Architectural Science Review
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tasr20

Design and fabrication with fibre-reinforced polymers in architecture: a case for complex geometry

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Published online: 11 Apr 2015.

Architectural Science Review, 2015
http://dx.doi.org/10.1080/00038628.2015.1020479

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Design and fabrication with fibre-reinforced polymers in architecture: a case for complex geometry

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(*Received 21 September 2014; accepted 15 February 2015*)

Fibre-reinforced polymers (FRPs) are a family of strong and lightweight composite materials combining fibres and polymers. FRPs are widely used in the aviation, naval and automotive industries for components that require a high ratio of strength to weight and durability. Despite some pioneering experimental architectural applications in the 1960s, it is only in recent years that a growing interest in FRP elements is evident in the architectural field. The following paper critically reviews the current use of FRP in architecture and proposes a framework and a method to design and fabricate freeform architectural elements and structures from FRP without the need for using moulds. The proposed method is examined in a case study design and fabrication of a shading structure for beach areas. The case study results are discussed and conclusions are presented for future developments of the proposed method for the use of composite materials in architecture.

Keywords: fibre-reinforced polymers; form finding; computer-aided fabrication; material system; composite materials

Introduction

A composite polymer is an engineered combination of fibres with a polymer matrix that makes it an extremely lightweight and strong material. The FRP family of materials (fibre-reinforced polymers) combines fibres, such as glass fibres, carbon, Kevlar and aluminium, 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 widely in the past decades across industries and in architecture too (Fernandez 2006). FRPs are widely used today by the aviation, naval and automotive industries for components that require a high ratio of strength to weight and durability (Gay 2007; Mallick 2008). The past decades have witnessed the spread of FRP composites into numerous other fields such as civil engineering and furniture production. In industrial practice, as well as in academic research, the material's ability to form complex morphologies, its biological structural logic, and, above all, its superior material performance, have made it a major point of interest for an extremely diversified group of agents.

All conventional fabrication processes for FRP are based on moulding. Among the most widely used moulding techniques are contact moulding, compression moulding, vacuum moulding, resin injection moulding and even injection moulding with prepregs or filament winding, each of which requires the use of a certain type of mould (Gay 2007). The cost of fabricating an element is directly connected to the chosen moulding technique, the scale and the formal complexity of the element/mould. Since architectural elements are usually rather large, this technical aspect of the fabrication process has significant implications. 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 Yitzhak Rabin Center in Tel Aviv),[1] while the second mode divides the basic 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 2016).[2]

Both modes of application present substantial barriers due to the high cost of moulds 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, highlight the issue of moulds, since such practices imply numerous complex moulds for each individual project.

The research presented in this paper addresses the limitations arising from the need for a mould in FRP fabrication when used in architectural applications. It describes the results of the study's first stage, which concentrated on developing a framework and a new design and fabrication method for creating freeform elements from FRP without using moulds. The suggested approach could be related to both modes of application mentioned earlier, thus allowing the fabrication of architectural elements in all scales.

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The paper begins with a critical examination of the use of FRP in architectural design. It demonstrates the limitations of the existing fabrication process and reviews the alternative presented by the classical form-finding discipline, as a form generation process. The second section sets forth a new design and fabrication method for employing complex geometry FRP architectural building elements. The proposed method combines a digital form-finding process together with techniques that originate in garment-making. The method is tested by physical experiments.

The next section presents a case study, which employs the proposed fabrication method, examining its potential application for small-scale structures. The paper ends with a discussion of the research results and conclusions for future development of the proposed method and the use of composite materials in architecture.

Composite materials in architecture

The use of composite materials has a long history in modern architecture, starting with the introduction of reinforced concrete in the latter half of the nineteenth century. 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 (Kolarevic 2005). In the past 5–10 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, especially where a high ratio of strength to weight and material durability was of major importance, and for repetitive elements where a single mould could be used to manufacture a large number of elements. As opposed to its limited use in architectural design, FRP materials are widely used in structural and civil engineering in a variety of situations including infrastructures, structural rehabilitation and the reinforcement of weak structures (Hollaway 2003). Changes in regulations and building codes, such as the recent amendment to the American IBC (International Building Code),[3] will most probably enhance the growing global interest in FRP architectural applications.

Two of the initial contemporary attempts to examine the potential of composites in architecture can be traced back to Greg Lynn (Lynn and Gage 2010) and Marcelo Spina (Spina 2012). These design research attempts focused more on the new formal opportunities the material offers than to the adaptation of its specific engineering and fabrication process to the architectural realm.

A review of the current status of FRP in architectural design (Table 1) shows that it is being used for various building elements: lightweight roof canopies; tiles for structural cladding of buildings and curtain walls; interior architecture elements, including partitions and built-in furniture; elaborate or lightweight maintenance-free pedestrian bridges and even integral pavilions. It can serve as structure, as skin or as both, but it is mostly used as a skin for a secondary structural system. It can consist of a modular or repetitive element, or of singular elements. While these can be of any typical geometry (flat, orthogonal, curved or double-curved), the great majority of applications are double-curved morphologies.

