Proceedings of the IASS 2024 Symposium
Redefining the Art of Structural Design
August 26-30, 2024, Zurich Switzerland
Philippe Block, Giulia Boller, Catherine DeWolf,
Jacqueline Pauli, Walter Kaufmann (eds.)

Nonshell: Porous Structure by composite fabric formwork system

Weiche LO[a,*], Shihyuan WANG[a]

[a,*]National Yang Ming Chiao Tung University
No. 1001, Daxue Rd., East Dist., Hsinchu City, 300093
Taiwan(R.O.C.)
willylou31@arch.nycu.edu.tw

Abstract

This research aims to advance fabric formwork systems for constructing freeform shell structures. Traditional methods involve labor-intensive wooden molds with limited precision. Our focus is on developing a system using composite nonwoven fabric as formwork material. We choose nonwoven fabric for its cost-effectiveness and customizable properties through post-processing. Heat-pressed with PLA film, it achieves a high bending-active ratio to support concrete weight. By the forming methods we adopt a stripes-based system from Mark Fornes, optimizing stress distribution with finite element analysis. This enables elastic freeform molds for concrete spraying. By showcasing a porous structure, we integrate overall casting and unit casting concepts into an efficient solution for freeform construction.

Keywords: Concrete Shells, Bending-Active, Fabric Formwork, Stay-in-place Formwork, Nonwoven Composite.

1. Introduction

1.1. Background

Concrete construction heavily relies on formwork systems to shape structures, wood and metal being the primary materials of choice due to their familiarity and versatility. While these traditional methods are effective, they often require complex subdivision of forms into modular units or the use of CNC milling, resulting in significant waste generation, high labor and processing costs. These challenges underscore the pressing need for more efficient and sustainable formwork solutions in the construction industry. [1].

This study explores using textile materials like nonwoven fabrics with bending-active properties as formwork, departing from traditional rigid materials. Nonwoven fabrics are cost-effective, globally available, and offer varied performance options like insulation and fire resistance. Which are also easily recyclable.[2] By using them as formwork for lightweight thin-shell construction, structures can achieve enhanced insulation, soundproofing, and other performance criteria while meeting design strength requirements.

This study demonstrates the use of interwoven concrete thin-shell forms, showcasing the feasibility and flexibility of nonwoven fabric as formwork. The methodology involves segmenting the form into stripes and optimizing their bending-active capability. Nonwoven fabric is then cut and assembled to create the shell-like form. Non-shrinkage concrete is sprayed on top, followed by fiber-reinforced concrete for added structure strength.

When dealing with the bending-active properties of this statically indeterminate structure, actual models, and finite element analysis (FEA) are employed to analyze and verify the thin-shell formwork. Therefore, physical tests are conducted at each stage, including bending-active capability, material bending strength, and load-bearing capacity, following traditional research methods to obtain reference data.

1.2. Aim and Research Question

By employing nonwoven fabric as formwork, several economic benefits can be realized in the construction of concrete thin-shell structures. At the material level, the recyclability of nonwoven fabric surpasses many other materials used in construction methods. Additionally, the bending-active properties of this material reduce the need for additional support at the bottom of the formwork, contributing to the conservation of resources and reduced consumption of additional materials.

Furthermore, nonwoven fabric remains in place after the formation of the thin shell. Its purpose extends beyond surface texture and appearance; structurally, the fabric provides bending resistance, enabling the pursuit of lightweight thin-shell structures further. Within the architectural context, the various thermal insulation, soundproofing, and other performance capabilities offered by fabric reduce the need for additional layers in construction, meeting the requirements of building environments more effectively.

2. Content and Previous Experiment

In research on modern concrete formwork systems, fabric formwork is classified under flexible formwork systems. Within the classification of fabric formwork, the formwork material and fabrication methods are considered influential factors in the formwork system. Several fabrication methods for fabric formwork have been proposed, including external support, air pressure, and stay-in-place knitting [1]. This study attempts to propose an alternative method beyond these classifications, utilizing the material's active bending properties as a means of assembly and support. This is a method of construction that is rarely included in existing classifications.

