Abstracts for IASS Annual Symposium 2017
Interfaces: architecture.engineering.science
25–28th September, 2017, Hamburg, Germany
Annette Bögle, Manfred Grohmann (eds.)

Layered *Fabric Materiality* in Architectural FRP Surface Elements

Arielle BLONDER*

* Technion Institute of Technology, Faculty of Architecture and Town Planning, Haifa, Israel.
Arielle.blonder@gmail.com

Abstract

Fabrics have particular material qualities, ranging across aesthetic values to unique structural capacities. At the basis of this research stands the term *Fabric Materiality* (FM), coined to represent the totality of qualities, attributes and techniques associated with fabric materials, which potentially interface between disciplines as a basis for transfer of technologies. Applied to the field of architectural FRP, its integration in design and fabrication is expected to remove current barriers for wider architectural application, tightly linked to the reliance on moulds. Following prior experimentation with FM integration in linear elements, this paper describes its potential in FRP surface elements, obtaining stiffness and introducing three-dimensional articulation by fabric manipulation and self-organisation. A multi-layered surface element is outlined, as a porous matter-structure of partial lamination, to potentially be resilient architectural skin.

Keywords: fabrics, materiality, self-organisation, resilience, moulds

1. Introduction

Fabrics have particular material qualities, ranging across aesthetic values to unique structural capacities. At the basis of this research stands the term Fabric Materiality (FM), coined to represent the totality of qualities, attributes and techniques associated with fabric materials, which potentially interface between disciplines as a basis for transfer of technologies.

The architectural discipline is experiencing a shift in the relation between digital form and material realm in recent years. Material is no longer seen as the sole expression of a digitally derived form, but rather as an active generator of design and adaptive agent of architectural performance (Menges [7]). Inscribed within the reading of materiality, this research wishes to explore the potential of Fabric Materiality in the field of architectural fibre composites, also referred as fibre reinforced polymers (FRP).

FRPs form a family of materials of exceptional mechanical characteristics of strength, stiffness, low density and durability, thanks to the composite combination of fibres with polymer matrix. The use of FRP in the construction industry is well established, for varied purposes and by different application modes (Hollaway [4]). As for the architectural field, although we witness a renewed interest in the material in recent years, 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 here are still outstanding gaps in the ability of FRP to respond to some emerging challenges in a sustainable and reasonable way (Blonder and Grobman [2]). 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 (Mallick [6]).

This ongoing research approaches the limitations of Fibre Reinforced FRP with regards to contemporary architectural applications, through the generative power of the material itself, empowered by its own tendencies and capacities. The fibre constituent of the composite is mostly used under the form of fabrics, thus potentially holding textile qualities (Blonder and Grobman [1]). Relying on the textile constituent of the composite material, an alternative approach to design and fabrication of architectural FRP is investigated by embedding *Fabric Materiality*,. The integration of FM attributes, through three main fabric traits identified as self-organisation, fabric manipulation and resilience, is 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.

The integration of FM in FRP design and fabrication was previously demonstrated in the case study of "The LifeObject" installation (Van-Essen et al. 2016 [9]). The properties exhibited in this case study (Blonder and Grobman [1]) serve as a starting point for the research presented in this paper, expanding the investigation of FM integration into surface elements. The extreme low density of a porous matter-structure, its resilient properties and material characteristics are all channelled to the development of a surface element, a potential resilient architectural skin.

Figure 1 :The LifeObject, resilient FRP structure by Fabric Materiality

The paper will start with a succinct framing of the use of FRP for surface elements, from modular segments to unitised planar products. It will then follow with the attempt to integrate FM in surface elements, described in three stages: the selection of three surface manipulations, the deployment of each of these manipulations in a single-layer surface, and the assembly of several layers to form a laminate. It will conclude with a brief discussion and the outline of further research on the prospect of an application as architectural skin.

