IASS 2018 BOSTON, JULY 16-20
CREATIVITY IN STRUCTURAL DESIGN

Proceedings of the IASS Symposium 2018
Creativity in Structural Design
July 16-20, 2018, MIT, Boston, USA
Caitlin Mueller, Sigrid Adriaenssens (eds.)

Pleated Facades: Layered *Fabric Materiality* in FRP Surface Elements

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Abstract
FMFRP is a material system of fibre composites (FRP) that relies on the textile qualities of the composite material. The essential material qualities, attributes and design paradigms of textiles, with their associated techniques and technologies of fabrication and transformation, coined as *Fabric Materiality* (FM), serve as a starting point for this continuous research. Embedding FM in FRP generated the FMFRP material system and it suggests alternative design and fabrication processes of FRP architectural element, which facilitate contemporary architectural practices such as variation, surface articulation and complex morphologies. The development of layered FMFRP surface elements results in porous, articulated light-weight panels, potentially suitable for façade cladding applications. This paper describes the initial mechanical testing operated on this matter-structure, being a first step towards a confirmation of the suitability of FMFRP to architectural applications.

Keywords: FRP, composites, fabric, self-organisation, façade cladding, materiality, fabrication

1. Introduction
Fibre reinforced polymers (FRP) are fibre based composite material family that offers very good properties of strength-to-weight ratio and durability, which have led to their wide implementation across numerous sectors of industry in the past decades. Their ability to take complex shapes through moulding, together with recent technological improvements and significant advances in building coding and regulation, brings a vivid renewed interest in the material (Bedon [1]). This is noticeable in several recent projects, exemplified in the state-of-the art façade of the SFMoma extension, currently being the largest composite façade in the US (Kreysler [2]). The 710 different panels of the façade, each laminated on a singular CNC milled mould, demonstrate the significant amount of energy invested in the forming process of the composite material, requiring moulds and by that facing challenges in high variation and surface articulation. This case study is representative to contemporary architectural tendencies and practices, searching for high level of variation, doubly-curved complex morphology, intricacy and surface articulation. Mould based fabrication processes, such as concrete casting and FRP lamination, stand in conflict with these contemporary architectural aspirations (Blonder and Grobman [3]), as can be testified by numerous research projects dealing with alternative, adaptive and reconfigurable fabrication and material systems (Veenendal and Block[4]) (Raun et al.[5]) (Hawkins et al. [6]).

Fabric Materiality FRP (FMFRP) is a material system that relies on the material qualities of the fibre constituent of the composite material. As part of a continuous research, the term of *Fabric Materiality* (FM) was coined to represent the essential material qualities, attributes and design paradigms of textiles, with their associated techniques and technologies of fabrication and transformation (Blonder and

Grobman [7]). Its application to the field of architectural FRP is the basis for the development of FMFRP material system, for the suggestion of alternative design and fabrication processes of architectural FRP.

Where the fibre component of the composite is used in its fabric configuration (woven, knit or non-woven), FM can be integrated in the design and fabrication process, relying on it textile qualities. The integration of FM attributes is conceived through three main fabric traits identified as self-organisation, fabric manipulation and resilience; these processes and properties are expected to reduce the absolute dependency on moulds in the fabrication process, as well as affect the resulting product in various aspects of design, structure and material.

In the continuation of previously presented works (Blonder and Grobman [8]), this paper presents the integration of FM in FRP surface elements, as an examination for a potential use as façade cladding tiles. Learning from the world of garment making, a simple manipulation of little energy is applied to the fabric, to generate complex morphology. The gathering fold type (Figure 1) was previously selected as the preferred manipulation type for further research and constitutes the basis for the formation of layered FMFRP material system.

Figure 1: Gathering fold type

FMFRP replaces the complex rigid mould with the self-organization capacities of the fabric material, using fabric manipulations as its forming process. A succession of fiberglass layers, formed by pleating, is partially laminated to form a volumetric surface, highly articulated and of extreme low density. The resulting material system, FMFRP panels, is singular both in its fabrication process and its resulting outcome. Its non-standard fabrication process does not comply with conventional FRP fabrication protocols, requiring optimal lamination, a complete adherence to mould form with absolute deterministic control. Its outcome is a patterned, porous matter-structure, with inherent randomness, strongly differing from the typical dense, solid, thin composite laminate. Consequently, the properties, performance and behaviour of this material system cannot be directly deduced from the well-established FRP data, but should be investigated experimentally.

