# MATERIAL FORM-FINDING OF MODULAR TEXTILE STRUCTURES

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## KEYWORDS

3D printing on textiles, material form finding, hybrid textile structures, elastic modular assemblies, flexibility in architecture



## ABSTRACT

This paper explores potentials of self-forming textile structures generated through 3D printing on pre-stressed fabrics. The need of more eco-friendly and lighter materials, more flexible designs and substantial cost reduction creates new possibilities for textiles as a construction material. New digital fabrication technologies such as additive manufacturing as well as development of highly engineered, programmable fibers allow for re-introducing textiles into the build environment as a lightweight, efficient and sustainable solution.

Proposed research focuses on potential applications of 3D printing on textiles while looking into modularity, variation, assembly logic and scalability. By introducing hierarchy into the 3D printed elements, various degrees of shrinkage are possible within one printed sample. Variable height and geometry of the printed filament allows local influence on the deformation of the fabric. This method enables precise control over the geometry and aims at minimizing the material needed for fabricating three-dimensional textile modules.

As additive manufacturing gradually becomes more affordable and textiles more and more robust, proposed methodology suggests potential novel applications for lightweight textile structures in the building industry.


## 1. INTRODUCTION

Textile structures have been used in architecture since humankind first began to build. Nomadic tribes from all over the world used fabrics to build shelters for themselves and their animals, taking advantage of their tensile strength, flexibility and adaptability.

The same characteristics, which led to the initial utilization of fabrics thousands years ago, nowadays have brought textiles to the forefront of innovation. Search for lightweight materials with high tensile strength and low carbon footprint contributed to the immense developments in the textile industry. New fabrication technologies, computer-controlled looms and knitting machines redefine the production process, while the development of highly engineered composite materials opens up the field of potential future applications. *“The cutting edge in architecture is not sharp, but sensuous and soft.”*[1]

## 2. TEXTILE STRUCTURES IN ARCHITECTURE

The purpose of the early nomadic textile structures was similar to the one of clothing: *“to provide privacy, environmental modification and protection, intended as a means of generating shelter when necessary rather than as enclosures of permanent space.”* [2] From these functional origins tents have gradually developed into recreational symbols of urban settlements such as theaters, shelters for circus troops or other public events.

The functional aspects of the textile structures reappeared in the nineteenth and twentieth century as reaction to the technological advancements in structural engineering. New construction methods enabled building first large scale tension-active structures where the overall geometry was informed by material tension. The world’s first hyperboloid structure (1896) by V. Shookhov and the doubly curved, pre-stressed saddle structure of the Dorton Arena (1952) by M. Nowicki are one of the first large-scale manifestations of the new structural aesthetics. Even though these projects were not built from the actual fabrics, they became the source of inspiration for the future textile structures.

## 3. MATERIAL DESIGN

### 3.1. HIGHLY ENGINEERED MATERIALS

Recent technological advancements and inventions on the molecular level of material composition revolutionize the world of materials, pushing the limits of scale and functionality. The everyday objects become smaller and smaller while their performance still increases. In the same time materials become smarter, lighter, stronger and more sustainable.
Similar tendency can be observed in the textile industry, where inventions of highly engineered fibers and yarns challenge the weight-to-strength ratio. New lightweight materials are produced with high tensile strength. Researchers and designers explore the new field of adaptive, phase-changing and living materials, being able to self-actuate and reconfigure. MIT Center for Bits and Atoms develop digital materials with programmable properties, continuously overcoming the limits of what is possible. [3]

### 3.2. MATERIAL FORM-FINDING

*"Material design is a frame of mind. A deeper education unlearning one's first education. An attitude. Questioning. Inspiring: thinking, doing, and making."* [4]

Early examples of designing through material behavior can be already seen in the hanging chain models of Antonio Gaudi [5], who derived catenary curves through gravity acting on interconnected strings. Other analogue examples are early form-finding experiments by Frei Otto, who used soap bubbles as means of expressing physical laws and studied the capacity of soap film to form minimal surfaces due to its surface tension. His material explorations gave foundations to the development of large-scale, lightweight, tensile structures such as the West German Pavilion for the Montreal Expo (1967) and the Olympic Stadium in Munich (1972). [6]