Some attempts also have been made recently to create systems for fabricating an entire building from FRP.[4] While the monocoque structure of the California Bay House by Leonard and Walker & Moody Architects still stands as an exception (Kreysler, 2012), most attempts are based mainly on orthogonal profile systems that imitate, in terms of form and joints, material systems based on aluminium. Some flat sandwich panelling systems offer low-cost simple housing units, based on conventional prefab material systems.[5] Thus it seems that in these cases, FRP was generally used to create similar architecture with different (stronger and more durable) materials. Moreover, these attempts, or any other attempts in architectural design that were not mentioned in this selection of case studies, did not seem to try to develop a new approach for design and fabrication of architectural elements, which is based on the exploration or use of FRP unique properties.

Examples listed in the review illustrate some of the following emerging global trends:

- The number of structures and projects making major use of FRP has risen sharply in recent years, reflecting a growing general interest in the material.
- As demonstrated in projects of an experimental nature (pavilions), there is increasing interest in utilizing FRP as a self-supporting structure in which it serves both as skin and as structural elements.
- Facade panelling in FRP has shifted from historic restorations to cladding systems of varied morphologies utilizing mainly repeating components.
- Most projects are of general curved morphology and composed of double-curved elements.
- The great majority of FRP applications in architecture are in the realm of cladding over a structure. Most applications in other industries make use of FRP material as a structural surface, taking advantage of its excellent properties of strength, stiffness and durability. Due to architectural conventions, regulations and specific structural characteristics related to scale, most architectural applications of FRP still pertain to the structure-cladding structural system.

Challenges for FRP in architecture

Along with FRP's unique properties and the array of opportunities it brings, its application in the field of architecture

Table 1. Selection of case studies for the use of FRP in architectural design.

Project	Location and year	Architect	Application type	Structure/ skin	Singular/ repetitive	Morphology
FG2000	Altenstadt, Germany, 1968	Wolfgang Feierbach	Cladding	Skin and structure	Modular	Orthogonal
Futuro House	International, 1968	Matti Suuronen	Pavilion	Skin and structure	Repetitive	Double-curved
Fly's Eye Dome	Patent: 1965	Buckminster Fuller	Pavilion	Skin and structure	Singular	Double-curved
Lincoln Park Zoo Pavilion	Chicago, 2005	Studio Gang	Cladding	Skin	Repetitive	Double-curved
Ftown apartment building	Sendai, Japan, 2008	Atelier Hitoshi Abe	Cladding	Skin	Repetitive	Flat
Chanel Mobile Art Pavilion	Traveling, 2008 (currently in Paris)	Zaha Hadid	Cladding	Skin	Singular	Double-curved
Walbrook building	London, 2010	Foster + Partners	Cladding	Skin	Repetitive	Double-curved
Celluloid Jam House	Yokohama, Japan, 2010	Norisada Maeda Atelier	Interior surfaces	Skin	Singular	Double-curved
ICD Pavilion	Stuttgart, 2012	Achim Menges, Jan Knippers and students	Pavilion	Structure and skin	Repetitive	Double-curved
Serpentine Donut	London, 2014	Smiljan Radic	Pavilion	Structure and skin	Singular	Double-curved
SFMOMAn extension	Chicago, under construction (2016)	Snøhetta	Cladding	Skin	Repetitive	Double-curved
Haramain High Speed Railway Station	Medina, Saudi Arabia	Foster + Partners	Roofing	Skin	Repetitive	Double-curved

faces some challenges. These could act as possible barriers for the material's wider adoption:

Cost: The overall cost of a finished FRP element is relatively high, compared to traditional building materials. This is due to the high cost of raw materials (especially glass and carbon fibres) and to its particular and demanding fabrication process, which is not typically carried out at the building site.

Fabrication process: The various techniques for fabricating FRP elements demand a high level of precision for setup and intensive manual labour for surface finishing. Thus, it is mainly suitable for off-site fabrication under controlled conditions. When dealing with large-scale architectural elements, this implies the segmentation of the finished element and its transportation to the building site for assembly there.

Uniqueness: All of the various FRP fabrication techniques are based on the use of a mould, over which layers of woven fibres impregnated with resin are laid (Gay 2007). Today moulds can be milled into practically any shape, using Computer Numerical Control technologies over foam or wood. Due to the size of large-scale architectural structures, the fabrication and manipulation of their moulds turns out to be complex and highly expensive. Moreover, fabricating architectural elements that are unique and non-repetitive makes the use of FRP inefficient and costly (Raun, Kristensen, and Kirkegaard 2012). The moulds are non-recyclable so they cannot be reused for another production (Eekhout 2010).

As experience in the application of FRP for architecture has been gained only relatively recently and is still quite scarce, other issues that need to be addressed by researchers and practitioners are the lack of sufficient perspective regarding the ageing of the material under various conditions and its effect on durability and fatigue, and the standardization of structural models for behaviour under different loads (Fernandez 2006).

Currently, as mentioned above, all of the FRP fabrication techniques for architecture are based on the use of a mould, over which are laid layers of fibres (mostly in the form of woven fabrics) impregnated with resin. Although there have been some attempts to create 3D printing of composite materials,[6] it seems unlikely that these attempts will reach the level of development and size necessary for architectural applications anytime in the near future. In mould-oriented processes, layering is mandatory as material size is limited and relates to the size of the architectural component; the layering process is also necessary to achieve a sufficiently strong laminate. These processes are usually labour-intensive and time-consuming, rendering this process unsuitable for *in situ* fabrication.