2.1. Nonwoven Fabric

The use of fabric as formwork for concrete casting has been explored since the Industrial Revolution, with Gustav Lilienthal, an avant-garde engineer, proposing the idea of using fabric molds to reduce assumed engineering and labor costs [3]. Throughout this period and for the following hundred years, research primarily utilized synthetic fibers such as nylon, polyester, or polypropylene for weaving fabrics for formwork [4]. However, the proportion of nonwoven fabric used as formwork is significantly lower.

Looking back over the past few years of research, much of the focus on nonwoven fabric has been on its unique material properties and its suitability for the circular economy. This type of fabric is processed by needle punching, hydroentanglement, or thermal bonding, which creates a physical interlocking of randomly arranged recycled fibers, resulting in numerous pores between them [5]. This porosity has sparked considerable interest among teams researching architectural insulation materials.

In the past, soundproofing and thermal insulation materials were typically developed independently [2]. However, the fiber characteristics of nonwoven fabric have made it possible to study both aspects simultaneously. Relevant research indicates that placing fiber products between building materials such as concrete or brick walls can outperform commercially available building materials in blocking sound and heat transfer [6].

The scope of research mentioned above largely views nonwoven fabric as an independent building material. However, there are a few studies that have explored the composite infusion of concrete with nonwoven fabric. Current relevant research can be categorized into two main types:

The first approach used nonwoven fabric as a formwork liner, research in this area focuses on how to enhance the concrete surface's ability to resist environmental and chemical influences, thus increasing the service life of concrete [7]. This method involves using nonwoven fabric as an intermediary layer between the formwork and the concrete. The fabric allows excess water and air to escape from the poured concrete while retaining cement particles, thereby reducing surface pores and voids [8]. As a result, the final concrete structure exhibits a lower water-cement ratio [9]. This approach aims to improve the durability and longevity of concrete structures by mitigating issues such as cracking and deterioration caused by environmental factors. It represents an innovative application of nonwoven fabric in construction, leveraging its permeability and mechanical properties to enhance the performance of concrete elements.

The second approach involving the use of nonwoven fabric is to utilize it as a reinforcing composite material by incorporating it into cast concrete. In past research, discarded nonwoven fabric has been recycled and subjected to needle punching processes to re-bind the fibers before being added to the concrete mix during casting. This method effectively discovered that the shear resistance significantly increases after material cracking and opening [10], [11].

2.2. Bending-Active Formwork

The concept of bending-active as formwork is not entirely new. As early as 2013, Julian Lienhard conducted research on the properties of bending deformation in the use of sheet materials [12]. Consequently, researchers have been pursuing the development of this concept, which make the simulations and analyses based on this method gradually taken shape. And started utilizing gridshell as the foundation that could adapted to various curved surfaces [13].

The practical implementation and testing of this concept can be seen in the 2019 project by Tongji University, which utilized bending-active combined with 3D printing technology to successfully create the large-scale Brick Shell Pavilion, demonstrating the feasibility of this system [14].

Simultaneously, research using flat materials that bend actively to form templates has also begun. Zhejiang University, for example, utilized locally common materials such as Moso Bamboo as a grid-like support, combined with plastic film and mortar, successfully demonstrating that the forces generated by bending materials can form the basis of a shell template system [15].

3. Composite Fabric Formwork System

This research utilizes materials bending as templates for concrete casting, eliminating the need for additional support. A shallow arch form demonstrates the system, analyzing each layer from heat-pressed nonwoven fabric to fiber-reinforced concrete. Structural behavior and relevant simulations for designing shell structures are discussed.

3.1. System Prototype

In this study, two prototypes of different sizes and shapes will be tested to verify the feasibility of using nonwoven fabric as a self-supporting template at first. This will involve considering the dimensions, density, and composition of the fabric. After testing the small-sized prototype, the joining methods between materials will be examined to study the techniques required for scaling up and dealing with the joining of materials when facing freeform surfaces.

