An Experimental Approach to Use Foldable Fabric-Formwork in Digital Craftsmanship

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Since the 1950s, various studies on fabric-formwork systems have been developed. However, since the 2000s, with the rise of computational methods, the relationship between fabric-formwork and craft has been explored from specific perspectives, leaving gaps in the field concerning the reusability of molds and the production of form variations. This study aims to explore the potential of integrating traditional and digital methods by examining the relationship between foldable fabric-formwork systems and concrete within the framework of digital craftsmanship in a form-specific manner. The methodology of this study comprises three stages, which are: i) the selection of folding pattern, ii) the production of foldable formwork through digital craftsmanship, and iii) the casting of concrete into fabric molds. These stages involve a feedback loop between the computational and analog modelling approaches. To investigate the potential of different form alternatives, a series of physical experiments were conducted. The experiments conducted revealed that the resulting forms were significantly influenced by the material mixture, the type and properties of the fabric, and the mold structure. Consequently, to ascertain the veracity of the physical products generated, simulations were initially conducted in a computational-design environment following the pouring concrete. Thereafter, the physical products were 3D-scanned with a comparison subsequently made. The findings indicate that the utilization of dynamic molds holds significant potential for future applications in various fields including engineering, architecture, and art.

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Dijital Zanaatkarlıkta Katlanabilir Kumaş Kalıp Kullanımına Yönelik Deneysel Bir Yaklaşım

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1950'lerden bu yana kumaş kalıp sistemleri üzerine çeşitli çalışmalar geliştirilmiştir. Ancak, 2000'lerden itibaren hesaplamalı yöntemlerin yükselişiyle birlikte, kumaş kalıp sistemleri ve zanaat arasındaki ilişki belirli perspektiflerden incelenmeye başlanmış ve kalıpların yeniden kullanılabilirliği ile form varyasyonlarının üretimi konusunda alanda boşluklar bırakılmıştır. Bu çalışma, katlanabilir kumaş kalıp sistemleri ve beton arasındaki ilişkiyi, dijital zanaatkârlık çerçevesinde, forma özgü bir şekilde inceleyerek, geleneksel ve dijital yöntemleri birleştirmenin potansiyelini keşfetmeyi amaçlamaktadır. Bu çalışma üç aşamadan oluşur: i) katlama deseninin seçilmesi, ii) dijital zanaatkarlık aracılığıyla katlanabilir kalıp üretimi, iii) betonun kumaş kalıplara dökülmesi. Farklı form alternatiflerini görebilmek için çeşitli fiziksel deneyler yapılmıştır. Bu deneylerin ışığı altında, ortaya çıkan formlar üzerinde malzeme karışımı, kumaş cinsi ve özelliği, ve kalıp strüktürünün etkili olduğu görülmüştür. Sonuç olarak, elde edilen fiziksel ürünlerin dijital ortamla doğruluğunu test etmek için ilk önce hesaplamalı tasarım ortamında beton döküldükten sonraki simülasyonu yapılmıştır. Daha sonra 3B sayısal-tarama yöntemleri kullanılarak fiziksel ürünler taratılmış ve bir karşılaştırma yapılmıştır. Elde edilen bulgular, gelecekte dinamik kalıpların kullanımının mühendislik, mimarlık ve sanat gibi birçok alanda kullanılabilecek yeni potansiyeller taşıdığını göstermektedir.

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Anahtar Kelimeler: Dijital Zanaatkarlık, Fabrigami, Katlama, Kumaş Kalıp.

1. INTRODUCTION

The use of flexible fabric formwork, which has significantly influenced the existence and production methods of concrete in architecture, dates back to the mid-20th century. This method emerged during World War II, particularly at a time when construction materials were scarce, offering several advantages such as resisting the hydrostatic pressure exerted by concrete, filtering excess water, and increasing the strength of the concrete (Orr et al., 2011). In 1941, the Irish engineer James Waller developed one of the first notable applications of this technique—the Ctesiphon roof system. This system utilized a combination of jute fabric and concrete to create wide-span and thin structures. In the 1950s, Felix Candela further advanced this method, leading to significant projects in Mexico. During the 1970s and 1980s, Spanish architect Miquel Fisac explored the potential of concrete using flexible formwork, producing highly detailed surfaces and complex geometric forms. He used these formworks to produce cladding panels with varied textures and forms by controlling their deformation during casting (Pedreschi, 2013).