The investigation of moulding 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. The research can be divided into two main avenues:

- Making the moulding system more efficient through reconfigurable moulds, which enable the multiple usage of moulding
- Creating mouldless form-making techniques that rely on form-active structures.

Reconfigurable moulds are mainly used as an offsite casting process, whether for polymer composites or concrete materials. The technique relies mainly on the application of a flexible membrane over a mechanical moving support system of pistons to serve as the casting platform (e.g. ADAPA Adapa Adaptive Moulds n.d. Adaptive Moulds from Denmark, North Sails 3DL moulding technique from the USA and FlexiMould from the Netherlands Flexi-Mould n.d.). These recently developed systems connect the mechanical piston system directly to the CAD software and automatically generate the precise configuration required (Raun, Kristensen, and Kirkegaard 2012). These systems' general limitations are the element's size, radius of curvature and level of detailing. It is therefore mostly suitable for off-site fabrication of elements for large-scale structures.

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 moulds for surface-active elements, such as shells. The membrane can self-organize under pre-stressing forces to produce anticlastic surfaces (Hensel, Menges, and Weinstock 2010; Van Mele and Block 2010), or under viscous pressure of the cast material, forming convex surfaces (extensively researched at the CAST lab for fabric formwork at the University of Manitoba in Winnipeg, Canada.[7] 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.

Form finding in architecture

Form finding or self-forming refers to a design/fabrication process in which form is not defined by the designer but rather generated by the definition of boundary conditions (Burry 1993). The notion of form finding is not new to modern architectural design. Antonio Gaudi's inverted model for the design of the Basilica and Expiatory Church of the Holy Family (Sagrada Familia) in Barcelona and Frei Otto's Munich stadium roof and experiments with material behaviour (Otto and Rasch 1996; Nerdinger 2005) are two early examples of using a form-finding process in architectural design. With the assimilation of digital design methods in architectural design, the idea of form generation (as opposed to design) and form finding has received increasing attention (Grobman 2011).

Form finding has been employed in architectural and structural design in various ways: as another method to generate a complex form, as in NOX's D-tower (Spuybroek and NOX 2004); as a way to increase or optimize the performance of the architectural form, as in Heinz Isler's shell (Chilton 2000); and as a way to involve materiality as a key factor during the early stages of the architectural process.

However, while the architectural use of computer-based form-finding methods is increasing, they are seldom deployed to deal with structural considerations. Cases that take into account structural elements can be found in Mutsuro Sasaki's work (Sasaki, Ito, and Isozaki 2007) and in some smaller scale attempts to employ topological optimization tools in architectural design, such as in the work of Andrew Kudless (Borden and Meredith 2011). Digital 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 modelling software). Its influence over the architectural academic discourse is apparent, mainly through students' projects and the research pavilions of various academic institutes, where the formal language of inverted membranes and tensile elements has been widely adopted. While digital form finding is spreading, its main focus remains as a tool for design. It relates to fabrication only in specific lines of research as described above, dealing with surface-active moulding systems.

Several experimental attempts have made use of form-finding principles as part of the fabrication process itself; Heinz Isler pioneered with his ice structures, in which water was turned into ice over self-forming fabric structures (Chilton 2000). This was followed by the use of membranes for the flexible moulding of concrete (Van Mele and Block 2010). Form-active structures naturally optimize in response to the given conditions, as the material presents no resistance to compression and configures itself into optimal form only when under tension. Using a form-active structure as a mould therefore incorporates within it the notion of structural optimization.

Form finding with FRP: A new design and fabrication method

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. Developed from an earlier technique devised by Blonder