The design of bending-active arch prototype I has a span of 20 cm, a width of 20 cm, and a height of 10 cm. For the material, heat-pressed nonwoven fabric is used with dimensions of 30 cm in length, 20 cm in width, 1.8 mm in thickness, and a density of 575 kg/m^3. The short sides of this rectangular nonwoven fabric are placed at both ends of the mold, where the endpoints serve as hinge joints, allowing the fabric to form an arch shape due to its inherent buckling behavior.

Through an exploded axonometric view diagram (Figure 1), the fabrication steps are as follows:

- Use the mold to constrain the bending of the fabric to achieve the desired curvature.
- Spray a 4 mm thick layer of non-shrinkage concrete onto the surface of the nonwoven fabric.
- Allow it to dry for a day, then spray a second layer of fiber-reinforced concrete (FRC) with 4mm thickness.

- Apply a thin layer of monolithic finish on the final surface.

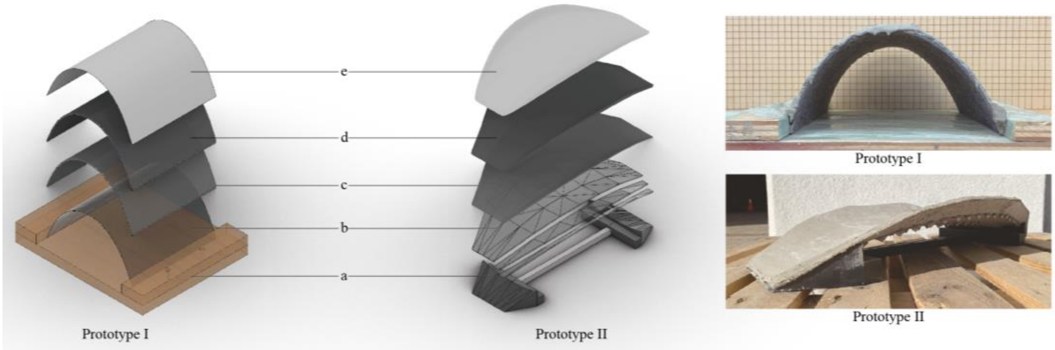

Figure 1: Exploded view showing the prototype layer. (a) timber support; (b) Nonwoven Fabric; (c) non-shrinkage concrete; (d) fiber-reinforced concrete; (e) monolithic finish

Prototype II is aiming to verify the feasibility of fabric joining for creating curved surfaces. Here, the method of using nonwoven fabric to construct self-supporting structures is employed, with the edge shapes cut from the fabric serving as self-locking joints, enabling the assembly of strip-shaped fabrics without the use of additional materials [16].

Prototype II has a span of 50 cm (excluding fixed frame), a width gradually transitioning from 16 cm to 30 cm and back to 16 cm, and a height of 10 cm. The difference in fabrication steps lies in the fact that while Prototype I used a single piece of fabric bent into shape, Prototype II involves joining multiple longitudinal fabric strips to form a hyperboloid shape with increased span.

In the testing phase, two prototypes were successfully manufactured and demonstrated the potential for ongoing development. Therefore, further research delves deeper into materials and forming process.

3.2. Material Properties

This study focuses on maximizing the performance of active bending for self-supporting structures. Two main materials are utilized: fabric materials for initial support and mortar materials for structural performance after solidification.

3.2.1. Heat-pressed Nonwoven Fabric

According to Julian Lienhard's research [12], the ratio of flexural strength to flexural Young's modulus will significantly impact the material's ability for bending-active. In this study, a nonwoven fabric with a thickness of 3mm and a weight of 170kg/m^3, primarily composed of synthetic fibers and partially polyethylene, is selected as the base material. Composite materials are added to achieve the required bending-active strength, and the fabric undergoes repeated testing through a heat-pressing process.

Various nonwoven fabric compositions are considered, leading to significant differences in material performance. Options include unprocessed 3mm nonwoven fabric, PLA film heat-pressed between layers, and three-layer heat-pressed nonwoven fabric. Testing also includes low-melting-point long fiber nonwoven fabric, offering bonding effects without PLA film and higher flexural strength. (Table 1)

Table 1: Heat-press composite material's properties.