At the beginning of the 2000s, interest in this technique increased further with the establishment of the research center CAST by Mark West, focusing on how flexible formwork can be used innovatively and efficiently in architectural design. Since then, technological advancements have led to the development of entirely new methods that integrate digital design and craftsmanship. Numerous concrete elements have been cast using fabric formwork, with the continuous development of precise tools through both digital and analog methods remaining a key area of research (Veenendaal & Block, 2012; Hawkins et al., 2016; West, 2016). Initially, in 2009, Andrew Kudless, founder of MATSYS Design Studio, created the installation titled "P_Wall" at the San Francisco Museum of Modern Art. This project utilized flexible fabric formwork and computational methods to create a dynamic simulation environment through form-finding. However, the physical formwork used remained static (Huang & Belton, 2014).

In subsequent years, Meibodi and Tessmann (2014) differentiated their approach by using CNC machining and handcrafting techniques to cast concrete into an MDF formwork that only moved along the diagonal axis, producing a hyperbolic paraboloid geometric form. In the same year, Schmitz (2014) introduced methods for using fabric formwork in the construction industry, including tensioned fabric formworks and air-inflated fabric formworks. These innovative methods offer advantages such as cost-effectiveness, lightweight, portability, design flexibility, and waste reduction. More recently, Szabo et al. (2019) employed the Smart Dynamic Casting (SDC) method with robotic fabrication to produce thin folded concrete units using a rigid and fixed formwork **(Table 1).** This study produced concrete units approximately 1.50 meters in size using digital casting; however, collapse occurred after reaching a certain height. Among the most innovative approaches in concrete production is the work by Lloret-Fritschi et al. (2023), who first introduced a two-state dynamic mold made from waxed paper for lightweight mold production. Although they demonstrated successful concrete production with these paper molds, their approach required the peeling of the mold for concrete removal, resulting in a single-use mold.

The examination of these concrete formwork systems has identified two key issues. First, there is concern regarding the durability and longevity of the fabric materials, which is particularly concerning in the case of single-use materials that may pose environmental risks. Second, there are the variations that can occur during the assembly, tensioning, and support of the fabric. These variations can lead to inconsistencies in the formwork geometry, increasing the risk of not achieving the desired shape after the concrete is cast (Liebringshausen et al., 2023). To address these challenges, the controlled assembly and use of fabric as formwork presents a more sustainable, lightweight, globally accessible, and reusable alternative compared to traditional formwork systems (Lo & Wang, 2024).

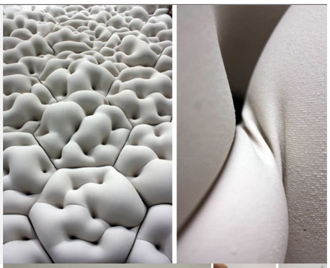
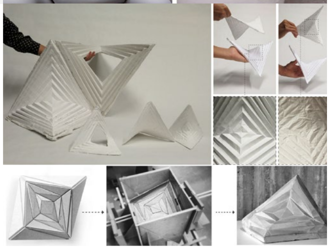
Order/ Researchers	*Geometric Form*	*Casting and Molding Material*	*Folding or Hinging in Formwork*	*Kinetic Mechanism*	*Design & Manufacturing Method*	*Impact & Performance*	*Images of Physical Prototypes*
1. Kudless (2009), founder of MATSYS Design Studio	-Hexagon modules	-Pouring plaster onto nylon fabric-formwork	-Fixed wooden dowels	-Fixed fabric-formwork	-Computational Form-Finding -Handcrafting (Nylon fabric stretched over wooden dowels)	-Rich configuration through varying distribution of dowels within modules -Formation of uniform organic forms	
2. Meibodi & Tessmann (2014)	-Hyperbolic paraboloid	-Pouring gypsum onto paper mold -Pouring gypsum onto plastic mold -Pouring concrete onto plastic mold -Pouring concrete onto MDF mold	- Folding with paper - Hinging in MDF mold (with textile-reinforced tape)	-Dynamic formwork (only movement on diagonal axis)	-Computational design and simulation -Handcrafting -CNC machining	-Reusable formwork -Easier form explorations with paper molds -Better gypsum performance in the plastic mold -Better concrete performance in the MDF mold	
3. Szabo et al. (2019)	-Thin folded geometry with a straight curve -Thin folded geometry with a bezier-curved -Thin folded geometry with a sine-curved	Pouring concrete into foil formwork	- Fixed folded foil formwork	-Rigid folded formwork	-Computational design -Robotic fabrication production using Smart Dynamic Casting (SDC) method	-Reusable formwork -Uneven distribution of the material within the mold -Collapse occurring at a certain height in the Bezier-curved prototype -Cracking in the Sine-curved prototype	
4. Lloret-Fritschi et al. (2023)	-Thin folded geometry with curved creases -Folded geometry with nested creases	-Pouring concrete into 2mm museum board formwork -Pouring concrete into 0.4 mm wax paper formwork	-Folding with paper	-Dynamic formwork (a bistable structure)	-Computational design -Robotic fabrication production using Admixture Controlled Digital Casting (ACDC) method -CNC machining	-Single-use formwork -Smooth surface finish with museum board mold -A relatively smooth surface finish with air pockets and minor imperfections with waxed paper mold	
5. Authors (2024)	-OctaBowl	-Pouring white concrete into kitchen cloth fabric formwork -Pouring white concrete into white-flannel fabric formwork	-Hinging and folding in fabric formwork	-Dynamic formwork (Multiple degrees of freedom with designed joints)	-Computational design and simulation -Handcrafting -Digital fabrication with 3D printer	-Reusable formwork -Relatively smooth surface finish except for the trace left by the mould frame -Formation of catenary curve shapes by concrete self-forming using fabric	

