# Introducing Fabric Materiality in Architectural Fibre Composites

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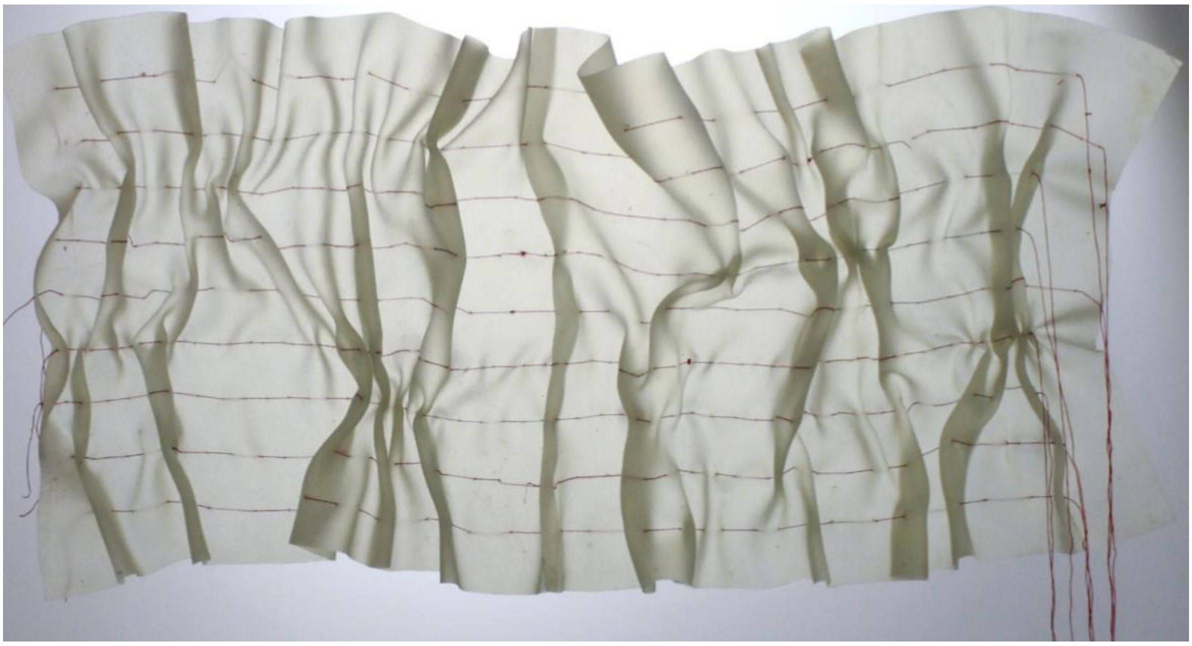

Fig. 1 reFrost, by Arielle Blonder and Shira Shoval, for the exhibition ‘Smart-Stupid materials’ (Curator: Shlomit Bauman), Vitrina gallery, 2016.

Additional Key Words and Phrases: fibre composites, fabric, materiality, FRP

## 1 INTRODUCTION

Textiles and architecture have long been associated, since early days of men. As the robe provides protection to the human body from external peril, so does the tent provide protection from the external environment and its hazards. Both the dress and the house define limits, guarding and projecting an image to the outer world. Seen as second and third skin, the strong connections relate the world of architecture to that of garment making, mostly dealing with textiles [1].

From the most primary act of raising a tent to the contemporary construction of large structures made of technologically advanced membranes [2], fabric has always been present as a material for architectural structures. Beyond the usage of fabrics as actual construction material, the nature and behaviour of textiles has served as a models of different kinds along the centuries. 19th century theoretician of style, Gottfried Semper, positioned textiles as the theoretical model for the primary origin of architectural element [3], and philosopher Gilles Deleuze places it as an abstract model of contemporary smooth space [4]. Textiles were used as structural models by engineers such Heinz Isler [5] and Frei Otto [6], studying their self-organising and natural optimisation capacities through physical models for the design and erection of pioneering structures of complex morphology, lightness and efficiency. Textile material practices serves as a design paradigm, in both architectural practice and experimental research and teaching [7] [8], demonstrating Semper’s theory of permeability and transposition between different abstract procedures of material making [9].