With the advanced computational design methods we are able nowadays to compute very complex forms and geometries faster, dynamically and more accurately. Moreover, we are able not only to digitally compute such geometries, but also to integrate a performance-based feedback and material constraints into the design process. In the context of the new technologies the role of the material in design attains a new understanding. Material becomes an active design driver and form generator. We are facing a perceptual shift, where "*materiality coexists with design in the form of explorative cyber-physical process".* [7]

Researchers from ICD/ITKE already implement such explorative design strategies by transferring biomimetic design principles and robotic manufacturing to fiber-based structures. Three full-scale prototypical pavilions test various aspects of utilizing coreless robotic winding methods for glass and carbon fiber reinforced composite elements. [8]

### 3.4. NEW PRODUCTION TECHNOLOGIES: 3D PRINTING

New digital production methods allow designers, architects and engineers to bridge between disciplines and look at projects beyond their categories. Such tendency can be observed in the progressive textile industry, which is increasingly influenced by technological advancements in the other fields.

Additive manufacturing has been one of the fastest evolving technologies in the last couple of years, continuously expanding the possibilities of fabricating physical objects. Various industries explore potentials of 3D printing by looking at different aspects such as scale, material or resolution. Construction industry for example uses robotics to overcome size limitations of the 3D printing machines. Researchers from IAAC developed a system of distributed small robots with various functionalities in order to print large-scale structures. [9] The fashion sector on the other hand experiments with 3D printing various materials directly on the textiles. The MIT Self-Assembly Lab for example developed the so called 4D printed textiles: the self-transforming structures that reconfigure into pre-programmed shapes, changing shape and function over time. [10] 3D printing becomes a more robust and increasingly affordable technology and has a lot of potential to be utilized in combination with hybrid textiles in the architectural scale.

## 5. RESEARCH DESIGN AND METHODOLOGY

### 5.1. RESEARCH OBJECTIVES

There are numerous examples of realized large scale textile structures which take advantage of their tensile strength and ability to economically span large distances, such as for instance the roof of the Hajj Terminal at Jeddah Airport (1981) or the 320 m diameter Millennium Dome (2000). However the majority of analogous projects look at textiles as homogenous, uniform membranes with given properties and they do not question the material properties itself.

Instead, the proposed research zooms into the micro scale of the fibers and the principles of the textile logic in order to explore different ways of introducing hierarchy and heterogeneity into the fabric structures. This search for diversity within one fabric is carried out by 3D printing on pre-stressed textiles and investigating the form-finding capabilities of created composite structures. Utilization of new fabrication technologies such as 3D printing in combination with highly engineered materials can create a ground for up-scaling textiles into innovative, revolutionary building solutions.

The research is carried out as a series of experiments, observations and evaluations in order to inform the design criteria and search for the unimaginable through discovery, surprise and error.

### 5.2. MATERIAL BEHAVIOR

The first series of experiments were developed during the 3D printing workshop at the ArcInTex 2017 conference, examining material behaviour and capabilities of the methodology as a form-finding tool. Experiments aim at optimizing a predefined 3D printed pattern in order to get a maximum deformation of the printed elements while maintaining the fabric in tension. All the tests use one arbitrarily chosen pattern as a base to find the right pattern proportions.