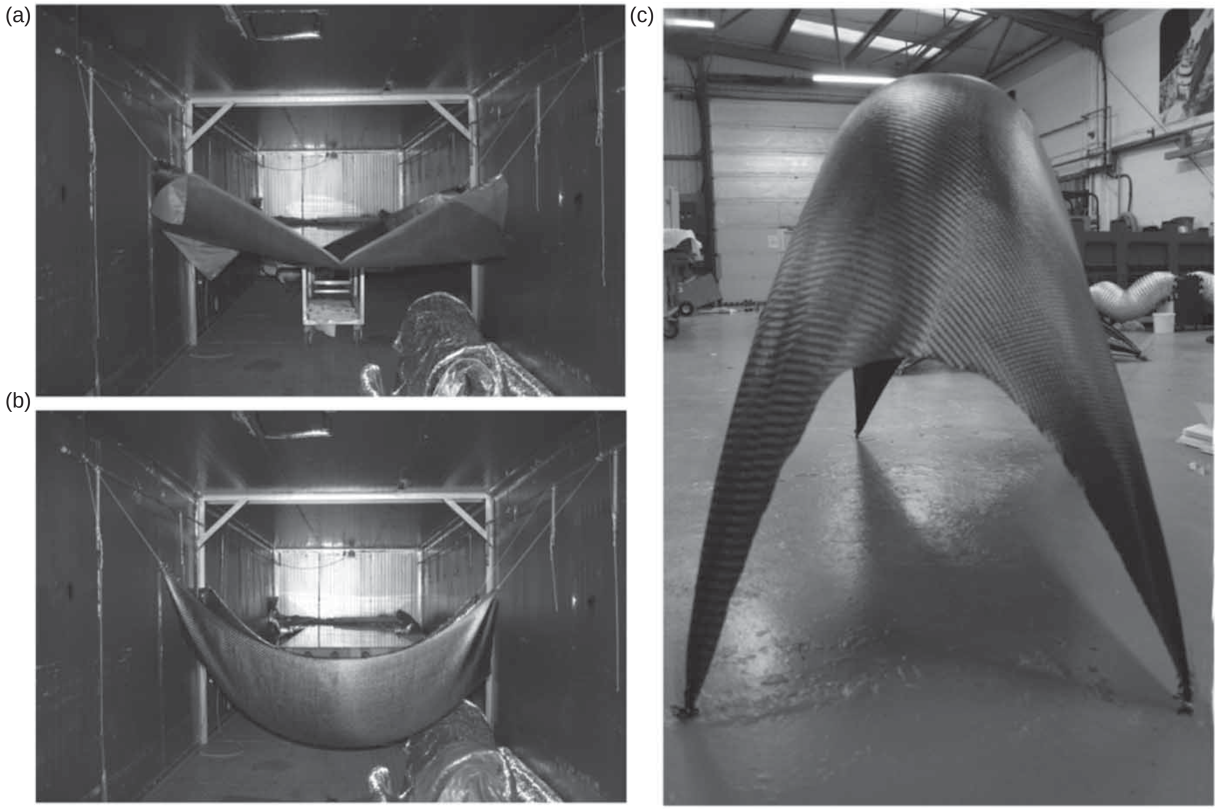

Figure 1. Basic fabrication process. Upper left: (a) hanging; lower left: (b) curing; right: (c) inverting.

(Blonder 2008), the proposed method is based on the textile characteristics of the fibre elements in composite FRP, in the form of woven fabric and its self-organizational properties. The method essentially involves 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).

Based on form finding with FRPs, the proposed method tries to obviate the need for moulds in manufacturing complex geometry. It consists of two interconnected parts, the first of which concentrates on the design of the architectural element and the second on its fabrication.

The design part makes use of the FRP membrane's self-organizational properties. It employs a simulation engine to calculate the behaviour of fabric under gravitational load. Changes in the boundary conditions (e.g. the position of anchors and height) or in its tailoring (e.g. the cut shape, holes and other textile manipulation features) are directly reflected in the fabric's drape simulation. It is, therefore, an iterative process in which the required final result is visualized through dynamic digital simulation. The simulation process is based on the calibration between the digital virtual realm and the fabric's physical materiality. It is material specific and requires the translation of material properties as parameters in the digital simulation interface (Hensel, Menges, and Weinstock 2006).

Fabrication process

The proposed fabrication process consists of the following detailed stages (Figures 2 and 3):

(1) *Tailoring composite woven fabrics to the desired shape*: Fabrics can be of varying fibres, thickness or weaving pattern. Prototypes of the process were realized both in carbon fibre and in glass fibre fabrics, using both wet lay-up and dry lay-up processes (pre-pregs). The tailoring of the membrane determines its organization in space.

(2) *Layering fabric plies*: Layering can differ throughout the completed piece in the number of plies, the types of fabrics and the cut shapes. This allows differentiated stress distribution in the final structure as well as local reinforcement. Fabrics are usually limited by the roll width (90–140 cm). Layering the fabrics allows the assembly of pieces for the manufacture of large structures, as well as the attainment of sufficient thickness.

(3) *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.

(4) *Setting the anchoring points*: The method used to anchor the fabric for the purpose of hanging is