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Inscribed within the renewed position of matter as a motor for design in recent years [10], this research revolves around the material qualities of textiles. It coins the term of ‘Fabric Materiality’, suggested as a means to revisiting architectural design and fabrication processes. Three key-assets of textiles are identified, through which the development of *fabric-materiality* material systems will be carried.

This paper will demonstrate FM integration through the case study of Layered-*fm*FRP, a material system of surface elements in fibre reinforced polymers (FRP), a fibre-based composite material. FRP standard fabrication processes rely heavily on moulds, restricting the possibilities for free architectural expression within a sustainable framework. The integration of FM as a FRP material-system releases the need for a mould, enabling contemporary architectural practices such as variation and surface articulation. Its outcome demonstrates structural capabilities, along with material properties of a porous matter-structure.

The paper will start with the definition of *fabric materiality* and its key textile attributes, followed by the presentation of *fm*FRP and the potential connection of FM to fibre composites. A case study of a FRP material system will be described, demonstrating the integration of *fabric materiality* principles through the textiles’ key-assets. Finally, the paper will conclude with the resulting structural capacities and unique material properties of its outcome.

## 2 FABRIC MATERIALITY

Fabric materiality has been present in architecture under different forms even when not defined as such. The special properties of textile turned it into a source of inspiration for architecture, serving as structural model, or building material. The term of Fabric Materiality (FM) is coined, to represent the unique qualities of textiles, their associated techniques and tools, assets and design paradigms. Inscribed within the contemporary positioning matter as a motor for design, it is suggested as an architectural design approach of ‘material-systems’, integrated as experimental research in material and fabrication in the field of architecture.

### 2.1 Terminology

‘Cloth’, ‘Fabric’ and ‘Textile’ all represent the soft and flexible piece of material, which is fibre based. As these three terms are interchangeable for their principle meaning, here the choice was made for the word fabric, for its Latin etymology, which associates it to the notions of fabrication (skilful production) as well as construction (structure). Its additional meanings refer to the construct of things, the basic underlying structure or framework of anything, the arrangement of physical components in relation to each other and anything constructed or made of parts put together (“Fabric Definition and Meaning | Collins English Dictionary” n.d.).

The term ‘materiality’ represents the new position towards matter in the design world, drawing on the ‘New Materialism’, an interdisciplinary, theoretical, and politically committed field of inquiry emerging at the turn of the 20th century [11]. Revolving around the primacy of matter, it promotes a renewed substantial engagement with the dynamics of materialization. Matter is perceived as an active force that is not only sculpted by, but also co-productive in conditioning and enabling social worlds and expression, human life and experience. In the architectural context, it highlights the shift from the postmodern tradition of visual formalism to a material perception of the world that deals with pragmatism, mechanisms of performance and morphogenesis processes. Through a revisited approach to causality, space and structure, it presents new understanding of matter as possessing morphogenetic powers of its own [12].This new position towards matter is tightly linked to the introduction of digital media into architecture in the mid-1990s, placing fabrication and generative design processes as core concepts of the architectural discourse [13]. It is not only an expansion of the architect’s palette of expression or methodology of design [14] but furthermore an ethical engagement and a contemporary understanding of the architect’s duty and professional responsibility as an active participant in the evolution of material culture [15].

Addressing material as a motor for design, implies subsequent changes in the usual process of making architecture, that traditionally separated between design and its making. The design-materialisation chain is viewed as one holistic process, integrated as experimental research in material and fabrication; the architect now plays an active role in the development of materials and their making. The concepts of emergence and self-organisation, complemented with advanced computational tools, deploy the material’s morphogenetic capacity as a system [16] [17]. Such systems do not differentiate between formation and its materialisation processes and link performative capacities to morphological complexity. Contrary to construction systems, material systems describe “… the complex reciprocity between materiality, form, structure and space, the related processes of production and assembly and the multitude of performative effects that emanate from the interaction with environmental influences and forces"[18]. The elaboration of a material system consists of the exploration of a design space established by its constraints; it relies on the identification of the system's performative capacities within its materially determined limits, deciphering the material's behaviour rather than focusing on its shape.