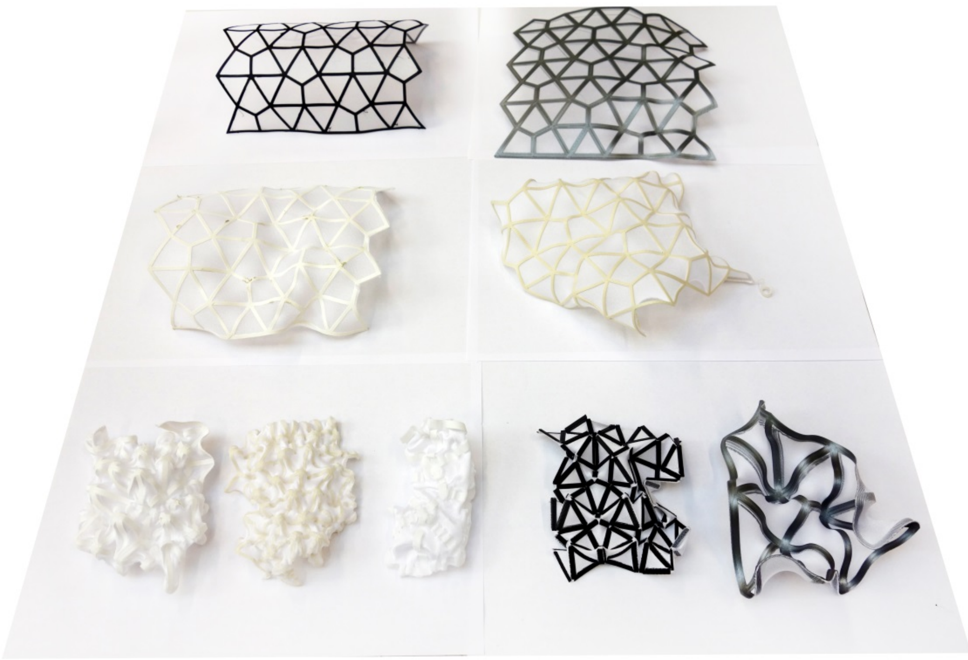

*Fig.01. Collection of material tests and various self.-forming behaviors*

#### 5.2.1. Set up

Height and width of the pattern are being alternated until the assessed outcome is reached. For the record and comparability of the tests, all the other parameters remain unchanged: the type of the fabric, pretension,

speed and temperature of the print.
The overall pattern fits in a square of 18,5 x 18,5 cm and consists or triangular and rhomboid shapes with an average edge length of 4 cm. The fabric consists of Polyamid (80%) and Spandex (20%) and it is stretched by 200%. Using the fused deposition modelling 3D printing technique (FDM), two types of filament are tested: PLA (polyactic acid), made from organic and renewable sources) and TPU 95A (thermoplastic polyurethane) - a semi-flexible and chemical resistant filament with strong layer bonding. All the models are printed with a 0,4 mm nozzle and the nozzle temperature of 195 degrees Celsius.

### 5.2.2. 3D printing method

The process begins with attaching the pre-stressed fabric onto a glass plate and placing it in the 3D printer. The height of the plate is then adjusted in such a way that the first printing layer attaches to the fabric but does not burn it. Once the print is finished, the glass plate is removed from the printer and the geometry is carefully cut out from the fabric.

### 5.2.3. Observations

Final deformation of the fabric turned out to be affected by several additional factors. One of the significant aspects was the time when it was cut out of the fabric and released from the tensioned plate. The later the print was cut out, the smaller the deformation.

Another important parameter was the attachment of the fabric to the plate. In the numerous tests the fabric loosened itself from the plate during the printing process. As a result, the first layer ended up being slightly shifted in relation to the other ones, affecting the precision of the print.

This series has finished with a 3D printed prototype with the following specifications: Material: elastic PLA, Fabric: Polyamid (80%) and Lycra (20 %), edge width: 2,5 mm, average edge length: 3,1 mm, height: 0,6 mm – 3 printing layers, nozzle: 0,4 mm, printing temperature: 195 degrees.

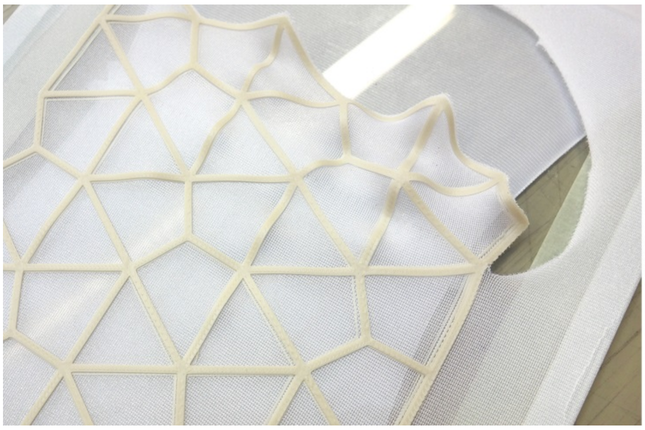

*Fig.02. Releasing fabric from the plate*

*Fig.03. Resulted textile structure*

## 5.3. MODULARITY

Once the material form-finding method of the desired hybrid textiles has proved to work, new questions arouse, one of them addressing the topic of modularity. Consequently, the next series of tests looked at the individual modules and their potential to create bigger assemblies.