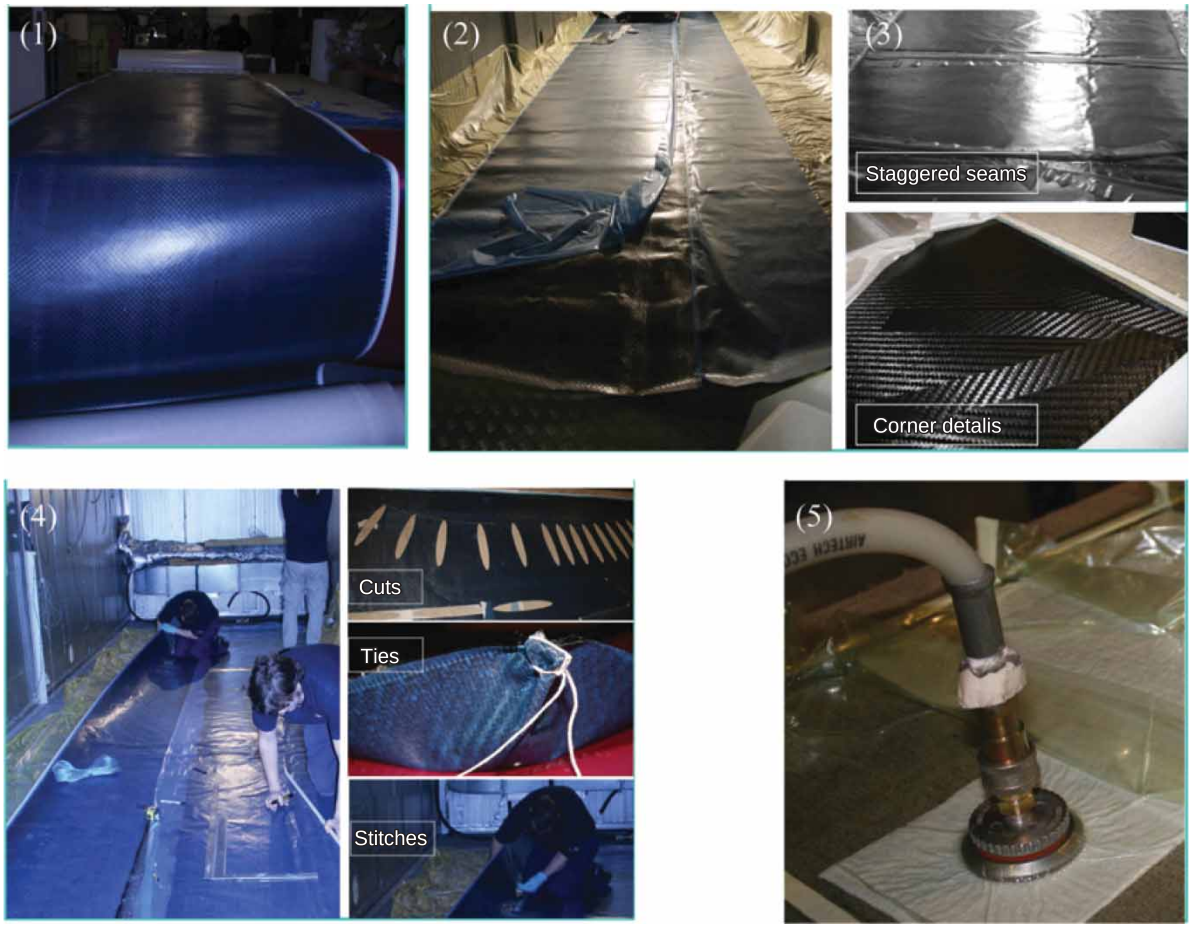

Figure 2. Fabrication process by stages. Top left: (1) tailoring composite woven fabrics to desired shape; top middle: (2) layering fabric plies; top right: (3) placing features; bottom left: (4) setting the anchoring points; bottom right: (5) vacuuming.

highly important, as it defines the local behaviour and stress distribution in the critical area where loads are transferred from the structure to the ground. Dealing with large structures with a heavy load of fabric requires a device crafted for the purpose. The hanging method for the prototype was based on using ropes to make simple corner ties in the fabric, which allowed the piece to be suspended from the ceiling.

(5) *Vacuuming*: An optional step of vacuuming the layered piece can be carried out at this point, to achieve higher uniformity and better quality of the final laminate by reducing the formation of air pockets between plies of the cured element. Contrary to regular tooling where the piece is cured while in vacuum, here the pressure is to be released before hanging.

(6) *Hanging the membrane*: The various anchoring points can be hung at different heights and locations, defining the resulting shape. 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) does not require an impregnation phase.

(7) *Curing*: The curing process is selected according to the chosen fabric and resin system. Wet lay-up fabrics often can be cured in a room with non-monitored temperature. Dry lay-up fabrics (pre-pregs) require a monitored curing temperature that can vary between 40°C and 200°C, depending on total curing time, ramping-up process and the materials chosen, and therefore curing is carried out in ovens. Curing ovens can be industrial and fixed, or temporary ad-hoc construction. Ovens exist in all sizes and can reach huge dimensions (such as those required for the construction of boat hulls, for example).

(8) *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

Figure 3. Fabrication process by stages. Left: (6), (7) hanging the membrane, curing; right: (8) inverting the stiff cured structure.

surface finishing such as sanding, coating and painting. The inverted structure will require further treatment for its placement and subsequent anchoring to the ground.

Features and manipulations of the membrane

As mentioned above, features taken from the world of garment-making, such as cuts, pinches and slots, can be introduced in the membrane to obtain a certain morphological outcome, or for local reinforcement of the structure. As the forms generated by the hanging cloth models behave structurally as surface-active structures, similar to classic shells, some similarities can be noted. Several typical issues that were addressed by the classical concrete master builders, such as the Wyss Garden Center in Solothurn, Switzerland, by Heinz Isler (1961) or the Palazzetto Dello Sport in Rome by P.L. Nervi (1957) can serve as valuable case studies for the forming of these FRP structures.

One of the principal structural issues of the concrete shell is its edge condition. This is the zone with the largest displacements and highest stresses to be expected. Isler manipulates the shell's boundary by creating a 'lip', thus getting a higher section, gaining in structural stiffness of the border and inverting the structural behaviour around the edges (Figure 4).

In a similar way, a lip is formed at the edge of the surface in the hanging FRP membrane by introducing cuts in the hanging fabric, thereby rendering it much stiffer (Figure 5). The stitch feature, when introduced close to the edge, also interferes with the edge's natural shape, adding additional local double curvature and transforming the stress distribution around it (Figure 5).

The introduction of slot features into the fabric can produce openings, transforming the local morphology and affecting the overall global geometry of the resulting structures. It offers the possibility of reducing the amount of material for better structural and material efficiency (Figure 5).

Potential scope of architectural application

The added value of the introduction of full-scale form finding as the fabrication process of FRP for architectural elements is mainly envisioned for two project types:

- Small to medium structures of complex free form morphology, treated as one whole form
- Large facade 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.