	Flexural Strength (MPa)	Flexural Youngs Module (GPa)	Ratio
Nonwoven	0.53	0.133	3.98
Nonwoven + PLA + Nonwoven	2.38	0.239	9.958
Nonwoven + Low Melt + Nonwoven	7.98	1.520	5.25
Nonwoven + PLA + Nonwoven + PLA + Nonwoven	5.82	0.444	13.108

According to research related to bending-active, materials suitable for active bending typically have a ratio of Flexural Strength / E > 2.5 (with Flexural Strength [MPa] and E [GPa]). However, when considering that the nonwoven fabric in the construction of shell systems will need to support over 15 times its own weight per square centimeter (concrete weight / nonwoven fabric weight), materials capable of providing higher flexural strength will be more suitable.

3.2.2. Mortar

In research on concrete and nonwoven fabric, adding nonwoven fabric to concrete structures improves various material properties. To address factors contributing to thin-shell concrete structure failure, compression, flexural, and three-point bending tests are conducted on mortar mixes and concrete slabs with nonwoven fabric templates underneath.

At this stage, the research is divided into verifying the compressive strength and flexural strength of mortar. Three types of mortar are considered: plain concrete, fiber-reinforced concrete, and fiber-reinforced concrete with a bottom layer of nonwoven fabric (Table 2). For the compressive strength tests, ASTM C109 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars is employed, using 50mm cube specimens for testing. (Figure 2)

Table 2: Mix Design of Mortar

	Water(g)	Cement(g)	Silica Sand(g)	Fiber(g)	Nonwoven Fabric at bottom	Compression Strength(psi)
Concrete	800	1700	3400	0	None	5472.28
FRC	800	1700	3400	17	None	5985.23
FRC + Nonwoven	800	1700	3400	17	Yes	5611.25

In the experiment to assess the flexural capacity of composite concrete, concrete slabs measuring 70cm in length, 15cm in width, and 3cm in thickness are used for the three-point bending test. The aim is to approximate the completed thickness of large-scale thin-shell structures. By examining the proportions of different materials and their performance upon failure, the actual effectiveness of the nonwoven fabric template can be evaluated.

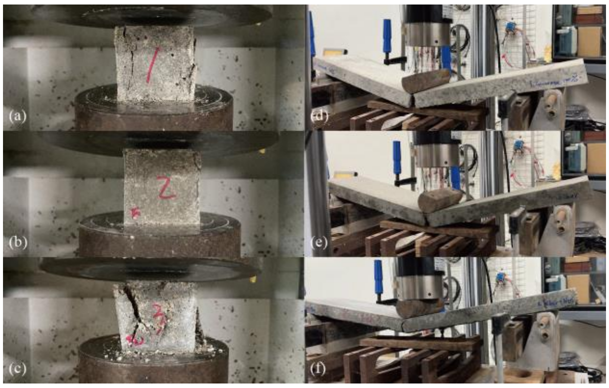

Figure 2: left compression test. (a) concrete; (b) FRC; (c) FRC with nonwoven at bottom.
Figure 3: Right three-point bending test. (d) concrete; (e) FRC; (f) FRC with nonwoven at bottom.

In the results of the three-point bending test, the combination of fiber-reinforced concrete with nonwoven fabric shows a 20% improvement in flexural capacity. The notable performance in this experiment is that both types of slabs, without the addition of steel reinforcement or wire mesh, exhibit localized cracking at approximately 50kgf of load. The concrete specimen fractures directly at 102kgf, which is a typical result for concrete without any added tensile materials. However, the slab with nonwoven fabric at the bottom withstands a load of 122kgf without fracturing. The nonwoven fabric acts as a significant restraint on the displacement of the concrete slab, and the test is manually stopped only when the slab gradually bends towards the bottom of the testing machine. (Figure 3)

3.3. Structure Analysis

Follow by the data from last chapter this chapter will analyze the relationship between form and structural strength. A sample of nonwoven fabric, measuring 70cm in length and 10cm in width, will be tested by bending it over a mold to achieve a span of 60cm (Figure 4). The single arch form will be supported at both ends with hinge supports. Which would be the foundation data for three-dimensions curvature under design experiments.