This paper focuses on the exploration of FMFRP behaviour through a series of mechanical testing. The paper begins with a short introduction to the FMFRP fabrication process followed by the presentation of the experimentation idea and methodology. Two series of tests, tensile and compressive, will be detailed and analysed, complemented with conclusions and designation of further research.

2. Fabricating Layered FMFRP

The fabrication process of FMFRP 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. 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 (Figure 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.

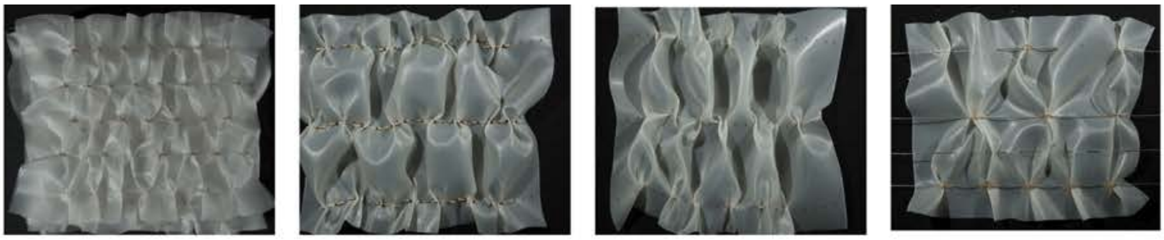


Figure 2: Different pleating patterns varying in number of rows and location of ties.
(Approx. panel size- 480X600 mm)

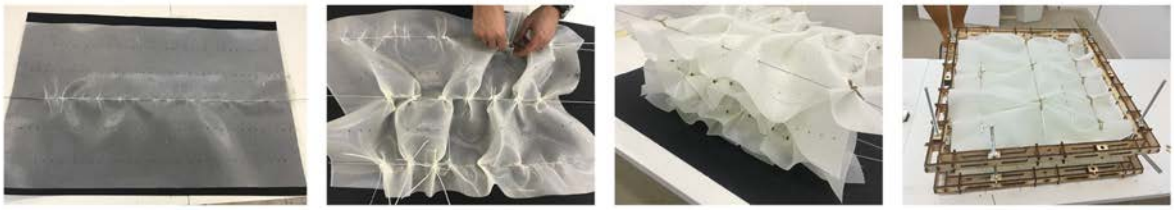


Figure 3: Fabrication process of FM FRP panel

3. Exploring FMFRP Properties

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 (Mallick [9]). 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 FMFRP 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. Structural simulation of the behaviour by calculation would require a theoretical model, constituted by generalisation; based on assumptions of simplifications of the highly variable and complex form. It would require an experimental validation to assure that simplifications are correct and do not significantly affect the result. Therefore, the step towards theoretical modeling of the system's mechanical behaviour is beyond the scope at this point and would be the outcome of further substantial experimental work.

A series of mechanical testing was performed on a variety of samples of FMFRP for collecting initial data and developing basic understanding of its performance. As a first inquiry, the aim of these experiments was to get first indications for typical values (ultimate force, displacement, stiffness, etc..), as well as some hints for the way these are affected by different parameters, such as number of layers, amount of contraction, directionality and more. Since no data has been collected yet on the mechanical properties of FMFRP and this is a preliminary mapping of properties, it was decided to run three different test series on the material, in correlation with three schematic attachment types of façade tiles (Figure 4): a suspension of the panel from a top fixture of continuous metal profile, attaching the panel along its width and across its thickness (a); full backing of the panel to the solid building skin (concrete wall) by a dense anchoring metal grid (b); point fixture of the panel to the solid building skin, as ventilate d façade. Three mechanical test series were run, to give first indications for a panel's behaviour under the dominant forces operating in three schematic loading scenarios of architectural usage as façade tiles:

a) Tensile test – for an analogous suspended façade tile
b) Compression test – for an analogous full backing of façade tile
c) Bending test – for point fixtures of façade tile

Since the model of the partially anchored scheme (c) requires additional testing, beyond the executed series of 3-point bending tests, to even roughly represent the behaviour of the panel (e.g. shear forces), thus anchoring scheme and its bending tests series will remain beyond the scope of this paper, for further experimentation and analysis.