2. FRP surface elements

Standard industrial semi-finished FRP products include linear elements such as rods and tubes, mainly fabricated by pultrusion, but the exploitation of the full potential of the material lies in surface elements. These are manufactured in a variety of techniques, from hand lay-up to RTM and infusion, as a laminate composed of multiple fabric plies. Suitable for external and internal uses, FRP planar products are applied as structural elements, skins, roofing, cladding, restoration and decoration (Knippers et al. [5]). The pioneering architectural experiments with the material in the 1950's-1960's used FRP for the fabrication of surface elements of overall curved or folded geometries. Whether double curved or angular, stiffness of the surface elements was achieved through the shell-like geometry overall structure. From the 1970's onwards, FRP surface elements started to be also implemented as planar products, such as unitised facade cladding.
Planar products of FRP are made as laminates, composed of several plies of fabric, impregnated with resin and formed over a mould. Considered as thin-wall laminates, 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 to enable larger dimensions for planar elements is typically achieved by profiling the cross-section (troughing), by including reinforcing ribs (ribbing) or by employing a sandwich form of construction (Halliwell [3]). Troughing in FRP performs similarly to

corrugated iron sheets, obtaining rigidity by continuous and repetitive cross section of local single-curved articulation. Sandwich construction is mainly achieved by the insertion of a lightweight core of lesser structural capacity (such as foam or honeycomb) between to laminates. This increases the structural lever arm of the laminate, which in turn increases the load carrying capacity and stiffness considerably (Knippers et al. 2011[5]).

.

3. Resilient FRP skin

The integration of FM in the design and fabrication of FRP surface elements relates to general stiffening strategies of thin planar elements, by profiling the cross section and increasing the structural lever. The following experiments attempt to obtain the articulation and stiffening of a FRP surface element by alternative means, through the implementation of FM by its attributes; thus, eliminating the need for shaped moulds and without layering of different materials. The dense layered construction of the laminate, and of the sandwich construction, is replaced with an attempt to create a porous matter-structure, as characterised in the previous FRP structure by FM. The stiffening by troughing was considered on the level of the single layer of fabric, where fabric manipulations and self-organisation would replace the need for a mould of a complex shape. The increase of structural lever was approached on the laminate level, where a construction of a porous matter-structure, as a "delaminated laminate", would replace the typical sandwich construction.

The material chosen for the experiments was woven fibreglass pre-preg (120g/m^2), a fabric pre-impregnated with resin and partially cured, that is stored frozen and is workable at room temperature for several weeks. For its manipulation, temporary pinning or clipping was used, taking advantage of the natural tackiness of the material. The shaped material is cured by oven, at a temperature of 120°. During curing process, the material initially softens by the temperature ramping up, reaching a fully rigid state after a curing time of several hours, and cooling.

The experiments are detailed under three stages; starting with an initial selection of three types of surface manipulations, each then will be deployed in a surface of a single layer, documented and comparatively analysed. One type of surface will then be used to compose a laminate of several layers.

3.1. Stiffening the single layer

The craft of fabric articulation that introduces three-dimensionality in the flat fabric material is traditionally achieved in a vast number of methods (Singer [8]). Based on a systematic categorisation (Wolff [10]) three different representative methods of fabric manipulations were explored: systematic folding using flat pleats, structured surface using darts and controlled crushing using gathering.

Pleating are measured folds formed at the edge of a piece of fabric where they are secured. Beyond the securing point (mostly done by stitching line), pleats become loose folds that continue the arrangement set at the edge [Figure *2*]. Knife pleats secured at both ends make a single-curved surface, highly ordered and controllable. The raised flange of the fully-secured knife pleat can reach considerable height, with a direct correlation to the fabric's. During curing, knife-pleats of considerable depth can collapse, due to the initial softening of the material in curing process. The one-sided knife pleats generate double curvature, with a less controllable effect on its free end.

