FUNGUS MESH

Non-woven Self-supporting Assemblies

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Abstract. This study aims to develop the application and exploration of digital manufacturing technology in the design of textile composite materials in the digital fabrication. The inspiration for this study comes from the folds of mushrooms and resulting caps. In nature, many organisms grow flexible bodies as structural systems instead of relying on hard bones. This raises the question of whether soft textile materials can also have the potential to serve as structural support materials. Research is divided into three parts. The first part aims to understand the application of non-woven fabrics in the construction field, and examine the manufacturing and reprocessing methods of composite materials. The second part aims to establish the logic of form finding and shape optimization. The third part is the design and manufacturing stage. This research not only establishes a digital fabrication work-flow based on composite fabric materials but also develops a large-scale self-supporting structure as a verification of this process.

Keywords. Non-woven Fabric, Soft Material, Material-Based Fabrication, Bio-inspired, Bending Active

1. Introduction

In the process of construction, we often aim to achieve the strongest and most rigid outer shells to support individual growth or sturdy skeletal structures to uphold entities. However, in nature, some organisms do not prioritize the development of robust structural systems yet still manage to utilize flexible materials to form self-supporting structures. For example, some fungi species use gills, folded structures beneath their surface, to maintain stability in their umbrella-like fruiting bodies. Therefore, this research endeavor aims to investigate the application of soft textile and explore what types of forms and structural patterns could be employed on a human scale.

Fabric, as a material, is considerably softer compared to metals, wood, or concrete. Therefore, this study aims to correlate fabric as a flexible material analogous to the self-supporting structures formed by fungal mycelium. This research intends to present a viewpoint different from the current usage of non-woven materials in the design industry.

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This study seeks to challenge conventional perceptions of textile materials by exploring them through the lens of self-supporting structures. In the selection of manufacturing materials, this study opts for non-woven fabrics. This choice is not only due to their widespread use in the industrial sector with well-established manufacturing processes but also because of their unique processing capabilities, offering a myriad of possibilities within the material domain. Such properties are seldom found in traditional construction materials. For instance, steel is a common structural material in the construction industry, yet its properties remain unchanged from factory prefabrication to installation. Conversely, woven materials exhibit significant differences post-processing, where the incorporation of various fibers during the needling process influences the final material properties. In the realm of architecture, where there is a substantial demand for customized solutions aligned with environmental conditions, this manufacturing method holds advantageous prospects.

This study will initially discuss existing cases and their relevance to inspire and establish the research's position. The subsequent phase will concentrate on material research and manufacturing methods, encompassing hot-pressing processes, fabric bonding types, and structural strength studies. Finally, the last section will demonstrate the progressive outcomes of applying the aforementioned material research in the current utilization of this system.

The following will be the contributions of this research:

- Unveiled new applications of non-woven fabric in design applications.
- Develop a material system and relative digital fabrication pipeline.
- Summary of current achievements and future development direction.

2. Content and Previous Experiments

The construction industry has started utilizing fibers in various forms over time. Initially, weaved reeds were added to concrete in the Roman period, and fabric molds were developed in the 18th and 19th centuries. However, these fabric molds were primarily used as cost-effective formwork and were removed after construction (Veenendaal et al., 2011). However fabrics have seen extensive use in other industries, especially in automobiles, where they serve as affordable insulation materials for heat, sound, and vibration, prioritizing safety considerations (Chen, 2014).

Recently, the exploration of fabric applications in architecture has gained traction. Projects presented at the Bartlett School of Architecture in 2014 (Majumdar et al., 2014), as well as project at Bartlett School of Architecture B-Pro & Autumn Shows in 2020 (Lee et al., 2020), have showcased the use of fabrics in innovative architectural structures. Another example is the Trash Kitchen project by MINIWIZ started in 2013, using waste fabrics and plastics for thermoforming into functional goods and interior decoration walls (MINIWIZ, 2013).

While some methods involve impregnating fabrics with resin to harden them into structural elements, these approaches often require additional frameworks for support until the structure solidifies. In this study, the focus is on CNC processing and cutting hot-pressed non-woven fabric, creating joint buckles for effective transportation as sheet-like disassembly units that can be assembled at designated locations.