Facade components can tolerate variations, as the difference in form does not imply the fabrication of a new mould, but only simple changes in boundary conditions and fabric manipulations, which are easily obtained. The size of each component can easily attain the average size of conventional facade elements, one story high, and are easily transportable to the construction site. The fabrication of such components would typically take place off-site.

For both structure types, the surface of the element itself could be articulated by fabric manipulations, as described above (stitches, folds, cuts, etc.), to obtain specific performance requirements (ventilation, reduction of weight, flow of forces, acoustics, stability, insulation, etc.). These mechanisms should be further elaborated to form a tight link between the resulting performance and the surface articulation.

Form finding with FRP as a fabrication process for large-scale whole structures would pose significant complications. Subdivision of the global form into smaller manufacturable elements, as would be done in parallel fabrication methods, is not applicable to the form-finding method, which always deals with a whole element, affecting its design. Thus, it would require the manipulation of very large elements on site (hanging and inverting), which is hardly feasible.

Case study

The case study set out to examine the feasibility of the proposed design and fabrication process. It addresses the abovementioned project typology of a small to medium whole structure of complex morphology. The study's chosen subject was a seaside shading structure, measuring about 4 × 4 × 4 metres, which would provide sun protection for people on the beach. The harsh environmental conditions in beach areas – salty water, high humidity and strong sunlight – provided a good challenge for testing the use of composite materials.

The case study included two main parts. The first was developing a design method for generating shading envelopes using a digital form-finding process, and the

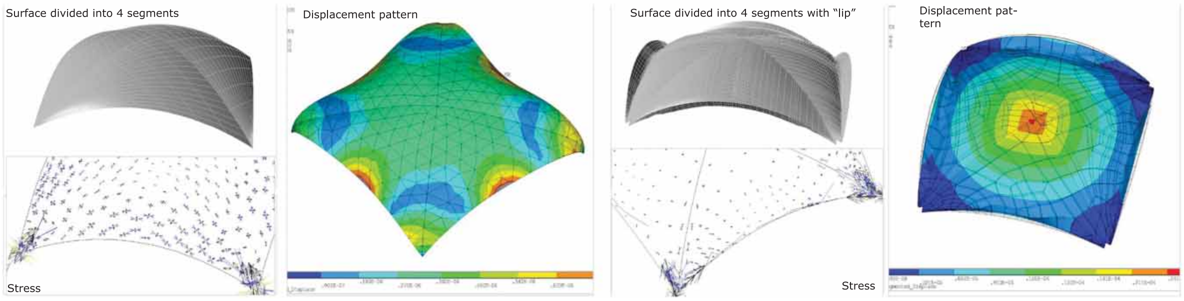

Figure 4. Reinforcing edge conditions by adding a lip to the shell's edge. Left: original shell surface. Right: manipulated surface.

Figure 5. Reinforcing edge conditions by adding features. Left: split; middle: stitches; right: slots.

second part concentrated on developing the manufacturing process.

Digital form-finding generation process

The design process, realized as a linear succession of simulations, took into account programmatic definitions as well as environmental considerations. It is the outcome of the desired shading timeframe (hours), and the number of people using each shading structure (area), the orientation of the structure (sun exposure), expected structural behaviour and wind loads, combined with the fabrication process (draping). The initial form-generation stage resulted in a design for the shading structure's preliminary envelope. It used an algorithm developed in MatLab software to calculate the area on a sphere that would be needed to provide shading for a specific location during a specific timeframe, for a given area (Figure 6).

The initial form was generated using a second form generation process that simulates the natural catenary draping of the cloth, deriving from the form-finding fabrication process. Using the input from the initial envelope's generation as a reference, it defined a second envelope that embeds the material properties and produces hanging points for the composite cloth material.

As a shape generated by form finding of a hanging membrane, it is globally naturally optimized as a shell, as ideal compression loads are the reflection of tension loads applied on the fabric by gravitation. Since we introduced manipulation and various boundary conditions that interfere in the simple naturally formed hanging shell, it was necessary to study its structural behaviour through digital simulation. The resulting envelope was used as a model for a finite element analysis in CATIA, to examine its general structural stability, expected behaviour of displacement and stress loads (Figure 7). At this stage of development, where the form was still loosely defined, the structural analysis was taken merely as a design guide to understand the general behavioural tendencies of the generated shell as affected by the manipulations applied on the generic hanging form and specific load conditions. Here, the results demonstrated in the structural analysis were integrated into the membrane's design through the introduction of two sets of operations that included cut-outs and edge manipulation. Locating areas with low stress levels in the structure, we then removed them by cut-outs in the cutting pattern. This saves material and helps to reduce the expected lift effect of wind forces over the structure.