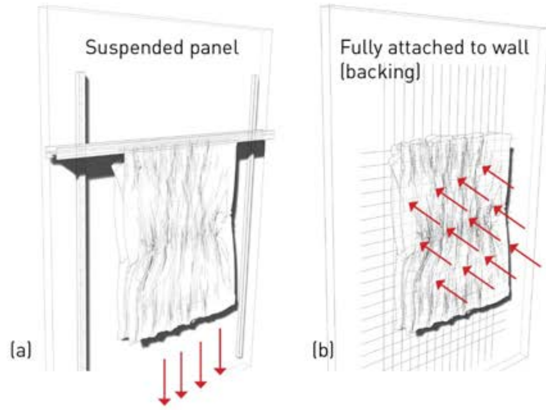


Figure 4: schematic anchoring types of façade tiles (a) suspension (b) backing (c) point fixtures

The unique configuration of FMFRP, with its articulate pattern and high randomness, raises difficulties in setting the testing framework. Its high porosity and highly articulated surface morphology, places it in between material and structure, oscillating between scales and definitions. The layered element can be regarded as a thick sheet material, a kind of laminate comprised of undulating layers of FRP and air; in such a case, it would require the testing of a representative volume of the material for the definition of its properties. Such an approach would assume scalability at a later stage, for a theoretical application of this material in different configurations and dimensions. Defining such a statistically representative portion of the material is hardly possible, with its high variability due to the fabrication process, based on self-organisation of the material both at the single surface level and at the layered level. This is accentuated by the pattern size, which is comprised of fold of 10-20 cm length.

At a different magnitude, the layered element can be regarded as a structural element in itself, in the given dimensions and configuration. If tested as such, a loading case should be defined for the element, determining the exact testing setup. Such an experiment would generate case-specific data, that would be hardly applicable for other loading cases and architectural uses. Being both matter and structure at the same time, the series of tests was configured and analysed taking both limitations into consideration.

3.1. Materials and methods

The samples for all tests were made with fibreglass prepreg material of 300gr/m^2, which is the raw flat material. The pleated layer of the FMFRP material has a ratio between the flat material used (Wreal) and the final pleated panel dimension (W) of ~1.7–2. The weight of one layer of FMFRP material is therefore about 600gr/m^2. The density of raw flat material is of 1000Kg/m^3, while the density of the porous FMFRP matter-structure ranges between 13 to 20 Kg only.

The samples were tested through tension, compression and bending tests. All experiments were performed on a servo hydraulic MTS 312.31 100KN machine, with a constant displacement speed. For all tests, displacement is plotted against force, over time. To set a general reference, a preliminary tensile test series was performed on un-manipulated flat raw-material. These tests were performed on an electro-mechanic ZWICK 1474 50KN machine, for five flat material standard specimens of fibreglass prepreg.

Three different samples were prepared for the tensile test on the folded sheets: a large element of one layer (tensile01), a small element of one layer (tensile02) and another small element of a double layer (tensile03). This is shown in Table 1 and Figure 5. The number of pleating lines varies according to sample size. Due to the irregular and undulating profile of the material, each sample was anchored to a steel U profile, with a special high-strength epoxy anchoring mortar (Hilti HIT RE 500 V3, Ultimate performance epoxy mortar for rebar connections and heavy anchoring). The U profile was connected to the testing machine through a ball joint for an optimal even distribution of the applied force. Elongation speed was of 2 mm/minute for all tensile tests, all three tests were pulled to complete rupture, where the sample was torn to two parts.

Table 1: Tensile tests of folded sheets - data

	Horizontal width W (mm)	Vertical length H (mm)	Thickness D (mm)	Number of layers	Number of lines	Spacing of holes (mm)	Length-sheet material W_{real} (mm)	W_{real}/W
Tensile01	564	485	50	1	5	25	980	1.7
Tensile02	300	126	40	1	3	25	600	2.0
Tensile03	320	203	50	2	4	25	600	1.9