Authors	Intent	System	Image
Fabrick Somdutta Majumdar et al. (2014)	Form Can be created in single piece of material.	Resin Impregnated Felt	
Fabric Hewn Tai-Jung Lee et al. (2020)	Combined fabric in a kiln, to create block for load bearing system.	Thermoforming	
TRASHLAB MINIWIZ (2017)	By thermoforming in mold to create tile with recycled fabric and plastics.	Thermoforming	

3. Methods

This research will focus on fabric materials as the core subject and is structured into four parts:

- Involves studying and manufacturing non-woven fabric materials.
- Proposes and tests assembly methods for these materials.
- Establishing a structural formation logic based on active bending, and testing on fabrics, seeking optimized structural configurations through testing between virtual and physical models.
- The manufacturing stage involves oscillating knife-cutting and subsequent assembly based on the configurations and forms achieved in the preceding parts.

3.1. MATERIAL STUDY

The study focuses on non-woven fabric due to its widespread industrial use and unique production method, offering diverse possibilities within the material field, unlike traditional construction materials. Textile materials, especially non-woven fabrics, show varied properties after processing, influenced by factors like the needling process and fiber types used. This versatility is advantageous in architecture, catering to customized solutions for diverse environmental conditions.

Non-woven fabrics offer flexibility in mass production and subsequent processing, a valuable asset in digital manufacturing requiring extensive customization based on design and demand. In contrast, woven fabrics demand specialized knowledge in textile design, sewing techniques, and material composition, complicating their manufacturing process.

The research focuses on a 3mm thick non-woven fabric weighing 600 grams per square meter, primarily composed of synthetic fibers and polyethylene. This fabric, post-processed using the hot-pressing method and laminated with plastic membranes, will be examined for its suitability as a self-supporting structure.

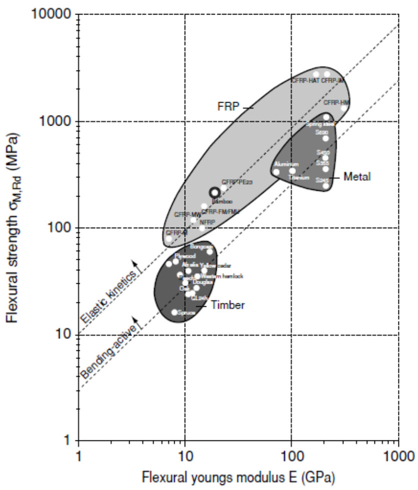
3.1.1. Laminated Non-woven Fabric

In the manufacturing process of non-woven fabric, the incorporation of different materials during the needling process can result in significant differences. Traditionally, non-woven fabrics primarily utilize short fibers as the main material. However, with variations in fiber length and differences in melting points, there exists an opportunity for non-woven fabrics to achieve improved mechanical properties.In the later stages of material processing for this study, a hot-pressing method will be employed to elevate the internal plastic to its heat deformation temperature. Simultaneously, pressure will be applied to facilitate bonding between the fibers. Following the hot-pressing process, the material will be removed and placed on a cold-press machine for secondary pressing. This step aims to prevent issues such as surface expansion, wrinkles, and unevenness that might occur due to cooling after the initial hot-pressing process.

During the material research phase, obtaining relevant parameters becomes a necessary process for conducting preliminary structural simulations on a design stage. The parameters needed to be acquired include Young’s Modulus (kN/cm^2), In-plane Shear Modulus (kN/cm^2), etc. In the testing phase, ASTM-D638-22 Plastic Tensile Standard and ASTM-D790 Plastic Three-Point Bending Test are utilized to conduct tests on composite textile materials. This includes various plastics with different layer numbers and types, aiming to identify suitable combinations within the processing range (Figure 1. Figure 2.).

3.2. JOINTS

The objective of this study involves constructing complex shapes using planar linear stripes as building materials. In traditional applications, bolts or rivets are used to fasten neighboring units together for structural integrity. However, considering the flexibility and properties of non-woven fabric fibers, this study proposes an alternative connection method. Instead of bolt fastening, this study explores textile-inspired techniques for unit connections. By leveraging textile processing methods like sewing, the idea is to overlap and fold adjacent fabric stripes at designated locking points, eliminating the need for additional materials or tools. Taking inspiration from everyday objects like self-locking paper breakfast boxes, the concept draws from origami principles. The design features male and female ends resembling folded paper latch mechanisms. The male end, cut into a protruding shape with folding ears, interlocks with the female end notches. Upon insertion, the ears unfold, creating a secure latch without requiring extra tools or materials (Figure 3.).