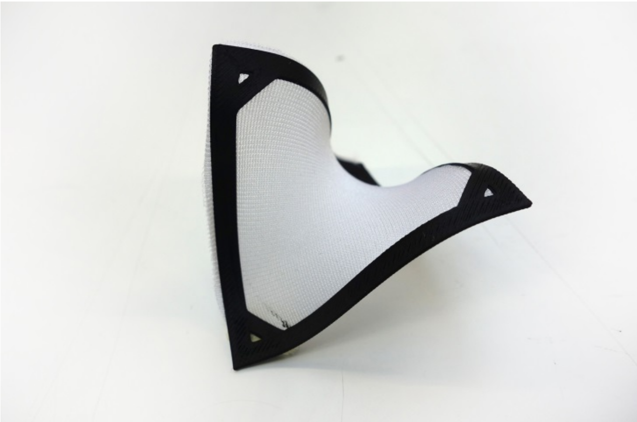

Fig.04. Single module

Fig.05. Modular assembly

The initial experiments started once again with the search for the right proportions and sizes, this time for an archetypal square module. The first tests consisted of 6 x 6 cm modules with connection elements in the corners; however it was difficult to compare the results and draw the conclusions because the overall size was too small and inaccuracy too big. The refined, enlarged module had the dimensions of 18, 5 x 18, 5 cm with a 5 mm edge width and 0,6 mm height and it became a base for further explorations.

Next series of models tested different dimensions and proportions of the printed edges by alternating the width and height, introducing abrupt transitions versus gradual transitions and integrating hollow spaces as placeholders for potential connection elements.

Another round of tests distorted the initial geometry of the square into a quadrangle with two extended edges in a way that all the vertices of the figure lay in the corners of a regular square, once the structure has found its final three-dimensional shape. Geometry of such module can be accurately controlled, multiplied and assembled into a larger construction.

*Fig.06. Three modules of 18,5 x 18,5 cm each with various 3D printed edge thickness (left: the same thickness of all the four edges: W: 5mm, H:0,6mm , middle: two edges W: 5mm, H:0,6mm and two wider ones: W: 15mm, H:0,6mm, right: 2 edges W: 5mm, H:0,6mm and two higher ones: W: 5mm, H:8 mm)*

**5.3.1. Observations**

Through a series of trial-and-error experiments it became clear that the behaviour of the hybrid textiles can be controlled with a relatively big degree of precision and accuracy. It is possible to integrate planar elements into the free-form textiles and design the transitions between rigid and flexible areas, what opens up a vast range of possible applications. Structures with different degrees of elasticity, stiffness, strength and porosity could adapt to different contexts and conditions.

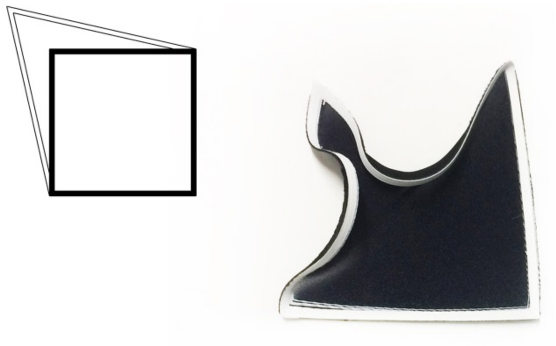

*Fig.07. Module with 4 equal edges* *Fig.08. Module with 2 longer edges*

One of the questions that arose during the production process addresses the basic definition of a module. Could the textile construction logic as well as the 3D printing methodology inform and redefine the idea of a building module? How different could a textile building element be comparing to the rigid, standardized brick units or concrete blocks? Could we take advantage of the flexibility of the material to create continuous textile modules for soft spaces?