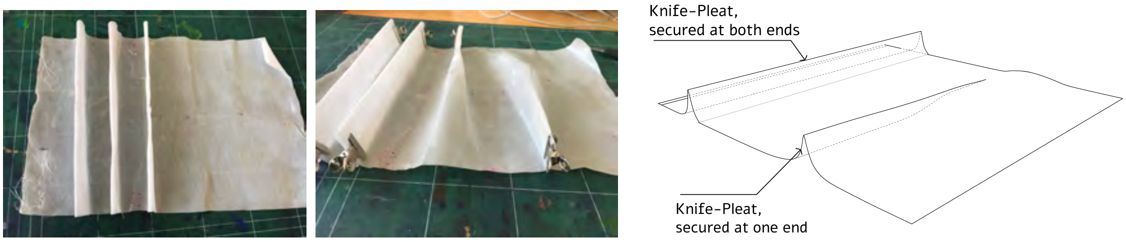

Figure 2 Knife Pleats, full secured and open

Darting sculpts the fabric's surface into highs and lows, by a shortened flattened fold of fabric [Figure 3]. The dart causes the level of the fabric to raise or drop in direct ratio to the amount of fabric it removes, making a hollow form that is partially collapsible (unless supported by other means). Darting can result in a very precise and predictable pattern, as it is practiced by garment makers to create three-dimensional form out of the two-dimensional flat fabric, to embrace body forms. When underlying support (such as the body wearing the garment) is not used, the ability of the fabric to maintain the sculpted shape depends on the inter-related parameters of material properties of the fabric, and of the geometry. With the softening of the material during curing, it is difficult to predict to what extent the sculpted form would maintain.

Figure 3 Darted surface generating a marked peak

Gathering converts the edge of a piece of fabric into mini-folds bunched together. At the location of the bunched folds fabric is shortened, and beyond it the full extent of the fabric erupts into irregular rolling folds [Figure 4]. Gathering can be placed anywhere along the fabric. Its width (the lengths of pulled stitch) determines the number of generated free-form pleats (“valleys” or “peaks”), in correlation with the fabric density. Gathering generates a main direction of curvature, in the plane of the gathering line and perpendicular to the pleats, but secondary and local double curvature is generated by the self-organisation of the fabric. While the primary curvature is rather predictable and controllable, the secondary one is highly complex and difficult to predict with certainty.

Figure 4 Gathering by a clip at centre of fabric

3.2. Single layer experiments

The three methods were implemented and tested each on a single sheet of prepreg fibreglass material of identical size (33X49cm). Each piece was designed deploying one manipulation technique, attempting to generate a variety of curvatures within the unit and to introduce significant three-dimensionality in the flat piece (height). The attempt in all three methods was to try and use the material optimally, so that an overall stiffness would be achieved, to resist distributed loading over the surface (perpendicular to surface plane). Out of the different parameters for evaluation, dealing with process as well as resulting morphology, this paper details the elevation of surface (distributed Z values), and stiffness (deformation in loading), identified as essential for stiffening of the planar element.

3.2.1. Surface design

The knife pleats surface design combined full-secured pleats with open ones. The full pleats were expected to serve as ribs to the surface, with a flange perpendicular to the surface, and the open pleats in the surface, were placed in the transverse direction, in the attempt to generate complex double curvature [Figure 5a].

The gathering pleats surface design combined two pleats located at the middle of the fabric, running in parallel, with two additional ones located near fabric edges, at both sides [Figure 5b]. Pinching the fabric closer to the edge generated undulation of the fabric contour, which is here balanced by the symmetry of the pattern [Figure 5e].
The darting surface design was based on two principle curves, running along the fabric as peaks. These were constructed by sets of darts, raying at each curve segment towards the radius of curvature. [Figure 5c].