In the context of new practices of material-making, blurring boundaries between processes of digital fabrication, craft and architectural design, *Fabric Materiality* is suggested as an approach to design and fabrication, explored through the development of *fabric materiality* material-systems.

### 2.2 Fabric Materiality Principle Assets

The definition of fabric materiality lies in the identification of key attributes; unique qualities of fabrics as a material, with their associated textile processes, material properties and capacities. With the objective of suggesting an alternative forming process for architectural FRP, it focuses on textile being a pliable, soft, and self-organising material that achieves complex forms. From that, three main attributes are identified as assets that constitute FM, to serve as the basis for the development of a FM material system: textile parametric variability, self-organisation and resilience.

*2.2.1 Textile Parametric Variability* refers to the multitude of parameters that affect the physical properties of the fabric, from the fibre itself to its internal spatial structuring. The fabrication of a textile product is a long chain of processes, potentially going from yarn manufacturing all the way fabric construction, and its end-treatments with coatings and paints. Each step is in itself a multiple-parameter process, affecting directly the quality of the end product [19]. Being an engineered material, its build-up is controlled by a great number of parameters; density, pattern, tension, fibre construction and type of machinery are just a few examples of parameters that affect the characteristics and behaviour of the resulting surface, enabling its parametric manipulation. The combined know-how of the textile engineer and designer determine the performative and the aesthetic properties of the material, making it an artefact in itself (prior to any application). These manipulations of parameters in the generation of textiles is perceived as the source of its agency as a medium of communication and as a conceptual apparatus [20].

*2.2.2 Self Organisation* refers to manipulations on a higher level of hierarchy, dealing with the fabric itself and its ability to embrace complex forms. Responding to the application low-energy stresses upon it, the material gains structural stability and spatial organisation of a greater order. The ability to apply low-energy stresses upon fabrics and generate complex three-dimensional structures is a unique property of the material that has been the founding principle of fashion along history. This ability to manipulate easily the material in order to achieve a desired structure has been channelled 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 three dimensional structures in space [21] [22]. This emergent behaviour of the material holds within it the capacity for natural optimisation; it is strongly present in the architectural tradition of form-finding, with leading figures such as Frei Otto and Heinz Isler using fabrics in physical models to study shape and structure [23][24].

*2.2.3 Resilience* refer to the ability of the material to recover after a shock or destabilisation. It is conceived as a part of the global attention accorded to the concept of resilience in recent years, being actualised in discussions about diverse entities as societies, cities, financial plans, ecosystems, materials and more [25]. The ability of a system "to bounce back" and return into stable state after a shock [26] is variably interpreted in different fields as adaptability, transformability, capacity to withstand disturbances and strategies for dynamic stability [27]. In textiles, resilience was first formalised and quantified in the late 1940's, as " the capability of a substance to return to its original state at some later time after the removal of a deforming stress" [28]. The resilient properties of fabrics derive from its internal structure that is based on a multitude of simple and weak elements interacting and constructing a greater whole, granting it with flexibility and ability to recover to an initial or improved state after stress events, demonstrating thereby soft stability and robustness.

Some general characteristics of resilience include an architecture that contains sub-systems, or multiple parts, in some network configuration. The multitude of elements with a degree of redundancy and reciprocal connections is essential. Such elements should be of similar kind, yet incorporating differences and variations. This diversity that is indispensable for the resilient system, is expressed through relative freedom of each component, while nevertheless being inter-connected [25] [29].

## 3 FABRIC MATERIALITY FRP

### 3.1 Architectural Fibre Composites

Fibre reinforced polymers (FRP) is a fibre based composite material family that offers extraordinary properties of strength-to-weight ratio and durability. Advanced fibres, such as glass, carbon or aramid, are combined with polymer resins, such as epoxy or polyester, to form a composite material with enhanced capabilities, in which each constituent retains its chemical and physical identities. Since their initial introduction in the 1940's, the use of fibre composites has spread across numerous sectors of industry, from aeronautics to industrial design, infrastructure and renewable energy. It is today a leading material solution wherever high performance is required, thanks to its lightness, strength and durability, combined with high versatility [30].