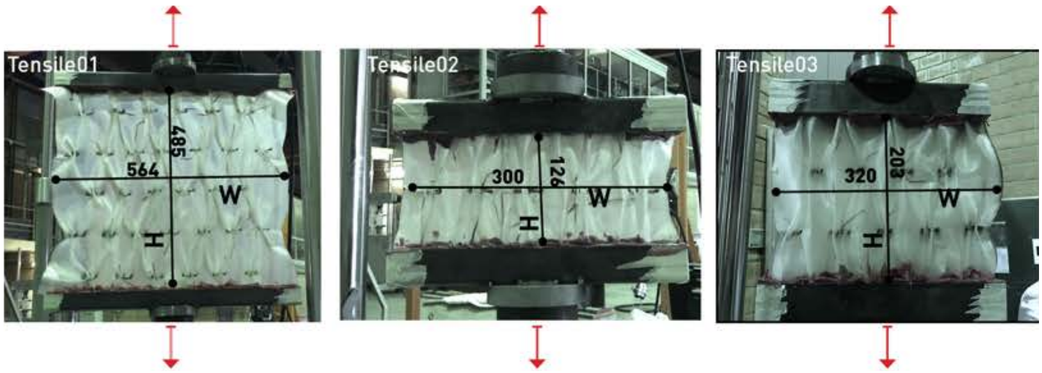


Figure 5: Tensile test samples: Large single layer (1) Small single-layer (2) small double-layer (3)

Five samples were tested for compression, between two steel plates of 300 X 300 mm. Compression rate was set for 2 mm/minute. Measurements were stopped when compression percentage reached up to 50% of initial panel thickness.

Table 2 Compressive tests of folded sheets - data

TestID	Horizontal Width W (mm)	Vertical Length H (mm)	Thickness D (mm)	#Layers	#Lines (of folds)	Spacing of holes (mm)	Length-sheet material W_{real} (mm)
Compress01	350	195	75	3	3	25	600
Compress02	360	190	95	4	3	25	600
Compress03	330	190	58	2	3	25	600
Compress04	340	190	38	1	3	30	660
Compress05	310	350	65	2 $_{perp}$	4	25	600
				Layers are assembled in perpendicular orientations			

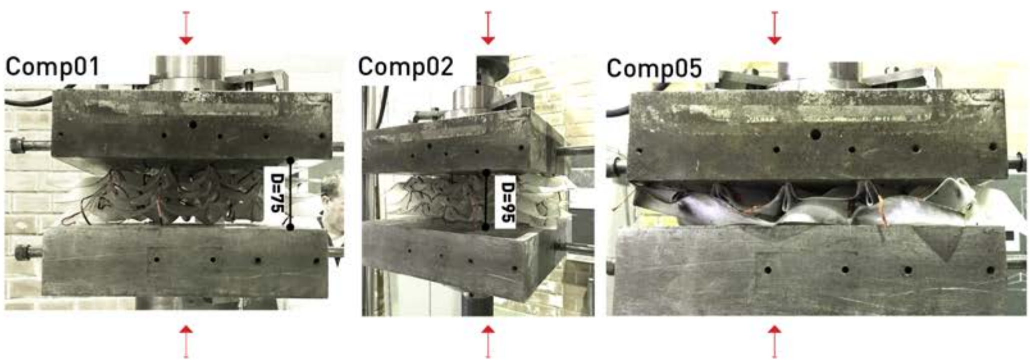
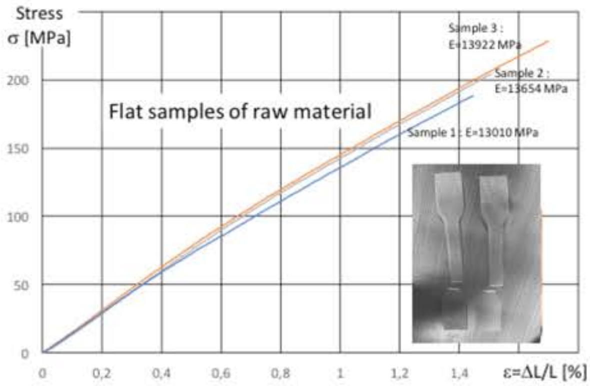


Figure 6: Compressive test samples: 3 layers (01); 4 layers (02); 2 perpendicular layers (05)

3.2. Results and analysis

3.2.1. Tensile tests on the flat sheet raw material

The values of the tensile reference tests on the flat material (Figure 7) were averaged to an ultimate strength of 215MPa, and a calculated Young's modulus of 15.5 GPa. These values correspond to the typical fiberglass composite values found in literature (Gay [10]). The ultimate displacement is of 1.5-1.8%, associated to an ultimate strength quite similar to mild steel (234MPa). However, there are two main differences with steel: the average Young modulus is about 13.5 GPa (compared to 210 GPa for steel) and the behaviour is fragile (no plastic deformation).