Table 1: A comparison between the existing concrete formworks and the dynamic formwork produced in this research.

Various techniques have been developed to effectively utilize fabric formwork during the form-finding stages. As commonly seen in existing studies, the fabric is typically fixed in place. However, Akçay Kavakoğlu (2020) proposed a novel approach by applying the fabrigami technique to fabric, enabling the production of dynamic formwork.

Since this technique draws inspiration from the fundamental principles of origami, it is essential to first understand the concept of origami itself. Origami is known as a generative technique used to create complex geometric forms by folding rigid surfaces according to rule-based relationships (Song et al., 2024), and originating from Japanese, the term is derived from “oru” (折る-*to fold*) and “kami” (紙-*paper*). This characteristic has inspired various disciplines and contributed to the development of diverse structures. One such technique inspired by origami is fabrigami, which is known as the art of folding fabric (Ahmed et al., 2020). To fold the fabric into the desired pattern, stitching lines are created on it, and folds are made along those lines (Wang et al., 2022). In architecture, Samira Boon and her Studio in Amsterdam explore innovative uses of fabric, combining origami techniques with digital manufacturing to create dynamic, interactive spaces (Boon, 2024). Some of the studio's projects are illustrated below **(Figure 1)**.

All of these processes require both analog and digital craftsmanship in terms of the level of detail and the need for artistic skills in fabric formwork. According to McCullough (1998), digital craftsmanship allows artisans to integrate traditional craft techniques with digital technologies, enhancing their ability to solve complex challenges and develop innovative solutions. This integration enables artisans to effectively use digital tools to overcome intricate problems and create novel solutions (Kilian, 2007). This study aims to explore the potential of combining traditional and digital methods, akin to McCullough's concept of digital craftsmanship, by a dynamic fabric mold is produced through a different crease-pattern, and the strengths and weaknesses of these outputs are discussed on a form-specific basis to evaluate their future applications.


(a)

(b)

(c)

Figure 1: Fabric folding studies, images sourced from Studio Samira Boon (2024)
(a) *Tsuru x Brighton College* project completed in 2024
(b) *Kumo x Lightnet* project completed in 2024
(c) *HERMÈS & RDAI* project completed in 2022.