The use of FRP in the construction industry is well established, for varied purposes and by different application modes [31]. As for the architectural field, the rising architectural interest in the material, due to its performance and ability to take complex shapes through moulding, is enhanced by recent technological improvements and significant advances in building coding and regulation [32]. However, although we witness a renewed interest in the material in recent years, initiated by the introduction of computation into the field [33], its application is still relatively limited. Despite the opportunities offered by the unique properties of the FRP, its application for architecture raises significant issues and there are still outstanding gaps in the ability of FRP to respond to some emerging challenges in a sustainable and reasonable way [34]. Numerous fabrication processes, methods and tools constitute the FRP know-how and best practice in the filed today [35] ; all methods rely on the application of the material over a rigid mould, and on ultimate adherence of the material to the mould with minimal gaps and absolute control along the process. The typically large scale and uniqueness of the architectural object, together with contemporary architectural practices such as complex shapes, surface articulation and the variation of form, highlight the limitation posed by the total reliance on moulds in the standard fabrication processes of FRP.

The heavy implications and limitations due to the reliance on moulds, together with the quest for morphological complexity and variation calls for an alternative approach to the design and fabrication of architectural FRP. The research realized at the ICD Stuttgart addresses this barrier by the minimization of the reliance on moulds with robotic filament winding techniques, as demonstrated in different research pavilions in recent years. [36][37]. This research develops an alternative approach focusing on the fibre constituent of the material, used largely under the form of fabrics; it suggests the integration *Fabric materiality* as a FRP material system.

### 3.1 Fabric Materiality FRP

While the fibre constituent in FRP is used mostly in the form of fabrics, its standard fabrication processes do not rely on its inherent textile qualities. Standard FRP fabrication processes press layers of fabric onto rigid moulds, utilising the fabric's ability to adhere optimally to the given rigid form (Mallick 2008); mechanical pressure on the mould overrides the fabric's inherent characteristics, leaving no expression for its unique capacity for self-organisation. The resulting morphology reflects only the morphology of the rigid mould, with no presence of any typical textile form; hence, the materiality of the constituting fabric is not expressed.

The three attributes of FM developed above, serve as means to introduce textile qualities into design and fabrication of artefacts and spaces. The integration of FM in architectural FRP entails the adoption of new textile-related design concepts organised through parametric variation, self-organisation and resilience. The development of a *fabric materiality*-FRP material-system (*fm*FRP-MS) is expected to release architectural FRP from the heavy limitations of the mould-based process, and by that enable free architectural expression.

A textile is an engineered material construction, in which performance is obtained by the respective spatial placement of a multitude of small and relatively weak elements, being the fibres. This similarity to the composite material, being an engineered material constructed out of a multitude of layers, creates inherent affinities between design paradigms related to textiles and those of fibre composites. In a similar way, design principles of biological composites, from cellulose-based plants to collagen-based living tissues, could be analogous to fibre composites [38]. Several characteristics were identified [39] to be of interest for future integration in the design of engineered architectural FRP. Such characteristics suggest that differently from the engineering problem-solving approach to biomimetics, the architectural one should aim for an adoption of principles and mechanisms at different scales of magnitude and with varying degrees of abstraction. With FRP, textile and biological composites, all being non-homogenous materials constructed out of fibres, connections can be traced between FM key assets and design features and biological or engineered design paradigms; embedding FM principles in FRP fabrication is expected to enable the integration of such biological design principles [40]. FM approach to composites redefines the role played by fibres in the making of the forms, suggesting a biologically inspired design approach. Replacing the restrictive moulds with fibres enables local differentiation, inherent optimization, ornamentation and sustainable variation, which are essential to architectural expression today.

## 4 LAYERED *fm*FRP: A CASE STUDY

*Fabric materiality FRP* is demonstrated through the case study Layered *fm*FRP (L*fm*FRP). Previous experiments in the research investigated linear elements in a biologically-inspired FRP system [41], whereas here, surface elements are developed.

Standard planar semi-finished FRP products are made as laminates, composed of several plies of fabric, impregnated with resin and formed over a mould in a variety of techniques. from hand lay-up to RTM and infusion [2]. Due to their typical small thickness in relation to the unit's overall dimensions, the strong but flexible planar element requires stiffening in order to enable larger spans. The necessary stiffening is typically achieved by profiling the cross-section (troughing), by including reinforcing ribs (ribbing) or by employing a sandwich form of construction [42].

