Carbon 0/90 Satin, 200 gr/m2 (2) Surface articulation by cuts and pleats, Pre-preg Carbon 0/90 Twill, 600 gr/m2 (3) Slot (4) Stitch

4.3 Digital Design Tool

As a shape that is generated by form finding, the surface cannot be designed in direct and full control as a simple 3D object; it requires a simulation engine that will emulate its fabrication process, by which its shape is actually defined. While the full physical simulation of draped fabric is still a complex computational challenge [17], commercial tools for 3D animation (such as 3Dstudio Max Cloth modifier) or real-time physics tools (such as Kangaroo add-on for Grasshopper parametric platform in Rhino 3D modelling software) enable a fair quick simulation of fabric behaviour. In the framework of such simulation tools, it is possible to calculate the behaviour of a fabric under gravitational load and other external physical forces, and introduce changes in the boundary conditions that are directly reflected in the fabric’s drape simulation. 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. 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 anisotropic character of woven fabric is taken into account (by U/V definitions) and features such as holes, seams, tears and folds can be easily defined. For both tools, the simulation process necessitates a process of calibration between the digital virtual realm and the fabric's physical materiality, which is not integral to the platform. It is material specific and requires the translation of physical material properties as parameters in the simplified digital simulation interface.

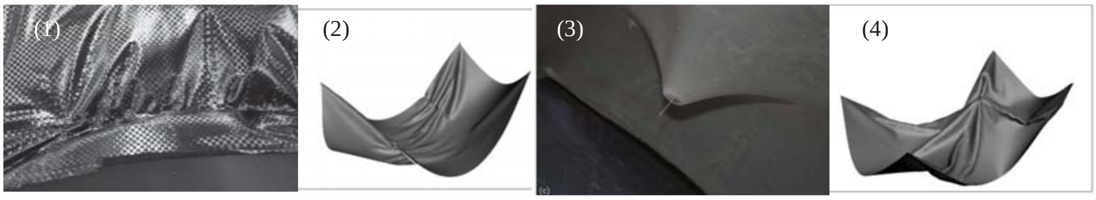


Figure 3: Fabric manipulation features in physical and digital models.

(1) Stitch, Physical model in carbon prepreg (over-turned). (2) Stitch, Digital model in 3Dstudio Max (hanging). (3) Pinch, Physical model in wet lay-up fibreglass (over-turned) (4) Pinch, digital model in 3Dstudio Max (hanging)

5 POTENTIAL ARCHITECTURAL APPLICATIONS

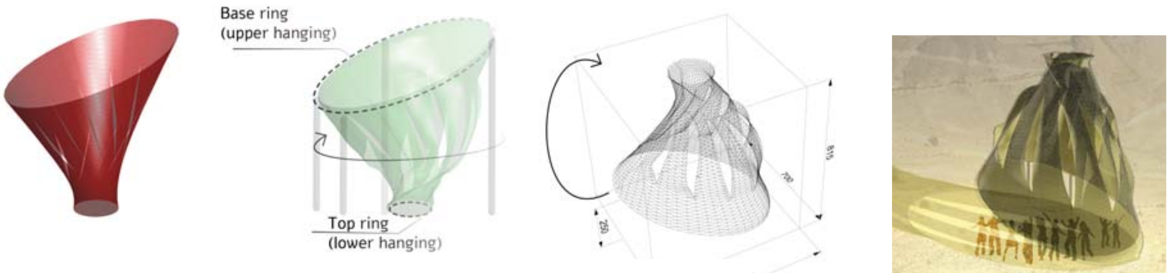
Two types of architectural applications are envisaged for FABRICation material system, on two different scales. On a small to medium scale, a pavilion-type structure, including structure and envelope; on a large scale, a cladding-type system comprised of smaller differentiated components. The main interest of the small/medium entire structure is its complex double curved global morphology whereas the main interest of the large component based cladding system is its ability to afford variations. Two digital experiments are presented as case studies, demonstrating the two different approaches to architectural applications. Both are realised with Kangaroo Physics for Grasshopper, Rhino.