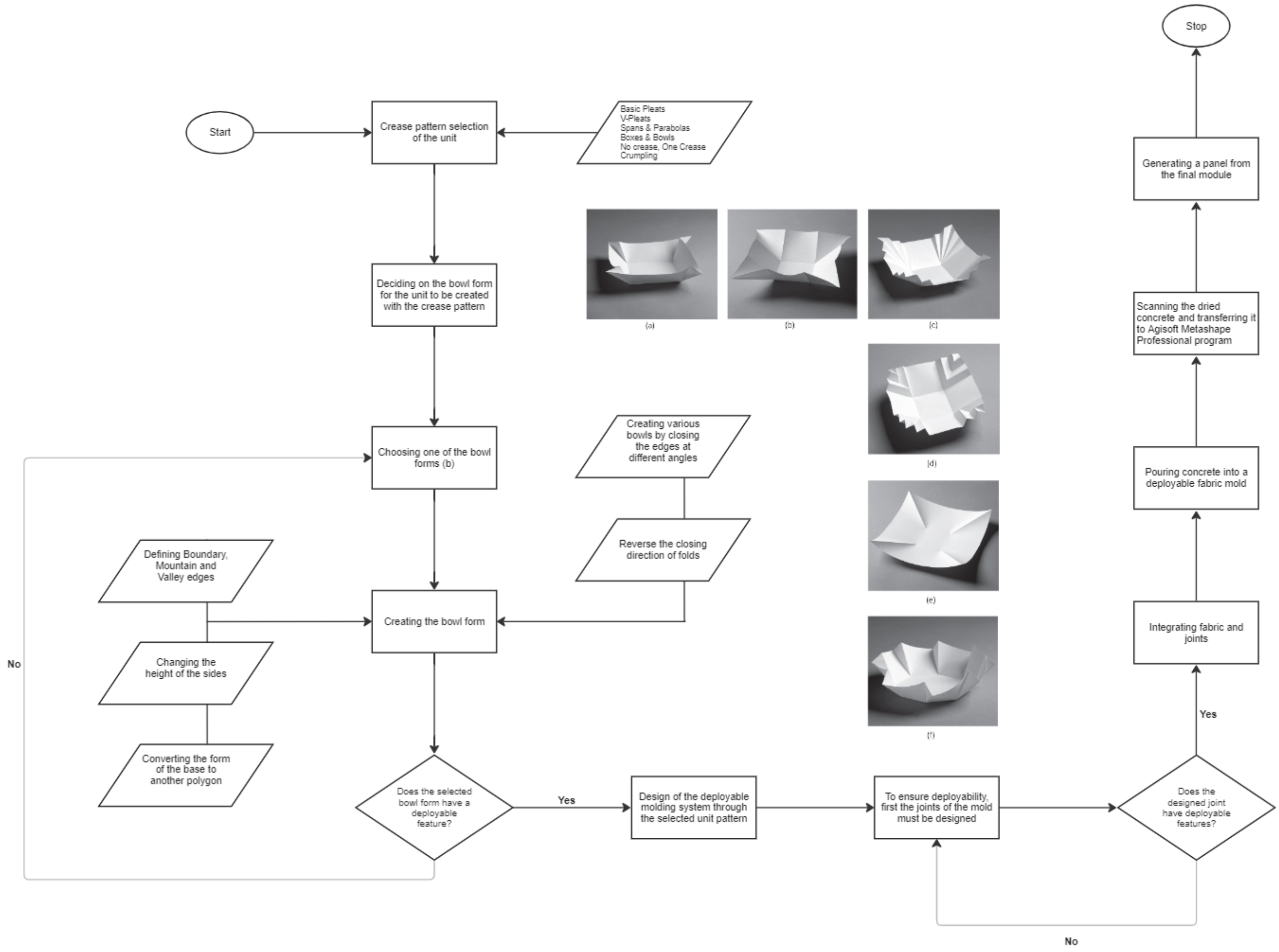
2. METHODOLOGY

The methodology of this study is developed based on the dynamic fabric mold system generated by fabrigami technique which is offered by Akçay Kavakoğlu (2020) for exploring the novel tectonics of fabric-formed concrete. The progress includes three modeling stages: algorithmic modeling, 3D geometric modeling, and analog modeling **(Figure 2)**. The research methodology comprises three stages: i) the selection of the crease pattern for the unit, ii) the design of the deployable formwork system based on the selected unit pattern, and iii) the casting of concrete into fabric molds.

I. The selection of folding pattern: Initially, a crease pattern is chosen to form a unit.

II. The production of foldable formwork through digital craftsmanship: This stage involves designing a deployable formwork system using fabric, leveraging the fabrigami technique. Given that the resulting form will impact its structure, initial emphasis is placed on designing connection details within the system. Various modeling methods are employed to conduct hinge experiments, and ultimately, the designed formwork structure is integrated with different types of fabric.
III. The casting of concrete into fabric molds: Various concrete experiments are conducted on deployable fabric molds.

Figure 2: Flowchart of the process and illustration of bowl forms adapted from Jackson's (2011) book.