### 4.1 Fabrication Process

The fabrication process of L*fm*FRP surface elements consists of the layering of fabrics (fibreglass), pre-impregnated with resin and manipulated by pleating, to form a porous laminate that is oven-cured. The individual layers of fibreglass prepreg material are manipulated separately in a simple manual process of gathering that creates pleats over the surface [43][1]. The gathering pleats are controlled by a thin metal rod that is inserted through a row of holes, along which the folds are formed with ties. The spacing of the holes and the ties constitute the folding pattern of the sheet [Fig. 2]. The density of the pleats and the spacing of their holes, which constitute the pattern, affect the resulting morphology of the sheet (radius of curvature and size of the pleats), its stiffness, thickness (section height) and aesthetics.

The manipulated layers are stacked for the curing process in a frame, contracting the layers so that contact areas between the layers are formed and the overall thickness of the stack is reduced. The outer layers can be hanging freely or levelled and flattened by top and bottom planes. A short oven curing is then needed to selectively laminate the layers. The result is a stable thick planar element, a porous matter-structure with highly articulated surface [Fig. 3].

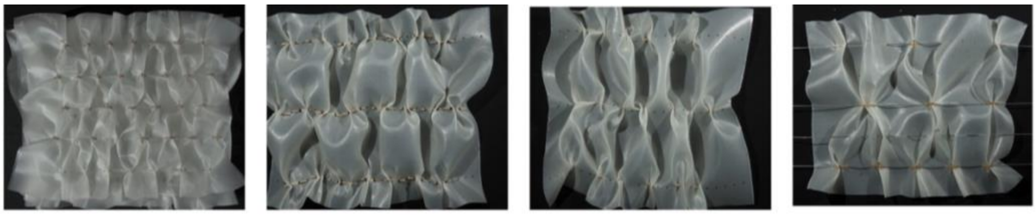

Fig. 2. Different pleating patterns varying in number of rows and location of ties. (Approx. panel size- 480X600 mm)

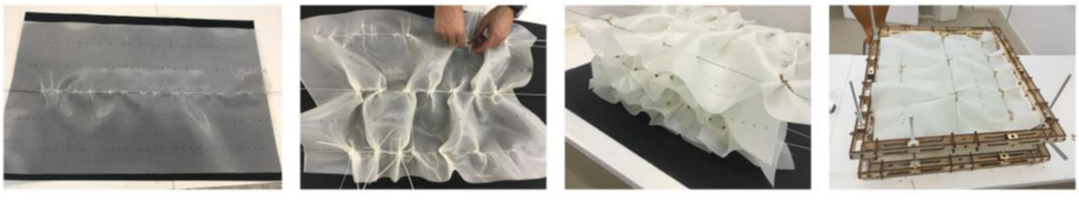

Fig. 3. Fabrication process of FM FRP panel

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[1] For a more detailed description of the gathering pleat and the forming of the single layer see Blonder, Arielle. 2017. 'Layered Fabric Materiality in Architectural FRP Surface Elements'. In Proceedings of the IASS Annual Symposium 2017 Interfaces: Architecture.Engineering.Science 25–28th September, 2017, Hamburg, Germany

### 4.2 FM attributes in L*fm*FRP

The development of the system follows the three main FM attributes.

*Textile Parametric Variability*- The ability to generate large amount of variation within the same system, with no (or little) additional effort, is essential to the concept of Fabric Materiality. In L*fm*FRP the variability is obtained by the variation of the pleating pattern of the single surface. For better control and prediction over the system, a limitation in one axis was added by the insertion of metal rods, along which the gathering is formed. Nevertheless, this still leaves an extremely large field of possibilities for variations. The number of lines over the surface, their orientation, their form (curved or linear) their orientation over the surface, the spacing of pinching holes along the line, and above all the pattern of pleating, allow for a very large number of variants [Fig. 4]. At the system-level of hierarchy, the layered element is varied by the number of layers and the spatial arrangement of the different pleated layers, forming each time a different assembly with potentially varying performance and visual aspect

Fig. 4 Variability in three pleated surfaces, differing in number of lines, their orientation, and pleating pattern

*Self Organisation* - The self-organising capacity of the textile material, with its capacity to generate large dislocations and complex geometry out of simple manipulations, stands at the base of this system. As in every self-organising material system, the type of boundary conditions and their quantity, will determine the freedom of the material to self-organise. On the level of the single-layer, boundary conditions are set by the lining rods and the pinching hole spacing.