The experiment will initially involve computer simulations to predict the bending pattern of the fabric and the weight it can support after bending. Subsequently, physical models will be used to verify any discrepancies and account for other possible variables during fabrication. The research data obtained in this chapter will aid in calculating information such as shell strength, thickness, and span in later stages.

3.3.1. Bending-active Arch Analysis

The testing procedure will first involve using simulation software to simulate the deformation of the material based on material parameters such as Young's modulus, flexural strength, density, etc. One end point will be set as a pin joint, while the other end point will be set as a pin-roller. Additionally, pre-stress will be applied to the material to induce buckling to achieve the designed 60cm span and 19cm height.

The simulation progresses through three stages corresponding to the fabrication process: nonwoven fabric, hardened nonwoven fabric, and nonwoven fabric with added fiber-reinforced concrete. Deformation caused by distributed load is calculated for each stage, determining the thickness of sprayed mortar and achieving thin-shell strength until completion. (Table 3, Figure 5)

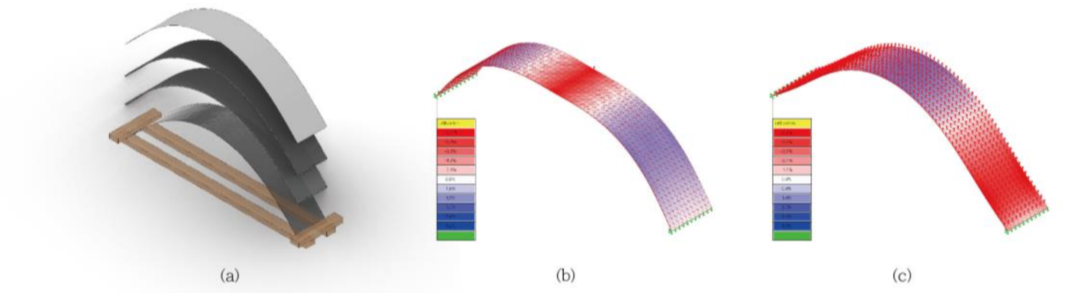

Figure 4: (a) Bending-active arch exploded view. Figure 5: FEA of the bending arch (b) concentrated load. (c) distributed load.

Table 3: Bending-active Arch data.

	Composite	Mass (g)	Height 1(mm)	Height 2(mm)	Height 3(mm)	Width 1(mm)	Width 2(mm)	Width 3(mm)
Arch-60-A	Nonwoven	88	1.12	1.30	1.88	102.45	102.65	101.97
Arch-60-B	Nonwoven + Non-Shrinkage Concrete	630	4.00	5.41	4.33	100.33	101.21	101.33
Arch-60-C	Nonwoven + Non-Shrinkage Concrete + FRC	1193	8.02	9.49	8.64	103.89	104.40	103.86

The actual manufacturing of the single arch will follow the designed process. Through the three-point bending test, the arch will be subjected to concentrated loading, and the load it can withstand at a deformation of 3mm at each stage will be determined. This data will then be used in finite element analysis (FEA) to calculate the weight the arch can bear under uniform loading. This information will be used to calculate the thickness of mortar required. (Table 4)

Table 4: Concentrated load and Distributed Load of Arch

	Thickness(mm)	Physical concentrated load(N)	Analysis concentrated load(N)	Analysis distributed load(N)
Arch-60-A	1.43	4.312	4.44	5.948
Arch-60-B	4.58	47.510	156.80	275.086
Arch-60-C	8.71	237.5226	1149.81	2145.171

3.3.2. 3D Scanning & Conclusion

After the actual manufacturing and bending test, it is observed that the ability of the arch to withstand concentrated loading is lower than the values obtained from computer simulations. Therefore, in the later stages of the experiment, a 3D scanning device is introduced to scan the arch at three stages to identify any discrepancies between the physical arches and their computer models. (Figure 6)

After scanning, regression analysis is conducted to plot the skeleton of the point cloud (Figure 7), revealing the factors affecting the unevenness of the arch's form. It is found that the accuracy of fabrication affects the uniformity of the arch's shape. In the first stage, issues such as uneven thickness may arise during the heat-pressing process (Table 3 "Arch Height"), leading to slight deviations in the material during active bending. This problem is exacerbated during the spraying process, resulting in discrepancies between the final form and the expected shape.