2.1 The Selection of Folding Pattern

The bowl form is selected as the basis for the unit to be created using the crease pattern. Due to the broad design parameters of bowl forms, it is possible to produce bowls in a wide variety of shapes. Various modifications are feasible, such as altering the height of the sides, changing the base to another polygon, creating different bowls by closing the edges at various angles, or reversing many folds. These variations, when combined in different ways, can result in highly diverse forms. In Jackson's book, *Folding Techniques for Designers: From Sheet to Form*, he demonstrates the folding techniques for creating bowl forms, progressing from simple to complex, and identifies six distinct bowl units **(Figure 3).**

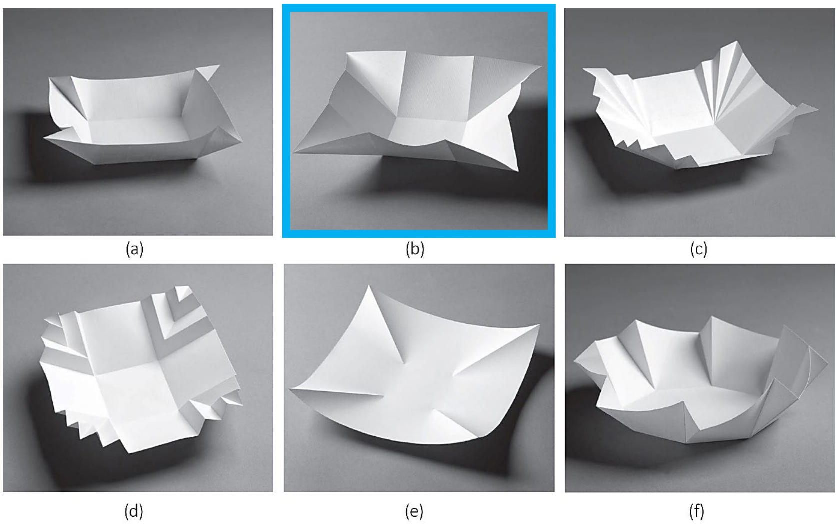


Figure 3: Six different types of bowl forms (Jackson, 2011).

In this study, the unit (b) is selected from among the bowl forms presented in the book. When comparing all the units, the units labeled (d) and (c) are not chosen due to the presence of excessive curvature at the ends of the diagonal axes, which could cause fabric folding difficulties and require more material for the rigid framework of the mold. Similarly, the unit (e) is excluded as it does not provide a suitable cavity for pouring concrete. The remaining units labeled (a) and (f) are also dismissed due to their inward protrusions, which could potentially cause issues during the demolding process.

One of the key advantages of the selected unit (b) is relatively its simple form, which allows it to adapt to the fabric and facilitate folding. This feature enables the use of a variety of materials, from paper to fabric, in the creation of dynamic molds. Such versatility supports sustainability by allowing the use of different design options at low-cost and maximizing the efficient use of available materials. Another significant advantage of the chosen bowl form is its capacity for rapid and mass production, which simplifies the creation of numerous units and modular designs. Furthermore, the ability to alter the folding direction of the unit, folding its ends either inward or outward, provides various design alternatives. The selected unit has two different versions: inward-facing and outward-facing, to be utilized in subsequent molding stages. However, considering that the inward-curving version would hinder the removal of concrete material once poured, the outward-facing version is preferred.

2.2 The Production of Foldable Formwork through Digital Craftsmanship

Following selecting the crease pattern to create the unit (b), the boundary, mountain, and valley details of the chosen unit are first digitally drawn. These edges are then defined within a computational design environment. Using the simulation component available in the Crane plug-in, the folding motion is simulated, and the resulting forms are observed **(Figure 4).** In the physical environment, the design of the connection details, which enable the system's mobility, is crucial for creating a deployable mold system. In this context, the connection details are initially addressed, and various connection designs are digitally generated to explore different possibilities and save time. Rapid prototyping methods are employed, with a 3D printer used as a manufacturing tool for these designs. The fundamental question at this stage is: *How can the movement of the system be achieved with joints?* Based on the answer to this question, the materials to be used are selected. Wooden rods are chosen for the strength of the system's basic framework, while a flexible material called *Thermoplastic Polyurethane-TPU* is selected for the joints to ensure flexibility.