On the system level, self-organisation is dominant in the assembly of the different manipulated fabric layers into a ‘laminate’. The contact between the different layers is achieved with the self-organisation of the layers under the compressive pressure generated by the spacing of the lining rods.

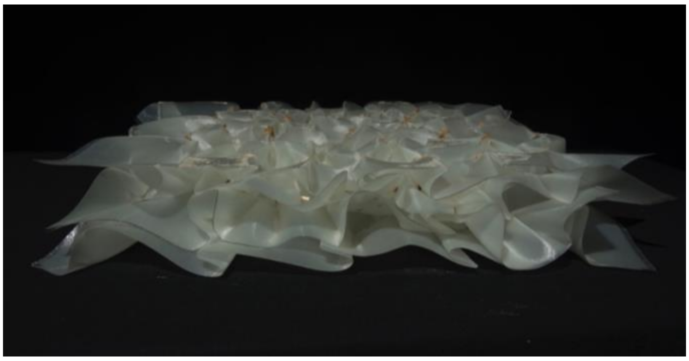

Fig. 5. A panel of 4 layers, 1.2 kg/mr2

*Resilience*-The structural capacity of L*fm*FRP is achieved through a multitude of thin and weak layers of material. Favouring the multiplicity of weak units over minimisation and optimisation of selected robust ones is a central resilient characteristic of the system. Similar to resilient natural design strategies, here too redundancy and seemingly-excess of material to afford the pleating, are essential. The layers of the laminate are similar, yet different in their pattern; as the form is achieved by self-organisation, even identical manipulations result in slightly different outcomes. This variation of the units within the whole, is an important property of resilient systems. The partial lamination and local adherence between the different layers is the key to its performance as one structural element. However, its resilient character entails the relative freedom of the layers, making it flexible yet structural, with enhanced structural height of the laminate,

### 4.3 Testing L*fm*FRP

The properties of FRP are well established in practice and academia, with mechanical properties and anticipated behaviour that inform digital simulations and detailed design and engineering [35]. These properties are based on standard fabrication processes, that require moulds and ensure complete and perfect lamination of the material layers, under strict fabrication specifications. The alternative fabrication process of L*fm*FRP does not correspond to such specification. As such, the properties of the resulting porous matter-structure could not be theoretically derived from literature, but should be acquired experimentally.

A series of mechanical testing was performed[2] on a variety of samples of L*fm*FRP for collecting initial data and developing basic understanding of its performance [44]. Three different test series were run on different material-elements, in correlation with a potential architectural application. All samples were realised in fibreglass-epoxy prepreg, plane weave, of 300 gr/sqm. As surface elements, cladding was selected and three schematic attachment types of façade tiles were imagined, to serve as a reference for testing [Fig. 6]: tensile tests (a-suspended panel), compressive tests (b-fully attached) and bending tests (c-local anchoring).

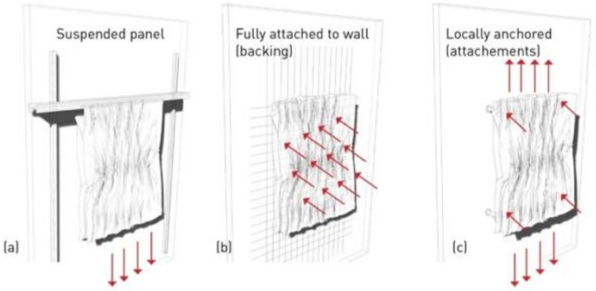

Fig. 6. schematic anchoring types of façade tiles (a) suspension (b) backing (c) point fixtures