5.1 Desert Pavilion

Entire structures of small to medium scale can be rapidly erected, with FRP serving as the structural skeleton of the structure and as its skin. The formal language of such structures would naturally derive from hanging membranes and their manipulation, and structural optimization is naturally embedded in the fabrication process. The fabrication of such a structure would typically take place on site.

The "Desert Pavilion" is a proposal for a medium-scale shading structure for on-site rapid fabrication for a festival in the desert. Its purpose is to provide shade and outdoor shelter during day and night, in a light and airy structure with an overall dynamic feel. The global form of the structure is designed as a tilted-cone shell, partially anchored to the ground and raised to allow entrance. Side openings are introduced in the shell for air circulation and to reduce lift forces, and a top circular opening is placed for natural lighting and airflow. The design of the structure is obtained by the simulation of its fabrication process: fabric is tailored as a truncated cone with integrated slots; its cutting pattern is generated by the final simulation-based digital model (Figure 4). Two fiberglass-rod rings are inserted to support the cone's base and truncated edges (1). Fabric is impregnated with resin and hung from its larger ring, anchored to wooden posts of different heights placed in a circular arrangement. The smaller ring hanging as the lower part is rotated around its vertical axis and anchored to ground, creating a twist of the overall cone. This rotation naturally open up the slots in the fabric and adds additional double curvature (2). After curing in ambient temperature, the structure is overturned and fixed. The cured structure rests partially on the ground and is raised by the posts that served for its hanging and the reinforcement rings serve for its anchoring. (3)

For the rough finish of the structure, with a “rocky” look, two materials are considered: fiberglass and basalt fabrics. The inherent optimisation of the structure (by its hanging) and the shell-like geometry allow for a thin surface of few layers; the structure remains translucent, affected by sunlight and changing its appearance during the day. No finish is applied, to keep a rough uneven appearance of a natural element[10].



(a) (b) (c) (d)

Figure 4 Desert pavilion.

(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

5.2 A Differentiated Façade Cladding System

Cladding systems can expand to a large scale and tolerate local variations, as they are comprised of components that can be differentiated. Applying FABRICation material system, the difference in form does not imply the fabrication of a new mould for each and every component, but simply 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.

The purpose of the differentiated façade is to allow variation over the façade, with component of complex curved geometry, highlighted by a spotless glossy surface finish. The design of the component is based on the simulation of draped rectangular membrane, anchored in four corner points and by an additional internal point (“Pinch” feature demonstrated above in Figure 3). All panels are identical in size, fabric characteristics, orientation and corner anchoring points. Differentiation between components is obtained by a parametric change of the additional anchoring point.

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[10] A reference to the type of desired crude finish can be found in the serpentine pavilion of 2014 by Smiljan Radic, http://www.dezeen.com/2014/06/24/movie-smiljan-radic-serpentine-gallery-pavilion-2014-model-hand-made-by-giant/ [15-2-15]

For the demonstration, two models were realized, differing only in the generating logic of their differentiation, in the placement of anchoring points (Figure 5 b,c). 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 (Figure 5, (e)), connecting the panels and the back surface. High-gloss finish of the element can be achieved by painting, for the required surface fluidity. (Figure 5(d))