### 5.4. HYBRID STRUCTURES

The following experiments aimed at introducing hierarchy between the individual elements within a single print. The first pattern is inspired by the dragonfly wings – a structure driven by performance and material efficiency, which consists of thinner and thicker elements depending on the function that they have. For this experiment an analogous pattern was simplified to elements with three different heights and three different widths. Due to the over-dimensioning of the elements, the overall deformation turned out to be minimal; however one could observe local differentiations.

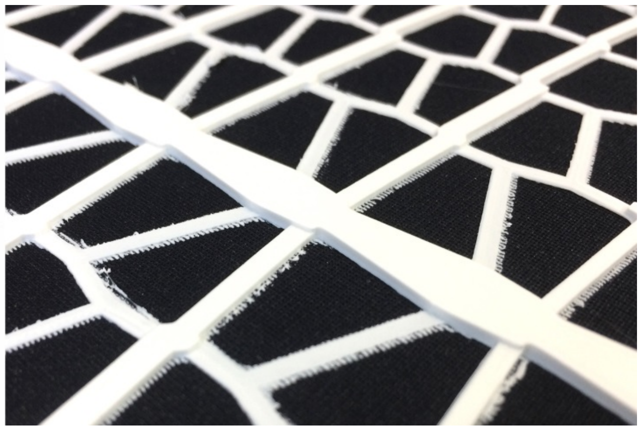

*Fig.09.3D printed pattern with three different edge dimensions* *Fig.10. 3D printed pattern with three different edge dimensions*

Another series of prints used a regular triangular grid in order to compare its different iterations: one with all the elements having the same proportions and its derivatives with variable heights. The first homogenous pattern was printed with uniform filament dimensions and resulted in a regular, repetitive doubly-curved textile structure.

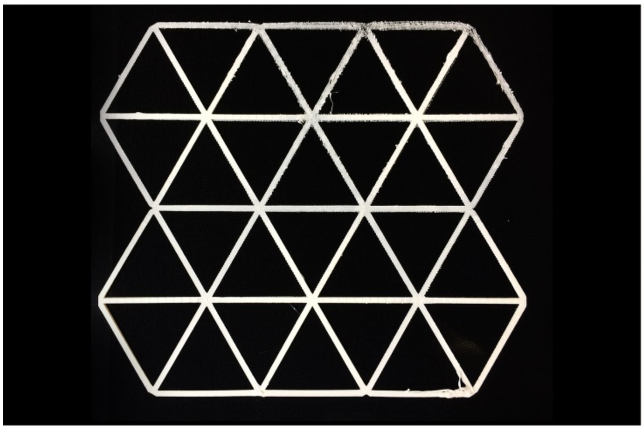

*Fig.11. Regular triangular pattern with equal height*

*Fig.12. Resulting geometry*

The second print was based on the same geometrical pattern, but the height of individual elements was gradually increased towards certain areas, reaching a high point in every second vertices. As a result, the print deformed very differently, creating a heterogeneous structure with stiffer regions and more flexible in-between spaces.

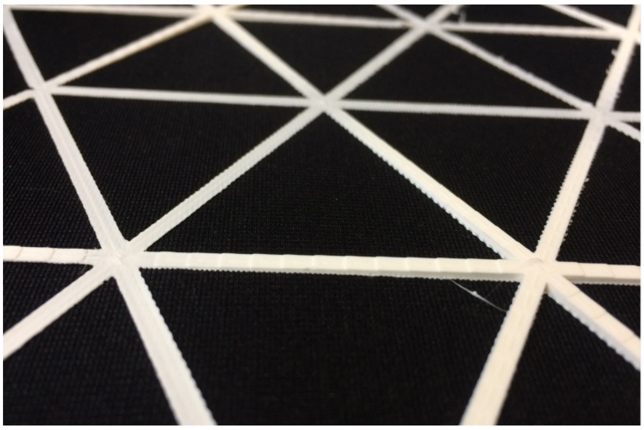

*Fig.13. Triangular pattern with variable edge height*

*Fig.14. Resulting geometry*

*Fig.15. 3D printed sample with a gradual height change*

*Fig.16. A sequence of four different samples*

Last two examples incorporated the non-linear height difference, what significantly affected the deformation. New pattern formations emerged by stiffening only half of the edge length and leaving the other half flexible. The stiffer areas were naturally pulled together, while the more flexible areas formed another in-between layer. Resulted system suggested potential applications as performative structures that open and close by pulling apart the stiffer elements and stretching the in-between zones.