The areas with the highest level of expected displacement were treated by edge manipulation. Special pockets to be injected with polyurethane were designed along the edge, thereby achieving structural height at the structure's weakest point, without the addition of significant weight. Both of these design alteration methods were expected to impact the structure's structural behaviour. This calls for an

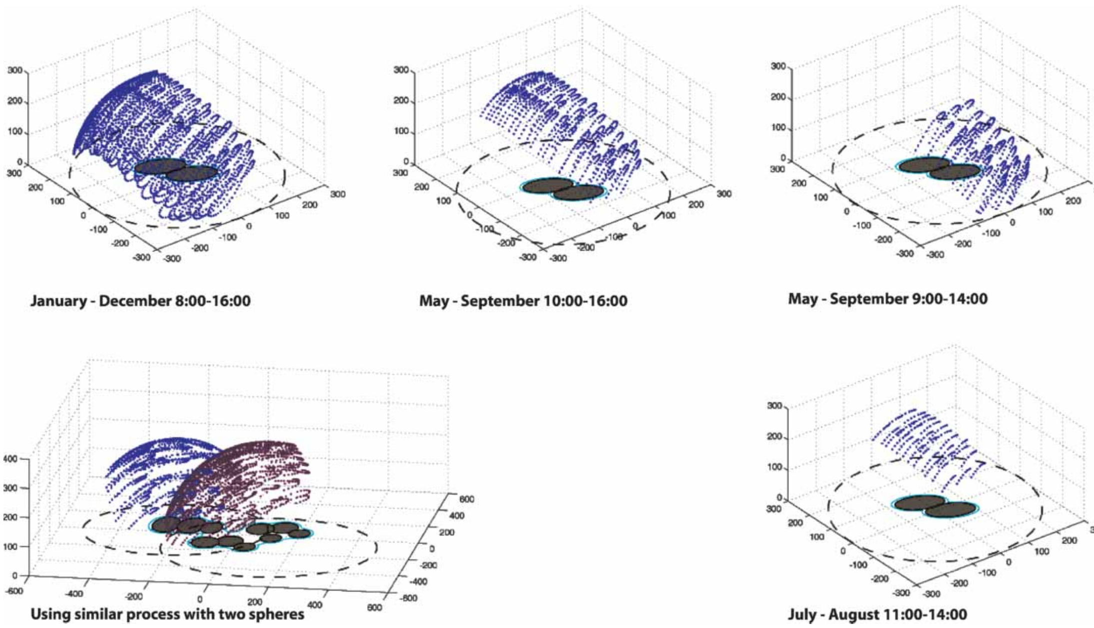

Figure 6. Examining the influence of different area and timeframe definitions on the shading envelope.

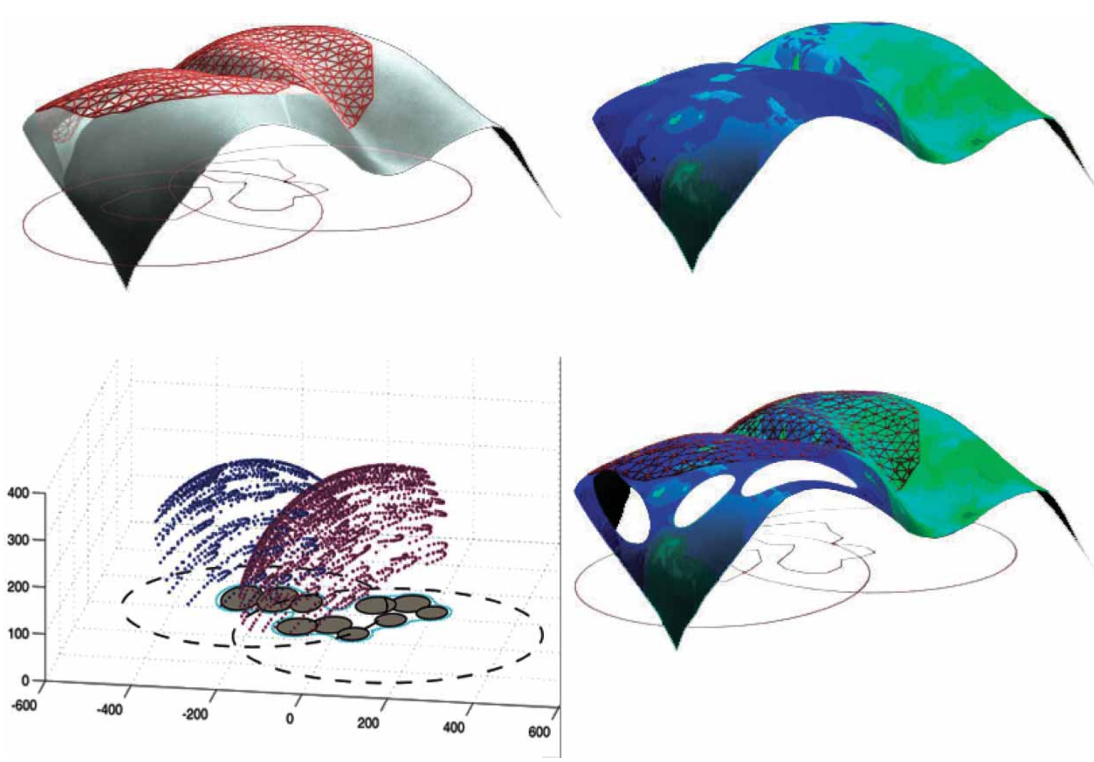

Figure 7. Lower left: Initial point cloud-generated envelope; upper left: merging the initial envelope with a second envelope that was generated in a gravitational form-finding process. Upper right: structural load/tension analysis. Lower right: perforating the envelope according to the structural analysis and other programmatic demands.

iterative process of design and analysis, in order to achieve an optimal end result based on the fabrication process and the specific conditions of its application as a project. The iterative design process was beyond the scope of this case study, but should be considered for further elaboration of the research.