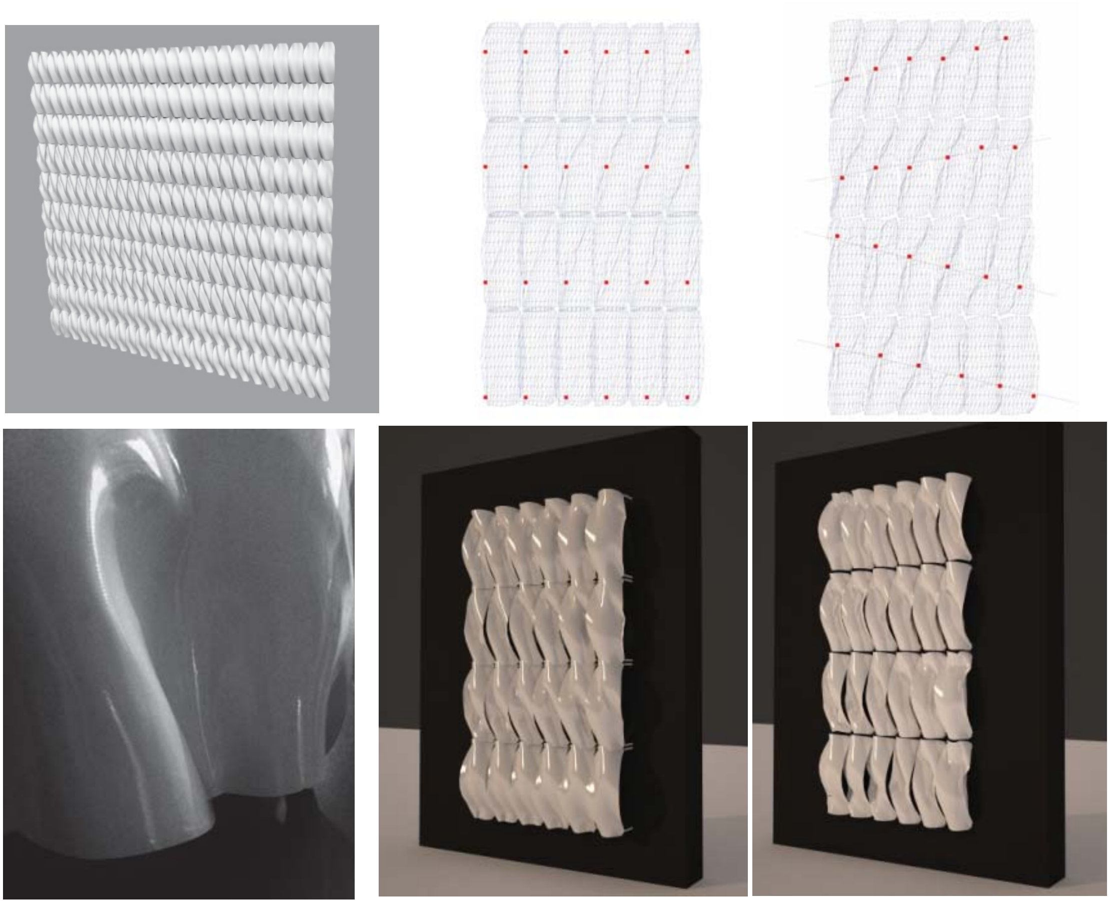

Figure 5 : Digital experiment for a differentiated façade system.

(a) `Expanding into a large-scale façade system as an array of 25X10 panels. (b): model A with anchoring points distributed by an incremental series. (c): model B, with anchoring points distributed according to attractor curves. (d) Physical model of material finish (e) model A, rendering (b) model B, rendering

6 CONCLUSION AND FURTHER RESEARCH

The paper describes a suggestion for an alternative fabrication process of FRP architectural elements, based on the notion of fabric-materiality. Based on previous stages, in which the principles and feasibility of FABRICation were initially developed and globally approved, this paper focused on the demonstration the envisaged types of architectural applications enabled by this process. Two case studies demonstrate the application of principles of form finding and features of garment making in the design process, which is fabrication based.

The paper presents the potential of fabric materiality for the generation of complex forms and articulated surfaces in FRP and demonstrates how this is translated into a design methodology and a tool. Expanding the catalogue of manipulation features, and linking each to the resulting performance

The The continuation of this initial research should focus on physical experiments of large scale and their structural testing. These mechanisms should be further elaborated to form a tight link between the resulting performance and the surface articulation techniques. For both structure types, the surface of the elements could be articulated by fabric manipulations (e.g. stitches, folds, cuts, etc.) to obtain specific performance requirements such as ventilation, reduction of weight, flow of forces, acoustics, stability and insulation.