### 5.4.1. Observations

Presented examples indicated the robustness of the proposed method and its potential to locally influence the self-forming behavior of the textile. Diverse qualities can be reached within one fabric by simply changing the parameters such as the height of the 3D printed filament or by introducing hierarchy between the elements. Such principle could be further studied a tool for material and structural optimization, enabling to create textiles with different properties without the need to introduce multiple materials or other manufacturing methods.

It's often errors and experiments that become sources of inspiration for the next tests. In one of the samples, a couple of weeks after printing, the filament started detaching from the fabric in certain areas. This gave rise to the following question: Could we use the fabrics only as an in-between product that steers the shaping process of other materials?

Another study inspired by the 3D printing error the so called "printing in the air" – printing porous geometries without the support, which locally detach from the fabric and result in another layer of fibrous constructs.. Could such fibers function as stiffening elements for the hybrid composites?

## 6. EVALUATION

The series of diverse experiments demonstrated potential of the proposed methodology for creating hybrid textile structures by 3D printing on pre-stressed fabrics. By taking advantage of the elasticity and adaptability of the fabrics we can fabricate complex, three-dimensional geometries without the need to design and model them in three-dimensionally beforehand. Instead, these textile structures can be developed by printing flat and controlling the way they shape themselves through surface tension. Such manufacturing process allows to skip the 3D printing of the support structures (which are necessary when printing directly in three dimensions) and as a consequence leads to significant material savings.

In the same time it also became clear what are the current limitations of currently available technologies and what other remaining problems need to be solved. For up-scaling the current findings, the notion of scale needs to be addressed, both in terms of the used materials and fabrication technologies.

## 8. CONCLUSION

As construction becomes increasingly digital and design more physical, the objective of this project is to re-introduce craftsmanship and materiality into architectural design and provide novel applications for lightweight textile structures in the building industry.

The proposed methodology of 3D printing on pre-stressed fabrics has shown a lot of potentials when considered a new construction process. Being an efficient and lightweight solution for spanning large distances, it has also numerous advantages for transportation and assembly. Since the textile components are printed flat, they could be also transported as flat sheets and installed in their final form already on site.

Moreover, it is also a method that allows to 3D print three-dimensional complex geometries without wasting additional material for support structures, usually required in such processes. As relatively inexpensive and efficient method to create three-dimensional geometries, it could be also utilized as an in-between product such as the formwork for shaping other materials.

The part of the investigation that is still remains a challenge is the up-scaling of the production process, however with recent technological advancements and material innovations, there is potential to overcome current limitations and suggest new solutions for the building industry. The next phase of the research will focus on the creative use of the additive manufacturing process by looking at custom 3D printing paths, resolution and continuity of the material deposition.