Heat-pressed Non-woven Composite parameters			
Material	Strength σM (MPa)	Stiffness E (GPa)	Ratio
Non-woven +PLA + Non-woven	239	2380	9.95
Non-woven +Low melting point + Non-woven	1520	7980	5.25
Non-woven +PLA +Non-woven +PLA + Non-woven	5820	444	13.1

Figure 1. Materials with ratio ofstrength σM (MPa) to stiffness E(GPa)(Lienhard, 2013).

Figure 2. Testing heat pressing composite at MINIWIZ

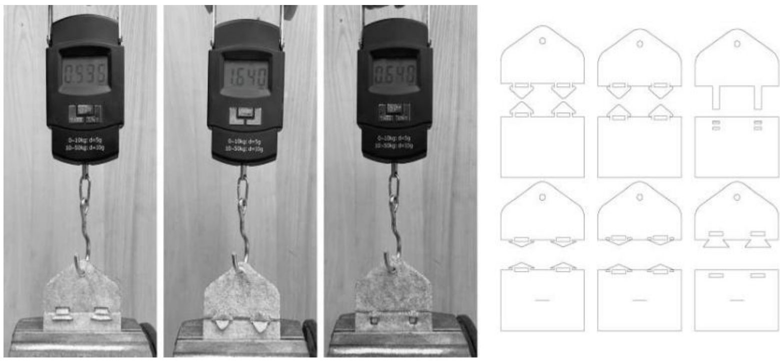


Figure 3. (Left) Self-locking strength experiment. (Right) Type of latch

3.3. FORMING

When designing with fabric material, one most contend with the characteristic of the flexible materials. Unlike construction materials such as metal or wood, fabrics are challenging to support individually. Achieving complete vertical or horizontal orientation with respect to the ground is almost impractical. Both situations would result in significant deformations. In most other cases where fabrics are used, external frameworks are employed for support and tensioning, such as membrane structures.

This chapter focuses on identifying the appropriate forms and stress patterns when using fabric as a structural material. Therefore, the choice is to utilize Karamba3D for FEA(Finite Element Analysis), which enables a more accurate simulation of the obtained material parameters and joint strengths from the previous chapter. By displaying utilization and displacement, it becomes possible to identify areas within the design that may experience stress concentration. This information can guide a more precise logic for segmenting (striping) the structure, aiming to prevent potential structural issues that may arise after actual construction.

3.3.1. Tube or Planar

Applying bending-active as the structural logic for the material, the method of forming its morphology requires thorough investigation. The basic bending-active arch shape involves fixing one end of a long strip-shaped material while horizontally moving the other end to induce bending, forming the arch. However, a drawback of this approach is the necessity for anchor points on both sides of the apex to maintain the arched shape.

Therefore, in pursuit of design and stylistic freedom, reducing or eliminating anchor points would enhance flexibility in the design process. By increasing the number of strips and connecting or bonding them at the material ends, the morphology can be maintained within a closed shape. The material, relying on its own pre-stress effect, achieves static equilibrium, enabling a form of self-support.(Figure 4.)

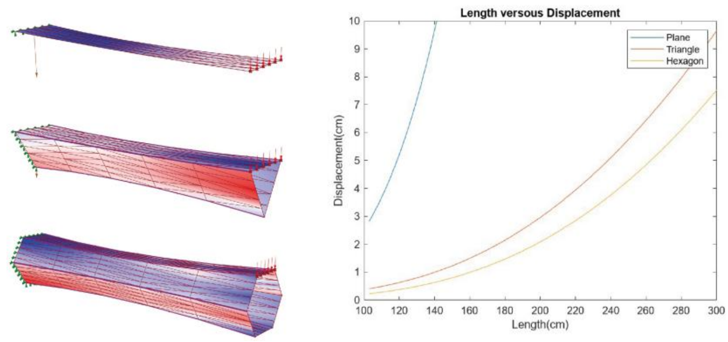


Figure 4. Tube examination: the more circular cross-section perform better strength.