The freedom to generate variations and the release from the constraints of needing a mould, 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.

7 REFERENCES

[1] Kolarevic, Branko, *Architecture in the Digital Age: Design and Manufacturing*. New Ed edition. New York: Taylor & Francis. ed. 2005

[2] Hollaway, L.C., A review of the present and future utilisation of FRP composites in the civil infrastructure with reference to their important in-service properties. *Construction Building Materials, Special Issue on Fracture, Acoustic Emission and NDE in Concrete* (KIFA-5) 2010. **24**, pp. 2419–2445. (doi:10.1016/j.conbuildmat.2010.04.062)

[3] Veenendaal, D., Block, P. Computational form-finding of fabric formworks: an overview and discussion" *ICFF Second International Conference on Flexible Formwork 2012*, Bath. 2012

[4] Spina, M., 2012. *Material beyond materials, composite tectonics*, First edition. ed. SCI-Arc Publications.

[5] Mallick, P.K., 2008. *Fiber-reinforced composites: materials, manufacturing, and design*. 3rd ed. ed. CRC Press, Boca Raton, Fla.

[6] Grobman, Y.J., 2013. Cellular Building Envelopes, in: Chakrabarti, A., Prakash, R.V. (Eds.), *ICoRD'13, Lecture Notes in Mechanical Engineering*. Springer India, pp. 951–963.

[7] Moussavi, F., Kubo, M., Seth Hoffman, J., *The Function of Ornament*. Actar, Barcelona, 2006.

[8] Picon, A., *Ornament: The politics of architecture and subjectivity*. Wiley, Chichester 2013

[9] Reichert, S., Schwinn, T., La Magna, R., Waimer, F., Knippers, J., Menges, A. Fibrous structures: An integrative approach to design computation, simulation and fabrication for lightweight, glass and carbon fibre composite structures in architecture based on biomimetic design principles. *Computer-Aided Des*ign **52**, 2014, pp. 27–39. (doi:10.1016/j.cad.2014.02.005)

[10] Eekhout, M., Composite stressed skin roofs for liquid design architecture. *International Journal of Structural Engineering* **1**, 255–279. (doi:10.1504/IJStructE.2010.033482)

[11] Raun, C., Kristensen, M.K., Kirkegaard, P.H., 2012. Dynamic Double Curvature Mould System, in: Gengnagel, C., Kilian, A., Palz, N., Scheurer, F. (Eds.), Computational Design Modelling. Springer Berlin Heidelberg, pp. 291–300

[12] Burry, M., *Expiatory Church of the Sagrada Família: Antoni Gaudí*. Phaidon Press, London. 2006.

[13] Wolf, T.D., Holvoet, T., Emergence Versus Self-Organisation: different concepts but promising when combined, in: Brueckner, S.A., Serugendo, G.D.M., Karageorgos, A., Nagpal, R. (Eds.), *Engineering Self-Organising Systems*, Lecture Notes in Computer Science. Springer Berlin Heidelberg, pp. 1–15. 2005.

[14] Hensel, M., Menges, A. (Eds.), Morpho-Ecologies: Towards heterogeneous space in architecture design. AA Publications, London. 2007.

[15] Hensel, M., Menges, A., Weinstock, M.,. Textiles, in: *Emergent Technologies and Design: Towards a biological paradigm for architecture*. Routledge, 2010. pp. 102–115

[16] Blonder, A. Grobman Y.J. Design and Fabrication with Fibre-Reinforced Polymers in Architecture: A case for complex geometry.” *Architectural Science Review* 2015,1–12. (doi:10.1080/00038628.2015.1020479).

[17] Cherouat, A., Borouchaki, H. Present State of the Art of Composite Fabric Forming: Geometrical and mechanical approaches. *Materials* **2**, 2009 pp.1835–1857. (doi:10.3390/ma2041835)