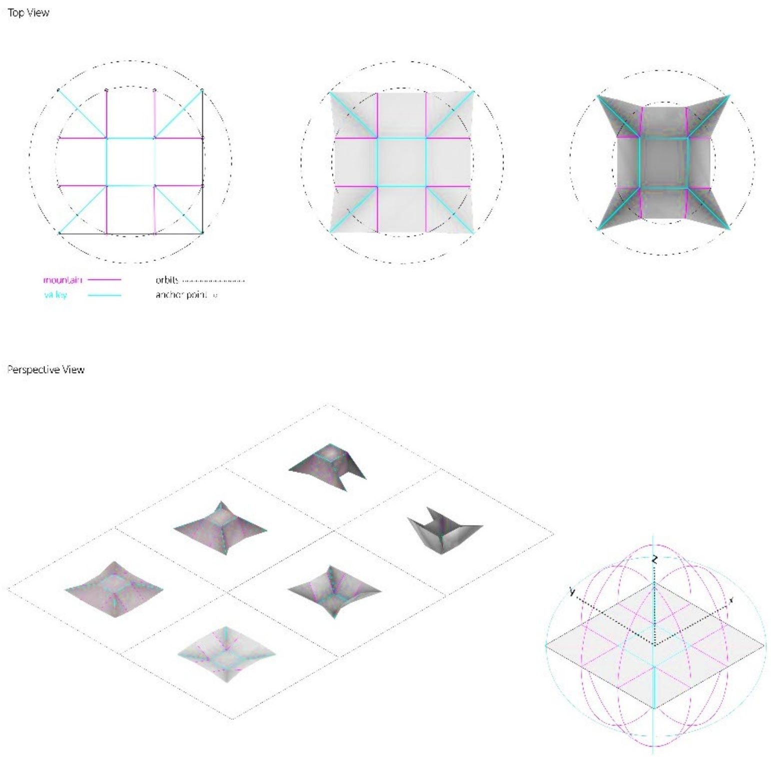


Figure 4: Identifying edges and exploring folding motion.

2.2.1 Joint Experiments

After deciding on the material selection, a joint structure is created in a computational design environment using open-source code from Parametric House (2022) to develop an idea for the connection detail. The joints are then integrated into the mold structure, as shown in **Figure 5**. To test the designed joint in a physical environment, it is produced using *Thermoplastic Polyurethane* through additive manufacturing, as depicted in **Figure 6**.

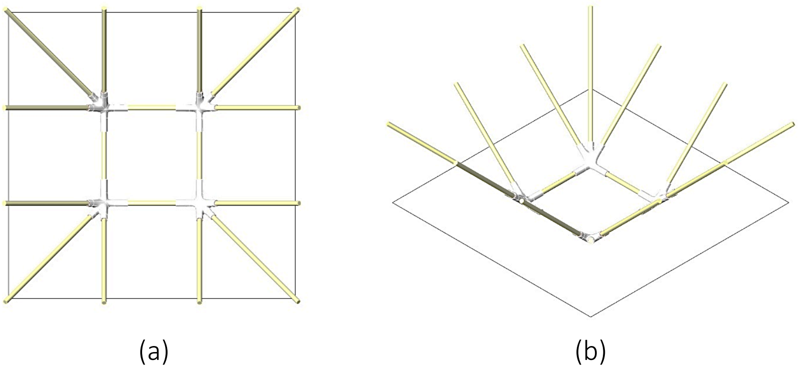


Figure 5: Views of the molding system consisting of joint type-1
(a) Top view,
(b) Perspective view.

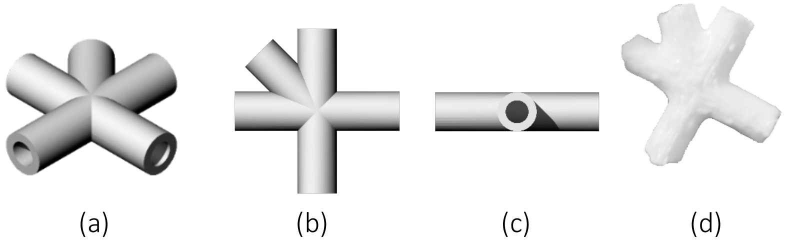


Figure 6: Views of joint type-1
(a) South-east view,
(b) Top view,
(c) Front view,
(d) 3D-printed model.

Joints are designed in a 3D geometric modeling environment for the second attempt. In this design, a central cylinder surrounded by cylindrical tubes is incorporated. It is aimed to allow the wooden bars of the formwork structure to fit into the cylindrical tubes with this configuration. The produced detail is fabricated entirely with TPU **(Figure 7).**

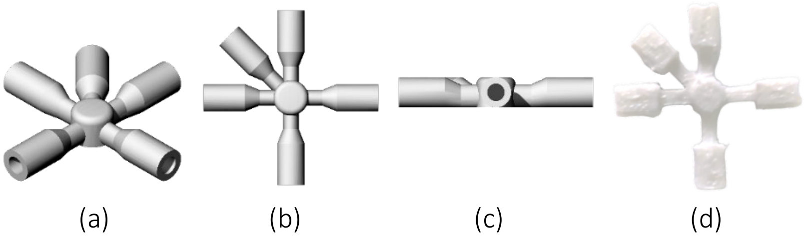


Figure 7: Views of joint type-2
(a) South-east view,
(b) Top view,
(c) Front view,
(d) 3D-printed model.