3.3.2. Stress Concentration

In Section 3.3.1. after experimentation, the utilization of closed forms as an applied structural logic exhibits superior structural performance and offers greater potential for variability and extension. This section will involve using closed forms for testing basic models on a small scale. The models will employ algorithms based on graph theory within Grasshopper using C# scripting (Mitani and Suzuki, 2004) to split the forms into stripes and subsequently assemble them through sheet fabrication.

In the small-scale models (Figure 5.), it was observed that certain plate junctions resulted in geometric irregularities. Additionally, simulations and physical compression tests revealed localized stress concentrations in specific areas. These areas experienced structural failure prematurely, collapsing before uniform pressure was distributed across the entire structure. Similar phenomena are observed in various designs, and the typical approach involves reinforcing the structure or enhance material strength. However, there is alternative approaches concerning the fabrication method of segmented parts. Addressing this issue requires revisiting the topological mesh relationship during geometric generation. Models in this system are generated by stretching grids through Grasshopper Kangaroo simulations, leading to potential occurrences of mesh stars. Directly segmenting the mesh might lead to stress concentrations at the mesh stars. To prevent stress concentrations from becoming locations of structural failure, it's necessary to avoid mesh stars during mesh segmentation or find more efficient splitting paths while considering material utilization.

Apart from the potential structural weaknesses caused by mesh stars, when mesh stars are segmented into planar linear stripes, it's common to encounter breakpoints within the middle of the pattern or multiple stripe endpoints converging at the same point. Also, there might be instances where the pattern requires segmentation into multiple linear segments, making it challenging to achieve seamless joins using a single plate. All these issues need consideration in designing such structures (Figure 6.).

3.3.3. Unroll Logic

In Section 3.3.3, has mentioned that the star in the mesh could become a stress concentration point leading to structural failure during structural simulations. Therefore, accurately partitioning the model is important. However, the conditions affecting the partitioning logic extend beyond just the star-shaped nodes. Circular division and longitudinal segmentation of the form also yield distinct structural behaviors (Figure 7.). Analysis indicates that longitudinal segmentation subjects the material to more bending-active forces, often exhibiting superior material utilization efficiency. Nevertheless, the material may not always accommodate all segmentation lengths. Therefore, within these constraints, it becomes necessary to devise partitioning options that correspond to the material dimensions, striking a balance between circular and longitudinal divisions. Finally, is to consider how the partitioning will impact the overall pattern of the structure.

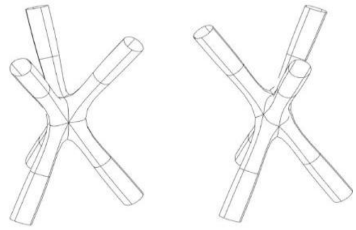
 

Figure 5. Small scale testing model. Figure 6. Mesh Star

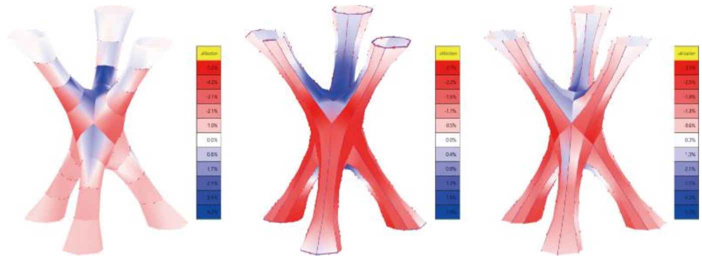


Figure 7. Through different unroll pattern could create diverse structure performance. (Left: Circular pattern, Middle: Longitudinal pattern, Right: Longitudinal but segmented in restricted length)

3.4. FABRICATION

After finalizing the architectural model's structural design and optimizing potential weaknesses in geometric singularities, the focus shifts to manufacturing. Given that non-woven fabric falls under textiles and undergoes thermal pressing, it's unsuitable for laser cutting. Hence, an oscillating knife-cutting machine becomes the preferred fabrication method. Conversely, using an oscillating knife for cutting intricate shapes has limitations due to tool path constraints. Laser cutting focuses a high-energy point for precise cutting, while the oscillating knife, using an actual blade, may create additional tangents or lines at corners due to its width. Considering these factors during path generation is crucial, as minor details or sharp corners may result in unnecessary cutting lines (Figure 8.).