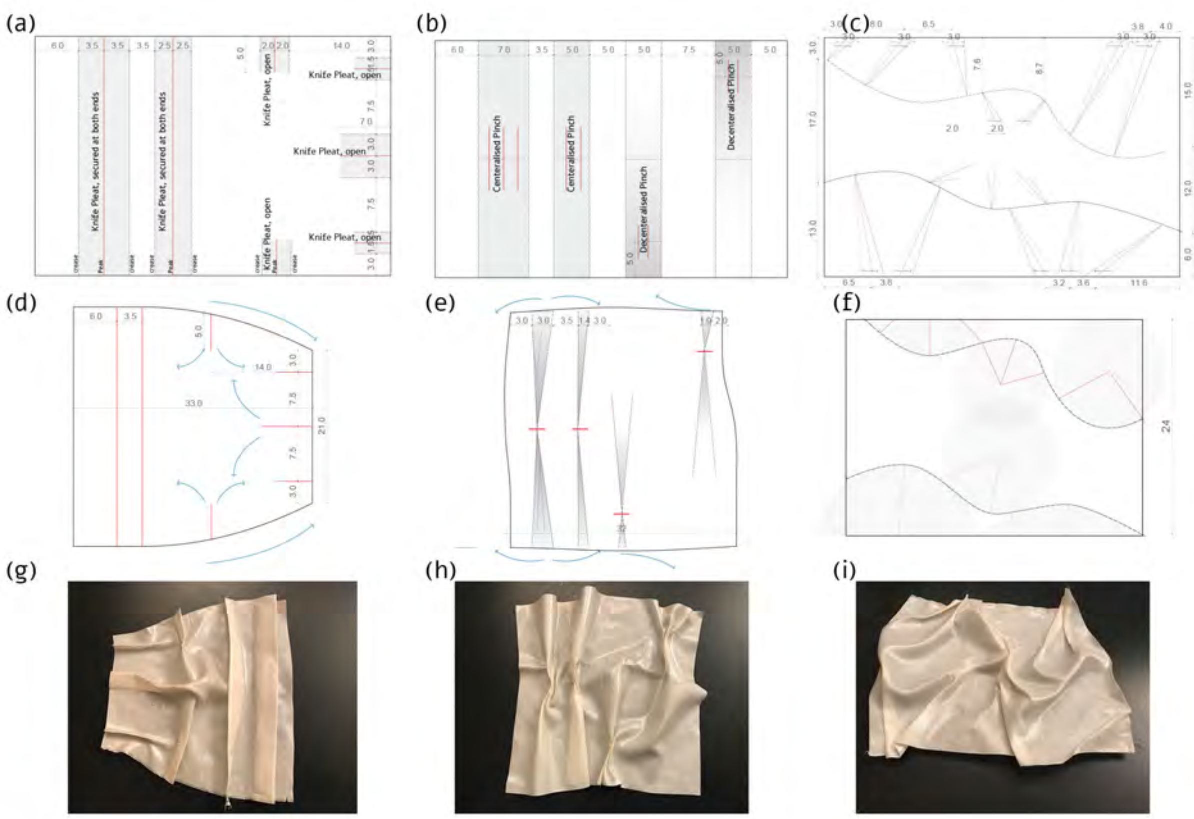

Figure 5 Three types of manipulated surfaces: Knife-pleat, Gathering, Darting. (a),(b),(c) -pattern drawing, (d),(e),(f)- expected configuration after manipulation, (g),(h),(i) – resulting surfaces.

3.2.2. Surface analysis

The correlation between the expected morphology of the manipulated surface and the resulting surface is affected both by nature of the manipulation, technical difficulties in its application, and the behaviour of the material during curing process.
Knife Pleats- The secured pleats were expected to serve as a rib to the surface, with a flange perpendicular to the surface plane, but it partially collapsed during curing due to softening of the material. The open pleats and their interaction with the perpendicularly orientated pleats introduced local double curvature as expected, but in a hardly controllable and predictable manner.
Darting- The nature of the material and its tackiness at room temperature made the manipulation surface less accurate and more difficult than expected. The darts were not sewn, but relied on the tackiness of the material and manual pressure to be positioned and to hold while curing. The overall softening of the material changed dramatically the location of the curve peaks and the marked effect of the dart folding

line. The resulting surface holds only a few characteristics of the anticipated resulting surface, with the two guiding curves merged into one.
Gathering- The surface was relatively predictable and rather easily controlled.