## 9. REFERENCES


1. *Quinn B.: "Textiles in architecture" in: Architectural Design: Architextiles, Wiley, 11/2006*
2. *https://www.designingbuildings.co.uk/wiki/The_history_of_fabric_structures*
3. *Gershenfeld N., Carney M., Jenett B., Calisch S., Wilson S.: "Macrofabrication with digital materials" in: AD Material Synthesis: Fusing the Physical and the Computational, Wiley 05/2015, pp. 122-127.*
4. *Viray E.: "Why Material Design?", 2011: "Material Design. Informing architecture by materiality", Schröpfer T., Birkhäuser*
5. *Tomlow J., 1989: Mitteilungen des Instituts für leichte Flächentragwerke. Das Modell. The Model. El Modelo. IL 34*
6. *Bach K., Burkhardt B., Otto F., 1988: Mitteilungen des Instituts für leichte Flächentragwerke. Seifenblasen. Bubble formations. IL 18, Universität Stuttgart*
7. *Menges A.: "Towards a Novel Material Culture" in: AD Material Synthesis: Fusing the Physical and the Computational, Wiley 05/2015, pp. 8-15.*
8. *Prado M., Doerstelmann M., Solly J., Menges A., Knippers. J., 2017: Elytra Filament Pavilion: Robotic Filament Winding for Structural Composite Building Systems, in Fabricate – Rethinking Design and Construction [Proceedings of the Fabricate Conference 2017], Stuttgart, pp. 224–233.*
9. *Jin S., Maggs S., Sadan D., NanC., Open Thesis Fabrication: Minibuilders, IAAC, 2013: http://robots.iaac.net/, checked on 20.11.2017*
10. *Guberan Ch.,Demaine E., Autodesk Inc, Self-Assembly Lab, MIT: http://www.selfassemblylab.net/ProgrammableMaterials.php, checked on 20.11.2017*


## 10. LIST OF FIGURES

*Fig. 01 –Fig.05: own figure, ArcInTex 2017*

*Fig. 06 – Fig.16: own figure*

## 10. BIBLIOGRAPHY


- Ahlquist S., Menges A., 2013: "Frameworks for Computational Design of Textile Micro-Architectures and Material Behavior in Forming Complex Force-Active Structures", ACADIA, https://www.researchgate.net/publication/290195848_Frameworks_for_Computational_Design_of_Textile_Micro-Architectures_and_Material_Behavior_in_Forming_Complex_Force-Active_Structures

- Bach K., Burkhardt B., Otto F., 1988: Mitteilungen des Instituts für leichte Flächentragwerke. Seifenblasen. Bubble formations. IL 18, Universität Stuttgart

*- Christie J., "Spatial Textile Hybrids: Self forming 3D Printing-induced structures", ETH Zürich, https://www.researchgate.net/project/Spatial-Textile-Hybrids-Self-Forming-3D-Printing-induced-structures*

*- Menges A.: "Towards a Novel Material Culture" in: AD Material Synthesis: Fusing the Physical and the Computational, Wiley 05/2015*
*- Menges A., Sheil B., Glynn R., Skavara M., 2017: "Fabricate: Rethinking design and construction", UCL Press*

*- Oldouz M., 2016: "Performative compositions - Material behaviour as an active agent in design and fabrication", Aalto University Digital Design Laboratory, https://aaltodoc.aalto.fi/handle/123456789/26630*

*- Otto F., 1988: Mitteilungen des Instituts für leichte Flächentragwerke. Experimente. Experiments. IL 25, Universität Stuttgart*


*- Otto F., 1988: Mitteilungen des Instituts für leichte Flächentragwerke. Experimente. Experiments. IL 25, Universität Stuttgart*


*- Quinn B.: "Textiles in architecture" in: Architectural Design: Architextiles, Wiley, 11/2006*

*- Palz, N. Ramsgaard Thomsen M., 2009: "Computational Material: Rapid Prototyping of Knitted Structures",*

*Proceedings of "Architecture and Stages in the Experience City", Aalborg University*

*- Ramsgard Thomsen, M., Karmon, A., 2009: "Computational materials: embedding computation into the everyday", Conference presentation “Digital Art and Culture: DAC09, UC Irvine, Los Angeles*

*- Ramsgaard Thomsen, M., Bech K., 2013:”Textile Logic for a soft space", CITA*

*- Schröpfer T., 2011: “Material Design. Informing architecture by materiality”, Birkhäuser*

- Semper, G., 1979: The Four Elements of Architecture and other Writings, Cambridge University Press, Cambridge

*- Thompson D’Arcy W., 1922: On Growth and Form, Dover Publications, Inc. New York*

- Tomlow J., 1989: Mitteilungen des Instituts für leichte Flächentragwerke. Das Modell. The Model. El Modelo. IL 34

*- Warnier C.,Verbruggen D.,2014: Printing Things Design, Visions and Essentials for 3D Printing, Gestalten*