In the third attempt to achieve the desired state, the concept of combining a sphere in the center with surrounding rings to attach it to the wooden frame has emerged. Additional cylindrical tubes are designed to fasten the wooden bars **(Figure 8).**

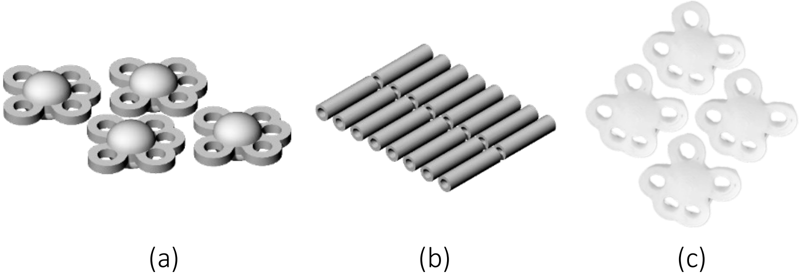


Figure 8: Views of joint type-3
(a) Sphere detail,
(b) Pipe profile detail,
(c) 3D-printed model.

To further enhance the deployable effect in the system, metal nuts are employed at the central parts of the joints. Around these nuts, pipe profiles fabricated with TPU are connected using flexible wires **(Figure 9).**

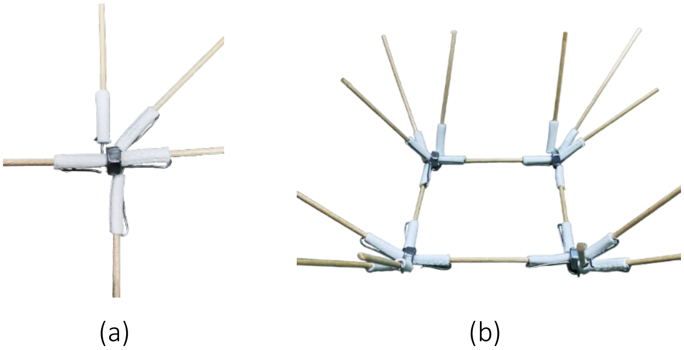


Figure 9: Views of joint type-4
(a) Metal nut detail,
(b) Integrating joints into the system.

In the latest joint attempt, a sphere designed in a 3D geometric modeling environment is created to facilitate the connection of five wooden rods emerging from the central piece. These components are then manufactured using a 3D-printer. At this stage, it is crucial to ensure that the central piece has sufficient clearance to accommodate the pipe profiles connecting to the sphere. The radius of this clearance is adjusted through the production of physical prototypes **(Figure 10)**.

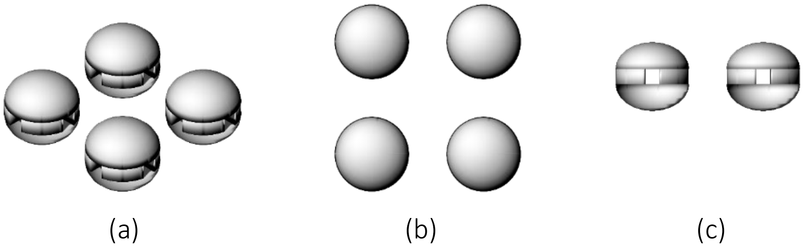


Figure 10: Views of joint type-5
(a) South-east view
(b) Top view,
(c) Front view.

To enhance the strength of the joint points for improved performance during concrete pouring *Biopolymer Polylactic Acid-PLA* is used for the central piece. After completing the 3D printing process, wires are integrated into the pipe profiles through this sphere **(Figure 11).** Below, it is shown that the deployable feature in the system is provided **(Figure 12).**

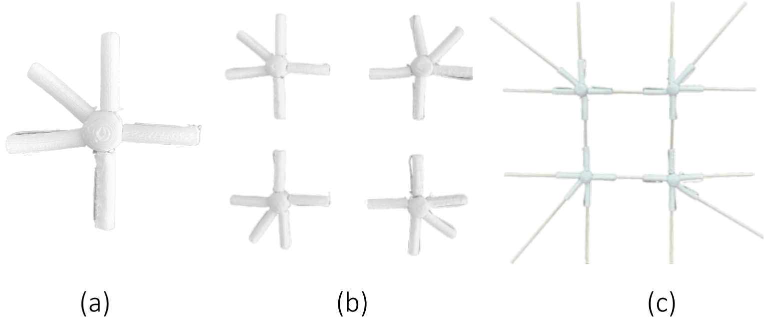


Figure 11: Views of joint type-5
(a) 3D-printed model of a single unit,
(b) Total joints used in the unit,
(c) Integrating joints into the system.