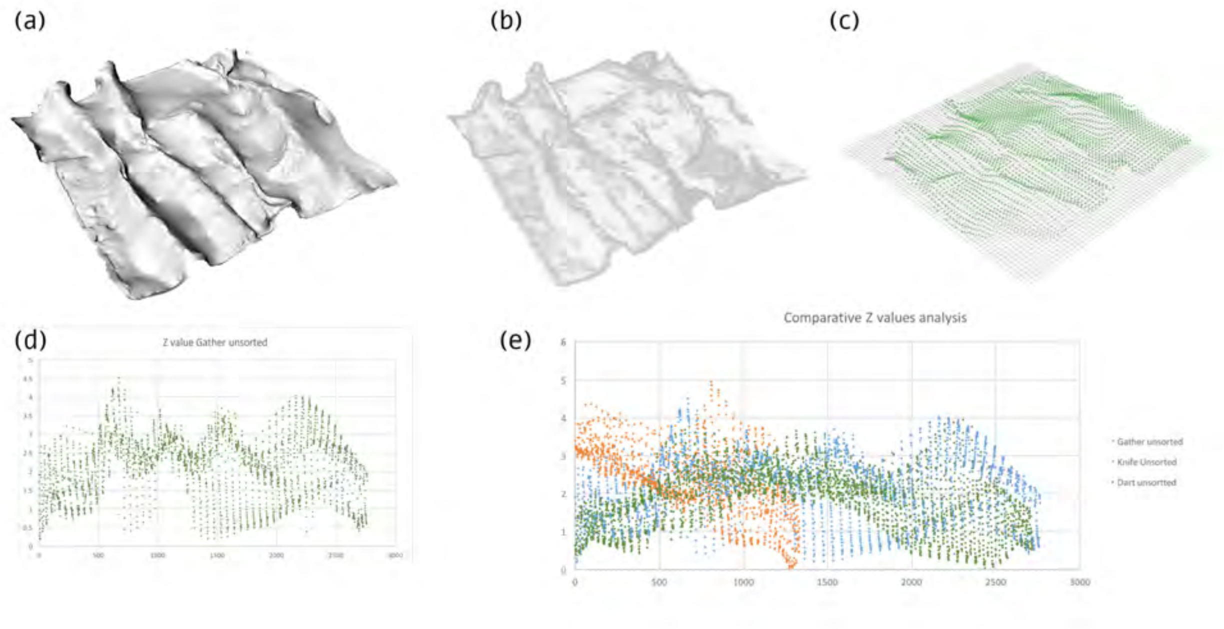

Figure 6 Gathering surface reconstruction and analysis. (a),(b)-reconstructed mesh. (c)- extracting z values of mesh (d)- plotted distribution of values (e)- comparative plotted values of three surfaces

The introduction of significant three-dimensionality is evaluated through the distribution of Z values over the surface. The finished surfaces were roughly mapped through photogrammetry (using Remake software by Autodesk), generating a 3D digital mesh of the surface. The systematic measurement of Z values of the mesh was plotted, showing the distribution of values over the surface [Figure 6].
The knife Pleats surface shows one localised high peak that is reached at the intersection between perpendicular pleats, but the rest of the surface is rather shallow (average- 23 mm). . Gathering and darting generated a more even distribution of height peaks, reaching medium height (average- 21.5 mm). Due to the softening described above, the darts collapsed and the resulting surface is the shallowest of the three (average- 18 mm).
Stiffness was assessed in a series of simple loading tests. Each surface was clamped to two parallel supports and gradual loading was processed, gradually reaching 20 loading units (17kg), though avoiding to reach the point of failure [Figure 7a]. Each surface was tested in two positions: with the main lines of curvature peaks running in parallel to the supports, and perpendicular to supports [Figure 7b, c]. Confirming the intuitive experience and understanding, the perpendicular direction of each surface performed significantly better than its parallel direction, with a lower deformation rate. [Figure 7d]. A comparative plot of the deformation graphs demonstrates that stiffening by gathering on the perpendicular direction was the most efficient and successful manipulation technique, with the most shallow and steady rate of deformation.