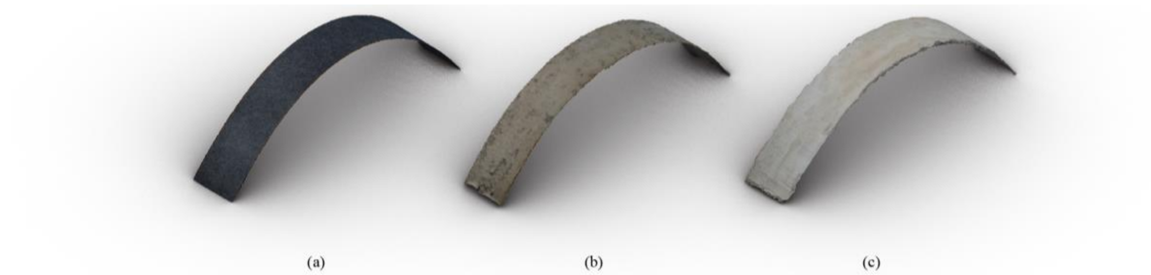

Figure 6: 3D scanning result. (a) Arch-60-A; (b) Arch-60-B; (c) Arch-60-C.

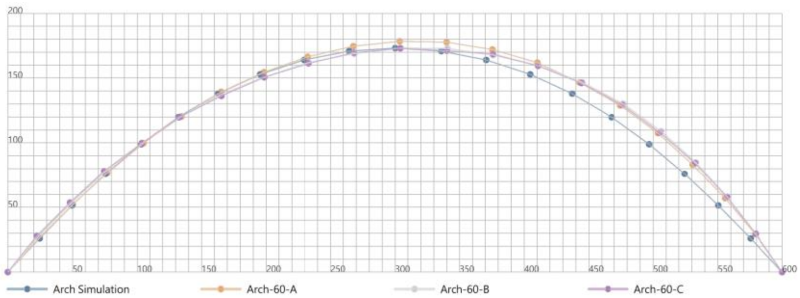

Figure 7: Comparison of design and each stage's curvature. (Unit: mm)

The method of mortar spraying can also impact material properties, potentially affecting concrete's shear behavior, as noted by T. Garcia [17]. Lower porosity from spraying may reduce shear strength. In this study, this lower strength might cause the arch to fail under calculated loads from simulations. Moreover, the absence of tensile materials like reinforcement bars in the concrete used in experiments leads to differences in flexural strength compared to standard concrete parameters.

However, the data obtained from the physical experiments in this study still effectively validate the feasibility of this method. Moreover, there is still considerable flexibility during the stage of spraying fiber-reinforced concrete to increase the material thickness, thereby achieving higher flexural strength performance.

4. Design Experiment

The challenge of this study lies in contemplating the design of Erwin Hauer and Peter Darvall's Upton Chapel (Figure 8), where continuous or woven surfaces are transformed into functional yet aesthetically pleasing designs that diffuse light and air flow. However, such designs are rarely seen in modern architecture, largely due to the complexity of their production process.

The manufacturing process for this type of design typically involves repetitive molding assembly, where a batch of identical molds is used for casting, followed by the installation of precast concrete by workers, who sequentially assemble and fill the gaps at the joints with mortar. This study aims to reinterpret this type of form using the technique of nonwoven fabric formwork, eliminating the need for extensive manual labor and reducing manufacturing costs, to create thin shell structures capable of diffusing light and air flow.