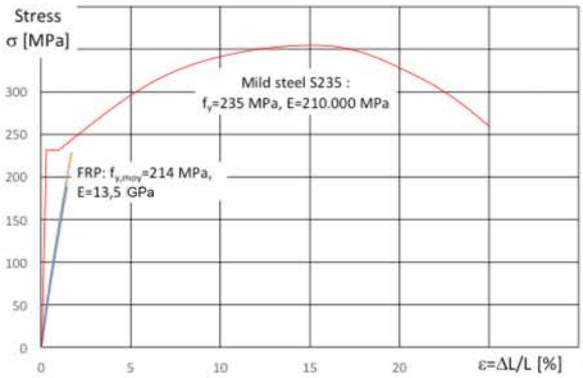
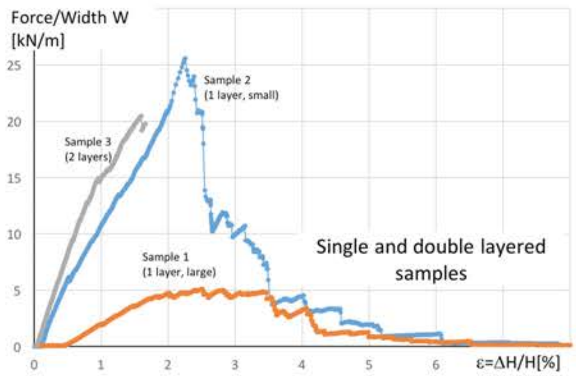


Figure 7: Tensile test on flat sheet raw material (left); Comparison to steel values (right)

3.2.2. Tensile tests on the folded sheet

Due to the complexity of the setup of the tensile tests for the folded panels, only a small number of samples were tested and it is therefore impossible to draw definite conclusions. Nevertheless, some tendencies and principles could be observed and analysed.

The tensile tests on the folded material show an ultimate displacement is around 2% similar to the flat material's properties, despite the undulation. (Figure *8* left). This is consistent for all three samples, and seems to be a typical value of the folded panels. The values of the large sample (Tensile01) are significantly low compared to the two other smaller samples (Tensile02,03), which probably indicates that despite the care taken in the test setup, stress did not distribute evenly and a non-symmetrical effect of the applied load took place, concentrating on the left side of the sample as observed in the test. It was therefore decided that its results would be discarded.



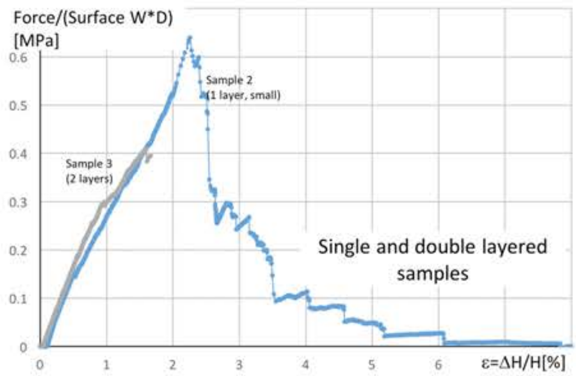


Figure 8: Tensile tests of single and double- layers folded samples: Force-displacement (left) and stress-displacement (right)

Comparing the tests of the two smaller panels, of single (Tensile02) and double layers (Tensile03), it seems that the effect of the double layer (Tensile03) does not improve performance, in terms of strength, as expected. This could be explained by the fact that both layers are parallel and one of them has probably, due to a different undulation, a slightly higher rigidity, but sufficient to concentrate the force. The result is that the two-layers panel probably behaves in this case as a one-layer panel. With only two tests, it is however impossible to draw reliable conclusions about the effect of the number of layers. Finally, the ultimate resistance is about 20-25KN/meter (of width), which means around 3 times less than for a flat sample, although the flat sample, which is not undulated, has an effective width about 2 times lower that the undulated one (see Table 1). In other words, for the same width of panel, the maximum traction is three times lower if it is undulated, but needs about twice the volume of materials. It is however unclear if this data is scalable, and could be predictive of the ultimate strength of larger elements. Figure *8*/right represents the apparent stress (force F)/(W*D), when the sample of area W*D is considered as a section full of material. Considering Tensile02, it shows that the maximum apparent stress is about 0,6 MPa. To be noted, is the extreme light density of the FMFRP material. Single sheets have a mass of 300 g/m^2, and each single layer has a mass around 600 g/m^2 for a thickness of about 50 mm. Based on the thickness of four-layer panels, ranging between 13 to 18 cm, FMFRP volumetric mass ranges between 13 to 20 kg/m^3.

3.2.3. Compression tests

The results of the compression tests demonstrate strong coherence, where all layered samples show a similar general behaviour of high flexibility (similar general slope of graph) and no rupture point. All tests were stopped at very high displacement level of 50-70%, with no complete failure (Figure 9).