To fully benefit from the structural analysis, there must be a validation of the digital model with regards to its physical behaviour. This cross-validation has not yet been processed, as it requires a higher level of accuracy throughout the fabrication process and a more detailed level of cloth simulation in the digital model. This higher level of

Figure 8. Left and centre: case study test model. Right: rendering of a proposed shading structure.

accuracy will enable the second level of required structural analysis, dealing with a buckling analysis of the structure, which is highly important.

Fabrication

The fabrication process used for the case study followed the stages described earlier (Figures 2 and 3). Two scale models were realized, using multilayer fibreglass fabric and basalt fabric. Both used epoxy resin as their matrix. The curing process took place during the summer when the air temperature hovered at about 35°C. The fibreglass fabric was cut and perforated according to the pattern generated by the digital simulation (Figure 8).

In order to locally increase the edge's cross-section, polyurethane was injected as structural reinforcement in special fabric 'sleeves' introduced as pockets in the tailoring of the membrane, according to the structural analysis. The use of polyurethane as foam during the course of the fabric's curing process enabled it to adapt to the natural draping of the cloth, thus causing minimum interference to the designed natural drape. The structure's fabrication was performed with a single curing phase, without applying post-curing.

Discussion and conclusions

The research study presents a framework for employing FRPs for architectural structures, by experimental fabrication processes. A fabric-oriented design and fabrication method was proposed and evaluated in a case study design of a pavilion-like structure. The suggested approach demonstrates a potential for a fabricating complex double-curved architectural elements, without the need of a mould. It shows the feasibility of forming a continuous surface by superposition of plies with no stitching or gluing, which enables the fabrication of elements at various scales. It also introduces a wide range of elements and surface manipulation techniques, taken from the world of garment-making, with structural attributes that can influence the overall behaviour of the FRP element both structurally and environmentally.

The preliminary research and case study highlight areas that require further development and research in several parallel directions. These areas are presented in descending order combining applicability and importance for the development of future architectural applications:

- As a fabrication system, which is at the same time a design process, the suggested approach requires an adapted digital design tool. While the current stage has made use of several available commercial tools with no custom development, the approach requires the tailoring of a specific digital procedure and linking tools from different disciplines. Further development might require a tailored API, which will successfully integrate elements from fabric manipulations in fashion and physical simulation based on material properties, under the scope of architectural applications (adequately dealing with scale and tolerance issues). It should enable a direct link between specific material data (type of fabric, weight, weaving, etc.), the fabric manipulations applied to it and its final morphological outcome.
- The formal language of the final architectural form to be realized by the proposed fabrication process is derived from the form-finding process itself, and the manipulations applied to the fabric. To avoid an overly direct representation of the process in the final architectural project and open up design possibilities within the suggested process, additional manipulation techniques and form-finding methods are necessary. Further investigation into the possible combination of different form-finding processes (e.g. pneumatics and tensile parts), additional fabric manipulations (e.g. stitches and folding) and the integration of local stiffening elements into the draped fabric will expand the limits of the actual formal languages demonstrated by the case study and the initial experiments.
- Fabric manipulations, borrowed from garment-making techniques, have been introduced in various parts. Based on the initial proof of concept demonstrated by the case study, manipulations such as the injection of polyurethane into pockets between material layers can serve as reinforcement features for the structure. Further experiments are required for the elaboration of the process, which must then

be assessed by research and analysis of its structural contribution.

- Scale is inherently linked to fabrication process in this approach. Several parameters, such as oven curing, matrix type and mechanical process of inversion, impact the final structural outcome. Further research and experiments should investigate the material limits regarding scale as well as the possible solutions for oven-curing requirements. It will affect the range of future architectural applications of the described experimental method.
- A possible derivation of the method for the realization of larger elements could be its use as 'lost form' moulding, where the mould serves as an integral part of the final structure and is therefore not considered as waste. Further research and experiments in that direction are needed to move towards a solid proposal.

Applications in architecture

Freeing the fabrication of architectural FRP elements from the need for a mould could potentially have a significant impact on the integration of FRP elements in architecture. In its current stage, the research aims at architectural elements of two generic types: the fabrication of entire structures on a small to medium scale and of larger systems made up of smaller differentiated components. The potential of the former has been evaluated in the case study of the beach shelter described above. One major size limitation inherent in the proposed approach has to do with the need to use an oven in the curing process. This limits the size of the expected product and influences the cost. However, ad hoc ovens on site are a plausible solution, and the use of resin systems that do not require curing at high temperatures can be developed. With further research and development, as suggested above, this could also apply to the building of small-scale structures, especially structures that require rapid construction and a high strength-to-mass ratio, such as post-disaster rigid shelters and service structures. FRP's durability also makes it especially compelling for challenging environmental conditions such as seashores and tropical areas.

As the proposed method allows for variants with minimal effort, differentiated elements can be fabricated following performance-based design processes, forming large systems of facade claddings. Its application as a component-based system that can easily integrate variability between its components is to be evaluated and demonstrated by further research and experiments. For this type of application, fabrication off-site seems preferable since it can rely on large-scale industrial curing ovens.

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 towards differentiation and responsible complexity of form.

Acknowledgements

The case study was developed in collaboration with Guy Austern, Mushit Fidelman and Tzach Harari. Their contribution is hereby acknowledged.

Disclosure statement

No potential conflict of interest was reported by the authors.

Notes

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