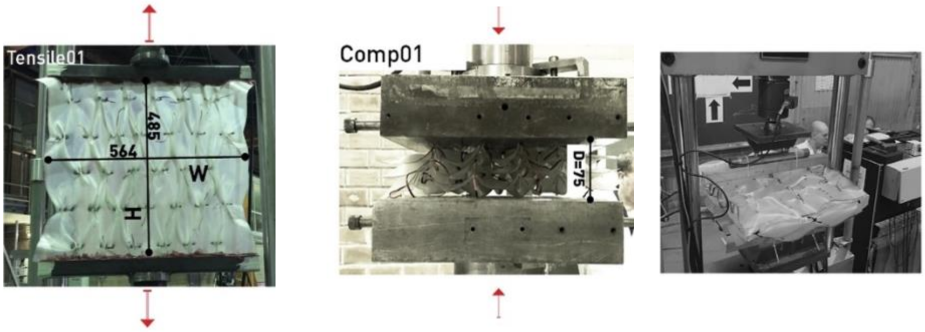

Fig. 7. Mechanical tests (a) tensile (samples of 2 layers, varying sizes) (b) compressive (samples of varying amount of layers, 2-4, typical size 340X190 mm) (c) bending (samples of 4 layers, typical size 600X550 mm)

### 4.4 L*fm*FRP Mechanical Performance

The system has demonstrated structural capacities under different loading conditions. The testing indicates that the L*fm*FRP panels is compatible for application as [illegible] he un-manipulated [illegible] dulus of 15.5 GPa,) [illegible] manipulated panels (20-25KN/meter of width) [Fig. 7]. Nevertheless, these values still indicate suitability for suspended façade panels, as the stress applied by vertical force of self-weight is minimal, thanks to its extreme lightness, and good stiffness values.

The compressive tests demonstrated a distinctive flexibility perpendicular to panel plane (50-70% displacement with good recovery and no complete failure [Fig. 9]. The outstanding recovery of the structure after release of pressure, and the ability to withstand very high displacement values, demonstrate an overall spring-like behaviour of the element, indicating its ability to withstand typical wind loads as a fully supported façade panel (less then 1mm of displacement calculated for 35m/s wind load).

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[2] For a detailed description of the testing and results see Blonder, Arielle, Yasha Grobman, and Pierre Latteur. 2018. 'Pleated Facades: Layered Fabric Materiality in FRP Surface Elements'. In Proceedings of IASS Annual Symposia International Association for Shell and Spatial Structures (IASS), 2018., 2018, no. 8:1–8.

Bending tests supplied an initial indication of the panels' expected deflection under wind loads (for example, for a partially supported vertical application) or under self-weight (for example, for horizontal ceiling application). The bending tests show an expected difference between each two perpendicular directions of loading for the same panel, with a significantly reduced performance when loading in parallel to main pleat orientation (perpendicular to gathering line) [Fig. 10]. An equivalent stiffness of the panel is calculated, based on a simplified model of the panel as monolithic material in order to apply the classical beam theory. Although this theoretical calculation necessitates further physical testing for its validation, it indicates a ratio of deflection to span that is higher than the deflection ratio of standard structural elements (1:100, compared to 1:200 -1:500). Doubling the number of layers (and panel thickness) would significantly reduce the deflection, close enough the expected standards. In any case, thanks to its low density and high flexibility, such deflections would not cause any concentrated stresses leading to rupture and failure.

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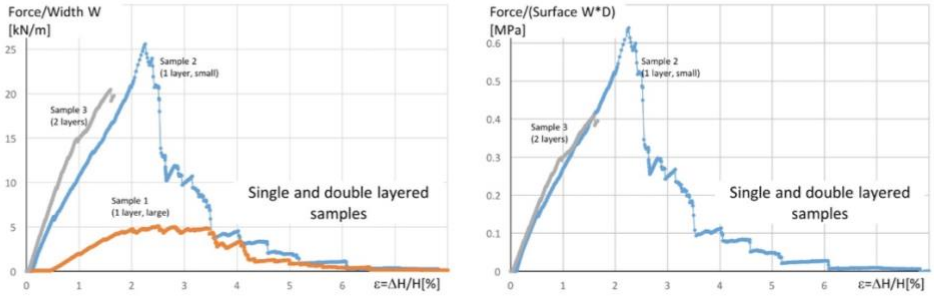