The outstanding recovery of the structure after release of pressure, and the ability to withstand very high displacement values (over 50%), indicate an overall spring-like behaviour of the matter-structure. For the analysis, an equivalent of a spring was calculated for the tested panels. An equivalent spring constant (K) can be calculated for the different samples based on the measured data (F: in kN/m^2, δ : displacement in m, for a 1 m^2 panel, K-spring coefficient), from the equation $F=K*\delta$. An average K value of between 900 and 1300 kN/m was calculated for a 1 m^2 panel. Based on these calculated values, a theoretical wind load of 35m/s applied perpendicularly to a supported panel surface of any surface would generate a distributed load of 0,735 kN/m^2, causing displacement of less than 1mm (0.56 to 0.81 mm, according to number of layers). Such a load would be negligible for the FMFRP panel in such anchoring scheme.

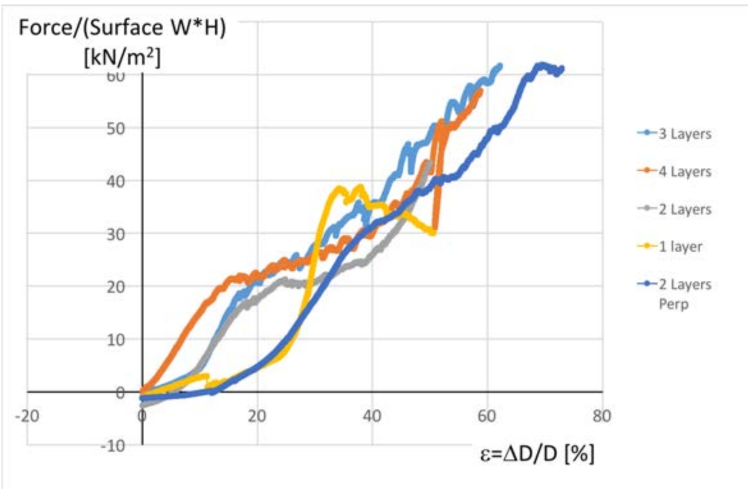


Figure 9: Compression test, Stress to displacement (%)

4. Conclusions

The experiments described in this paper are a first step in the understanding of the FMFRP behaviour and properties, towards future potential applications. The result of the combination of the mechanical properties of flexibility and lightness of FRP material, together with the unique geometrical properties of complex double curvature and intricate articulation of textiles is a porous, articulated layered matter-structure.

Interestingly, the typical density of layered FMFRP surface elements (ranging between 13 to 20 kg/m^3) resembles the typical density of FMFRP linear spatial configuration of the LifeObject case study (of 9-10 kg/m^3) (Blonder and Grobman, [7]). This demonstrates the way by which the integration of FM principles in FRP fabrication following the same principles of self-organisation, resilience and fabric manipulation, leads to a typical materiality, of the resilient, porous matter-structure.

Concerning the stiffness, tensile tests on the FMFRP samples demonstrate similar properties to the ones of the un-manipulated flat raw material. Its extreme lightness, together with the good stiffness indicate that its application as suspended façade is to be considered. The compressive tests demonstrate the distinctive flexibility perpendicular to panel plane, indicating its ability to withstand typical wind loads as a fully supported façade panel. Based on these promising indicators, its ability to withstand impact is to be further investigated, as well as its acoustic and thermic characteristics and its reaction to cyclic loading,

The tests supply first hints for the effect of different parameters such as number of layers, pattern and fold density over its performance. Further experimentation is necessary for the validation of tendencies observed. The experiments also supply an initial understanding of FMFRP mechanical behaviour under different forces, a first step towards a confirmation of the suitability of FMFRP to architectural applications. For more elaborate and conclusive statements, specific applications should be further developed and designed and further testing should be realised at the structure level.

Acknowledgement

Arielle Blonder is grateful to the Azrieli Foundation for the award of an Azrieli Fellowship.
The research was partially sponsored by The Ministry of Construction and Housing grant number 2022402/2015.
The mechanical tests were realised at the Laboratoire essais mécaniques structures et génie civil, UCLouvain, with the kind and knowledgeable assistance of Vincent Forzee et Quentin Mestrez. Special thanks to Prof. Pierre Latteur, for his invitation, support and advice in the realisation and analysis of the experiments.
Special thanks to Julian Perlstein for his valuable assistance.

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