4.1. Form Finding

In the testing phase, a local model (60cm*60cm) was used to assess applying the technique to woven thin-shell structures. The design follows Erwin Hauer Design 1, focusing on unit element continuity. Physical simulation tools aided form finding for a thin-shell structure supported by three points. Mesh topology was adjusted to match unit element patterns, followed by morphing to finalize the design. (Figure 9)

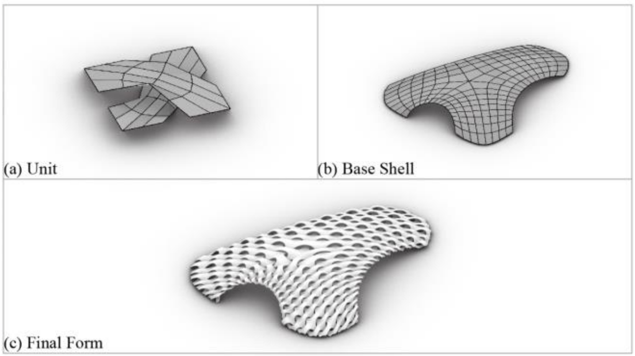

Figure 8: (Left) Design by Erwin Hauer. (Right) Façade by Peter Darvall. Figure 9: Process of porous shell.

4.2. Joint

In the manufacturing process, seamless connection of nonwoven fabric is crucial. Instead of traditional bolt locking, alternative unit connection methods are proposed. One method involves a stripes-based system, where the fabric is divided into segments. Using the concept of origami, male and female ends are created for connection. The male end is triangular with foldable edges, while the female end has incisions to accommodate the folded male end. This creates a sturdy folded clasp, enabling continuous joining between fabric segments.

4.3. Construction

Overall, the manufacturing process consists of eight steps, as shown in the diagram. The first two steps involve structural analysis and load simulation in the computer. Following this, nonwoven fabric is cut in to stripes, and then installed onto the framework of a self-supporting template. Finally, concrete is sprayed sequentially onto the top to harden and complete the structural concrete, followed by the monolithic finish. (Figure 10, 11)

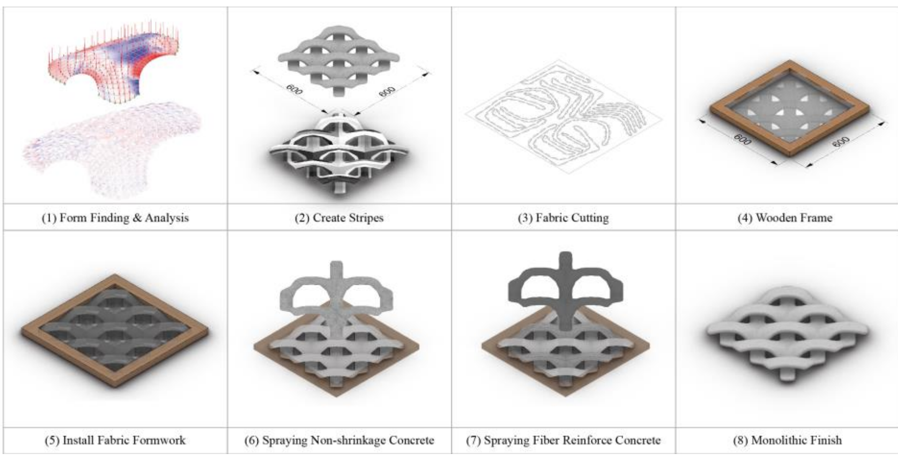

Figure 10: Construction Process.

5. Conclusion and Future Works

This study proposes a different perspective on shell structures by utilizing the bending-active characteristic of nonwoven fabric. A simple arch or curve can be created without extra support. Moreover, by employing nonwoven fabric as stay-in-place formwork, customizable materials could easily enhance the required functions such as sound absorption, fire resistance, insulation, etc.

In this study, the methods of concrete spraying mainly follow pneumatic formwork or other kinds of stay-in-place formwork, which provide strong support for the formwork to prevent collapse due to the weight and force of the concrete. In the bending arch experiment, the weight of the concrete does create deviations in the final form due to the uneven distribution of the mortar and some other fabrication lapse. However, under the porous shell, the deviation has decreases, as the three-dimensional surface creates higher strength against vertical force. This opens up the possibility for further explore of these methods by forming specific type of three-dimensional curvature this might be opportunity for larger scale structure.

Figure 11: Result (Height 60cm, Width 60cm).