Fig. 8. Tensile tests of single and double- layers folded samples: Force-displacement (left) and stress-displacement (right)

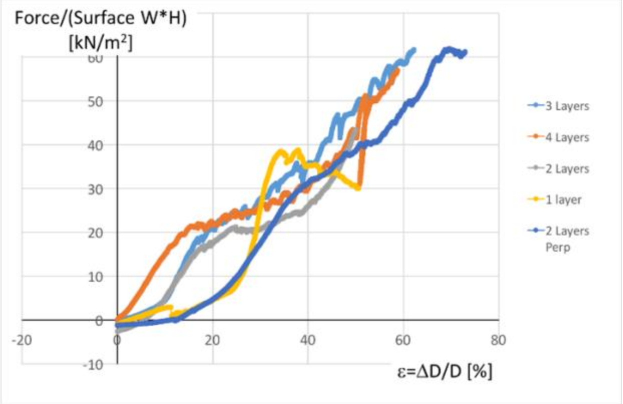

Fig. 9. Compression test, Stress to displacement (5 panels tested) (%)

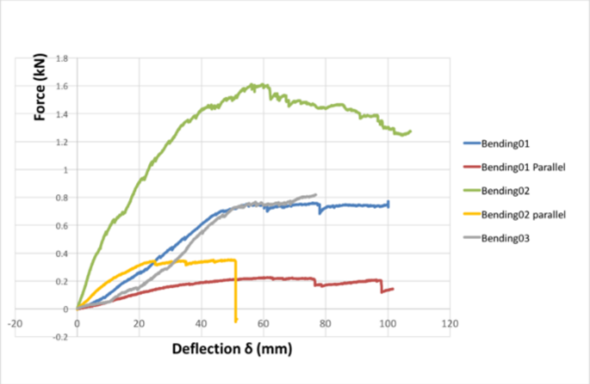

Fig. 10. Four-point bending tests of three panels in two perpendicular directions

## 5 DISCUSSION AND CONCLUSIONS

L*fm*FRP is a material system of surface FRP elements, generated through the integration of FM principles. The combination of FRP mechanical properties of flexibility and lightness, with the unique geometrical properties of complex double curvature and intricate articulation of textiles, results in a porous, articulated, layered product. Its high porosity and highly articulated surface morphology, places it in between material and structure, oscillating between scales and definitions. This outcome is at the same time material as it is structure, depending on the hierarchical level of observation and control. It can be characterized as a structural porous matter-structure, with a typical density ranging between 13 to 20 kg/m$^3$. Interestingly, this extreme-low density is similar to the density of the linear *fm*FRP material system, 'LifeOBject' (9-10 kg/m$^3$) [41] developed previously in the framework of this research. There too, the product of the material system could be qualified as an articulated porous matter-structure, with characteristics that resemble those of L*fm*FRP, and differ from traditional FRP materials.

The L*fm*FRP experiment has demonstrated that founding the process on textile qualities has indeed released from the absolute need for rigid moulds. By that, it has liberated the free-form expression by the material, enabling the generation of complex free-form morphology. The articulation of the surface is inherent to the system and its fabrication process; while such architectural aspirations pose a challenge in standard FRP fabrication, they are the natural outcome for the FM material systems. In the same way, its parametric variation is easy and requires no additional effort. The initial mechanical tests indicate its structural capacity for architectural application, and call for further exploration of specific loading cases and architectural details.

Beyond the fulfilment of the research' objectives and the demonstration of its structural capacities, experimenting with *fm*FRP material systems has surfaced new notions within architectural FRP fabrication. Soft and open-ended control is a key concept to the design and fabrication processes, for the generation of the layered material which relies on the self-organisation capacities of the material. The various samples can be identified as similar on a global level, while being each unique and the result of a partially random material self-organisation. However different, these variants demonstrate common properties and typical mechanical behaviour, which enable their general mechanical and geometrical characterisation. As such, it contrasts the tightly-controlled process of FRP mould-based fabrication, usually engineered with minimal tolerance and ultimate precision. Conceptually and practically, it is an interesting field of further exploration, especially in regards to future interfacing of FM elements with other systems of classical engineering logics.

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