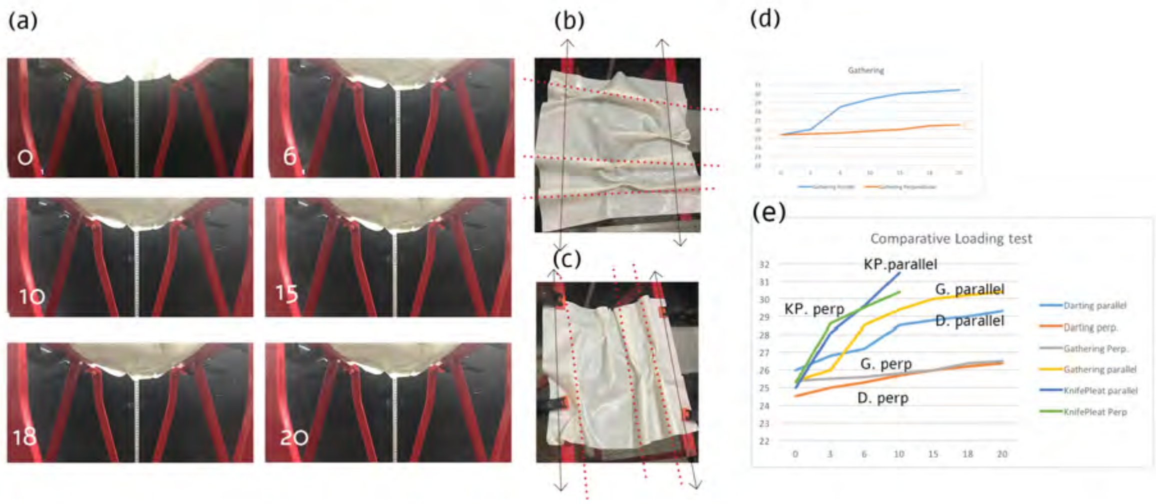

Figure 7 Loading tests of surfaces (a) loading from 0 to 20 units (b) perpendicular surface position (c) parallel surface position (d) deformation graph of gathering surface (e) comparative deformation graphs of all surfaces

3.3. Multiple layer experiments

Gathering method was chosen for further development, considering the level stiffening achieved, the even distribution of peaks and average Z value, the ease of manipulation and possible prediction and control. Following the characteristic of a porous matter-structure, the approach was to try and obtain a porous planar element, composed of superimposed single layers, partially connected. The standard FRP sandwich construction is based on the relatively minor structural role of the central zone of a component carrying loads in bending, using a material of lower strength and low density (Knippers et al. [5]). Here instead, the structural lever arm of the laminate is achieved by a porous structure, with no secondary material but its own three-dimensional complex geometry containing voids, obtained by FM.

The experiment consisted of three layers of fabric each designed with 2-3 gathering pleats, with a relative shift between layers so that pleats between will not coincide when superimposed. The flat space between pleats was used for the placing of connection points between each two adjacent layers (3 and 4 connections). Each layer was manipulated separately, and the connection was done by a flat circular disc, pressing the layers together locally for lamination between the layers.

Three layers of 20X33 cm each constructed a finished element, planar on the bottom side and undulated at the top, with varying thickness reaching 63 mm at its maximum, and with an average of 28.9mm. The section is highly irregular, varying across the surface [Figure 8b].

The loading test of the element, performed similarly to the ones described above, revealed once again a strong advantage for the perpendicular orientation over the parallel one. Maximum loading generated a minimal deformation of less than 5 mm, which requires additional examination with the appropriate testing facilities.

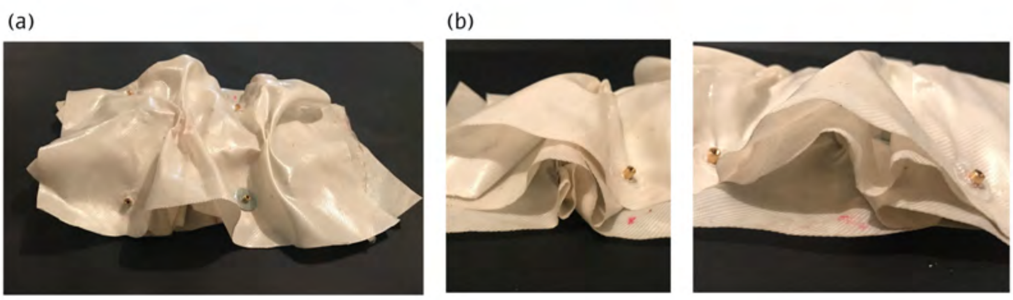

Figure 8 Multi-layer experiment (a) global view (b) local sections

4. Discussion and Conclusions

This experiment described in this paper explored an alternative approach to the design and fabrication of FRP planar elements, as part of an ongoing research on the integration of Fabric Materiality in architectural FRP; it sets the ground for the further development of a porous surface matter-structure, as a resilient architectural skin.