Figure 8. (a) Oscillating knife-cutting machine. (b) Closeup

4. Design Experiments

In this research, the effective utilization of thermally pressed non-woven fabric materials for assembly in space is the primary focus. Material testing aimed at examining the material's supportability and structural system. Therefore, this experiment attempted to manufacture a structure with a 4-meter diameter, using a three-point base to better reference the material and structural design at an architectural scale.

In the design process, the test results from Section 3.3.1 were employed. A tubular design was adopted, consisting of three tubes bundled together, gradually tapering from an 18 cm diameter at the base to an 11 cm diameter at the top, eventually joining at the apex to form an arch. Subsequently, the initial phase of FE analysis was performed on the overall structure to identify areas experiencing tensile and compressive stresses, serving as references for the model's segmentation (Figure 9.). Following the principles described in section 3.3.3, the segmentation avoided the intersection of stripes' ends with star nodes. The length of stripes was determined based on the dimensions of the composite non-woven, 80*120 cm, while areas experiencing different stress patterns employed suitable ordinary non-woven fabric for tension and composite non-woven fabric for better compression performance. Finally, various elements were cut using an oscillating knife and manually assembled.(Figure 10.)

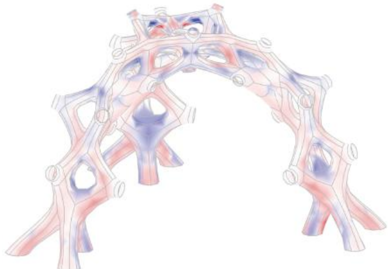


Figure 9. (Left) FE analysis base on stripes to find compression part (Red) or tension part(Blue). Tension part for normal fabric (Middle, White), Compression part for composite fabric(Left, Black).

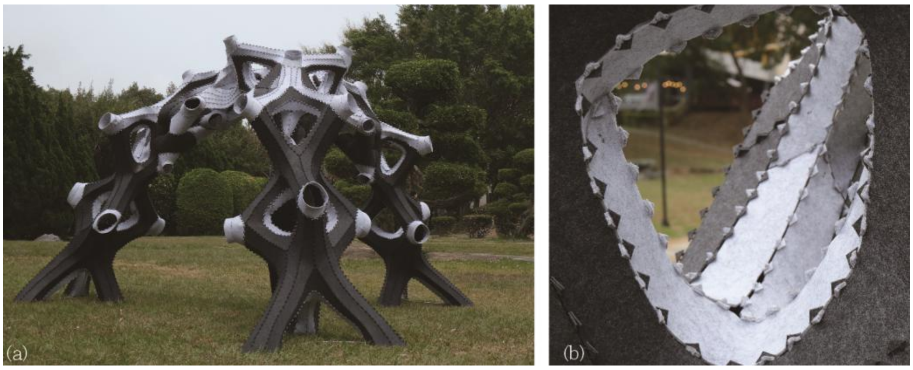


Figure 10. (a) Final Model (Diameter: 2M, Height: 2.2M). (b) Detail closeup.

5. Conclusion and Future Work

The experimental pavilion highlighted the potential use of non-woven fabric as a self-supporting structure in architectural applications. While traditional construction materials like concrete and metals offer sturdiness, many architectural elements like partition walls or temporary pavilions merely require self-supporting conditions. Non-woven fabric, with its added benefits of sound absorption, thermal insulation, and non-flammability, coupled with self-supporting capabilities, presents a promising alternative. This innovative construction method allows architectural infill materials to serve independently as spatial elements.

However, this research pinpoint areas for improvement: excessive labor in assembly and the loss of bending-active properties after bending. Common indoor wall assembly methods involve straightforward processes but require additional materials like nails or mortar. In this study, utilizing fabric's flexibility in a self-locking design circumvented the need for extra materials but increased manual assembly. Addressing this challenge could be a focus for future research. Moreover, irreversible loss of bending-active effects in materials after bending is a concern. Bending-active characteristics allow materials to retain elasticity within a specific range but result in irreversible deformation if the load surpasses the material's yield strength. Therefore, incorporating safety factors into structural design becomes crucial for such applications.

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