References

[1] W. Li, X. Lin, D. W. Bao, and Y. Min Xie, "A review of formwork systems for modern concrete construction," *Structures*, vol. 38, pp. 52–63, Apr. 2022.

[2] F. Karimi, P. Soltani, M. Zarrebini, and A. Hassanpour, "Acoustic and thermal performance of polypropylene nonwoven fabrics for insulation in buildings," *Journal of Building Engineering*, vol. 50, p. 104125, Jun. 2022.

[3] D. Veenendaal, M. West, and P. Block, "History and overview of fabric formwork: using fabrics for concrete casting," *Structural Concrete*, vol. 12, no. 3, pp. 164–177, Sep. 2011.

[4] H. Abdelgader, M. West, & J. Górski, "State-of-the-Art Report on fabric formwork." In *Trabajo presentado en The International Conference on Construction and Building Technology*. June, 2008.

[5] D. Antolinc and K. E. Filipič, "Recycling of Nonwoven Polyethylene Terephthalate Textile into Thermal and Acoustic Insulation for More Sustainable Buildings," *Polymers*, vol. 13, no. 18, p. 3090, Jan. 2021.

[6] Vitaliy Datsyuk *et al.*, "Polystyrene nanofibers for nonwoven porous building insulation materials," *Engineering reports* , vol. 1, no. 2, Sep. 2019.

[7] A. M. Neville, *Properties of concrete*. Harlow Pearson Education, 2012.

[8] T. Krishnan, T. Sai Krishna, P. Sugumar, and E. Narasimhulu, "Influence of nonwoven fabric as controlled permeable formwork liner in concrete," *Materials Today: Proceedings*, vol. 64, pp. 1048–1053, 2022.

[9] S. A. Basha, K. M. Reddy, C. M. Babu, & K. Anand. "Effect of Controlled Permeable Formwork on Concrete," 2017.

[10] P. Sadrolodabaee, J. Claramunt, M. Ardanuy, and A. de la Fuente, "Characterization of a textile waste nonwoven fabric reinforced cement composite for non-structural building components," *Construction and Building Materials*, vol. 276, p. 122179, Mar. 2021.

[11] J. Claramunt, L. J. Fernández-Carrasco, H. Ventura, and M. Ardanuy, "Natural fiber nonwoven reinforced cement composites as sustainable materials for building envelopes," *Construction and Building Materials*, vol. 115, pp. 230–239, Jul. 2016.

[12] J. Lienhard, H. Alpermann, C. Gengnagel, and J. Knippers, "Active Bending, a Review on Structures where Bending is Used as a Self-Formation Process," *International Journal of Space Structures*, vol. 28, no. 3–4, pp. 187–196, Sep. 2013.

[13] Y. Yavaribajestani, M. Herrmann, & S. Schleicher, "Parameter sensitivity analysis of hybrid gridshells with bending-active formwork." In *Innovation, Sustainability and Legacy-Proceedings of the IASS Annual Symposium 2022* (pp. 19-23).

[14] X. Wang, K. M. M. Tam, A. Beaudouin-Mackay, B. Hoyle, M. Mason, Z. Guo, ... & P. Block . "3d-printed bending-active formwork for shell structures." In *Architectural Intelligence: Selected Papers from the 1st International Conference on Computational Design and Robotic Fabrication (CDRF 2019)* (pp. 295-314). Springer Singapore.

[15] Q. Zhang, F. Ye, Z. Li, X. Zhu, Z. Shi, F. Marmo, ... & C. Demartino. "Development of an active bending formwork based on bamboo mortar shells: preliminary results." In *Proceedings of IASS Annual Symposia* (Vol. 2022, No. 7, pp. 1-9). International Association for Shell and Spatial Structures (IASS), Sep. 2022.

[16] W. C. Lo & S. Y. Wang. "Fungus Mesh: Nonwoven Self-Supporting Assemblies." In *Proceedings of CAADRIA, Apr. 2024.*

[17] T. Garcia, A. Blanco, and S. H. P. Cavalaro, "Shear behaviour of sprayed concrete," *Construction and Building Materials*, vol. 124, pp. 722–731, Oct. 2016.