Contrasting with standard FRP planar elements, this development integrates the resilient nature of fabrics, searching to construct a robust element that is comprised of a multitude of relatively weak components, redundant, varied and of similar kind. As demonstrated in the previous Fabric Materiality FRP structure, intrinsic to the resilient character is the ability to generate variations, and the potential of structured randomness. The partial randomness that is inherent to fabric manipulation combined with self-organisation, holds a potential structural value eliminating main paths of failure and limiting crack propagation, yet to be explored. The integration of FM on the different levels of design and fabrication results in an element of a non-typical nature. The resulting element is both matter and structure, a porous laminate that enhances delamination and partial contact between its layers. Its aesthetic is unique, expressing its fabric nature. Further elaboration in design and fabrication is required for the development of a semi-structural architectural skin element of resilient nature, including the deployment of manipulations, their predictability and control, the layering process and its quality of local lamination, and the standardisation of boundary conditions of the element for assembly and continuity.

The different tests and analysis realised in the framework of this experiment serve as an initial proof of concept and an indicator for the issues requiring deeper observation and rigorous testing. Its structural properties should be determined: stiffness, strength and the ability to withstand impact. In parallel, the possible and requested levels control, predictability and randomness should be determined and observed through the scanning and analysis of comparative models. In addition to its primary purpose of stiffening, the resulting matter-structure suggest potential architectural benefits such as thermal and acoustic insulation or the integration of different building systems within it. These should be considered in the future development of the resilient architectural skin by FM.

[1] Blonder, A. and Grobman, Y., Crafted Variation in FRP: Resilience by Fabric materiality. *In Proceedings of the IASS Annual Symposium 2016 "Spatial Structures in the 21st Century"*, Tokyo, Japan K. Kawaguchi, M. Ohsaki, T. Takeuchi (Eds.). Tokyo, Japan. 2016

[2] Blonder, A. and Grobman, Y.J., Design and Fabrication with Fibre-Reinforced Polymers in Architecture: A Case for Complex Geometry. *Architectural Science Review* 2016;59(4); 257–268.

[3] Halliwell, S. M., Research Establishment Building, and Britain Great Polymer Composites in Construction. Building Research Establishment Report, 405. Garston, Watford: Building Research Establishment, 2000

[4] Hollaway, L. C. 2010 A Review of the Present and Future Utilisation of FRP Composites in the Civil Infrastructure with Reference to Their Important in-Service Properties. *Construction and Building Materials* 24(12). Special Issue on Fracture, Acoustic Emission and NDE in Concrete (KIFA-5): 2419–2445.

[5] Knippers, J., Cremers,J. Gabler, M. and Lienhard,J. *Construction Manual for Polymers + Membranes: Materials/Semi-Finished Products/Form Finding/Design*. Basel: Birkhauser Verlag AG. 2011

[6] Mallick, P. K. *Fiber-Reinforced Composites: Materials, Manufacturing, and Design*. 3rd ed. Boca Raton, Fla: CRC Press, 2008.

[7] Menges, Achim 2015 Fusing the Computational and the Physical: Towards a Novel Material Culture. Architectural Design 85(5): 8–15.

[8] Singer, Ruth. *Fabric Manipulation: 150 Creative Sewing Techniques.* Newton Abbot: David & Charles, 2013

[9] Van-Essen, Y., Bauer, B., Blonder A, and Lazarovich N., eds. *Lifeobject: Merging Biology & Architecture.* Sternthal Books, 2016

[10] Wolff, C. *The Art of Manipulating Fabric.* 1st edition. Radnor, Pa: Krause Publ., 1996

Acknowledgement

Arielle Blonder is grateful to the Azrieli Foundation for the award of an Azrieli Fellowship, and to the Technion Institute of Technology, the department of Architecture and Town Planning for its general support.

[9] Van-Essen, Y., Bauer, B., Blonder A, and Lazarovich N., eds. *Lifeobject: Merging Biology & Architecture.* Sternthal Books, 2016

[10] Wolff, C. *The Art of Manipulating Fabric.* 1st edition. Radnor, Pa: Krause Publ., 1996