Figure 12: Examining the deployable feature of the mold
.

2.2.2 Fabric Experiments

Subsequent to designing the mold system, the next phase involves integrating this structure with fabric. In this regard, a kitchen-cloth fabric composed of 70% cotton and 30% polyester was selected to assess its flexibility as fabric type-1. The fabric is cut to 21x21 cm to match the unit size. To ensure precision, a two-dimensional structure of the unit is created by sewing stitches onto the fabric using a sewing machine, followed by sewing another piece of fabric on top of these stitches. This method allows for the integration of wooden bars into the fabric system by passing through these interstitial spaces **(Figure 13).**

Figure 13: Integrating fabric type-1 with the mold system and discovering its deployable feature.

To explore different behaviors of concrete in subsequent stages, white-flannel fabric composed of 100% cotton, which is thinner and more flexible compared to fabric type-1, is chosen. Similar to the first fabric, a piece of fabric is cut to match the size of the unit. Stitch-marks are made on the fabric to align the wooden sticks correctly. Additional pieces of fabric are sewn on top of these stitches. This process creates intermediate spaces through which the wooden rods could pass, similar to fabric type-1 **(Figure 14).**

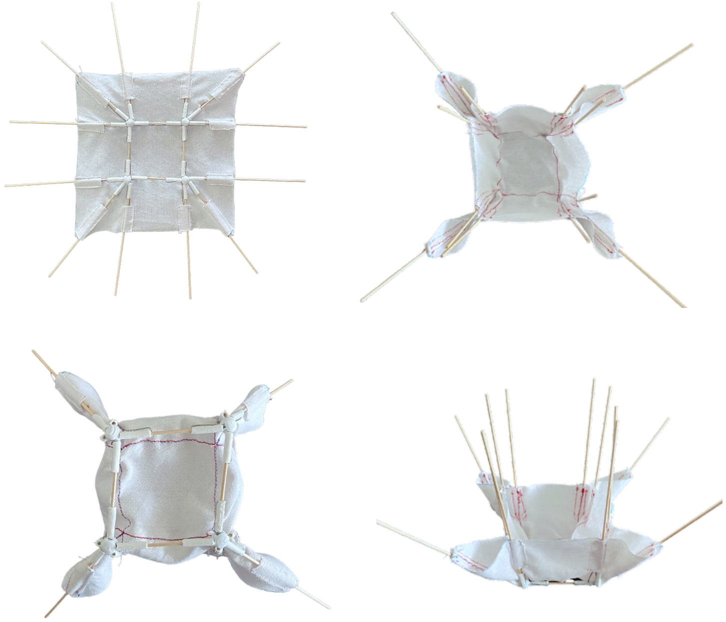


Figure 14: Integrating fabric type-2 with the mold system and discovering its deployable feature.

2.3 The Casting of Concrete into Fabric Molds

To observe the behavior of concrete in formwork systems created with different types of fabrics, various experimental setups are established. Initially, an experimental setup is prepared using fabric type-1. In the initial stage, to prevent concrete adhesion to the mold and facilitate multiple uses of the same mold, a light stretch-film is placed inside the mold. For preparing the concrete mixture, a ratio of 3 parts cement to 2 parts water is used to achieve a fluid consistency that ensures the mixture is not excessively watery. This prepared mixture is poured onto the stretch-film and left undisturbed for approximately twelve hours to allow the concrete to dry and take its full shape.

In experiments involving fabric type-2, a mold structure is constructed to investigate dynamic factors such as wind and gravity. The mold made of fabric type-2 is integrated into this structure for testing purposes **(Figure 15).** In these experiments, concrete mixtures of different weights are prepared, and the behavior of the concrete is observed. Keeping other variables constant, only the ratio of the mixtures is changed. As in the previous stages, stretch-film is placed inside the mold, and concrete is poured. After waiting for approximately twelve hours, the dried concrete is removed from the mold.

Figure 15: Mold structure where the deployable fabric-formwork will be placed.

3. RESULTS

3.1 Joint Experiment Results

The design of the connection details was of paramount importance in order to achieve a deployable effect and to create a dynamic mold system. Accordingly, prototypes were manufactured utilizing a range of modeling techniques, with multiple trials conducted to further improve the system. The outcomes of these trials are presented in the table below **(Table 2).**

Table 2: Positive and negative situations obtained from joint experiments.

ANCHOR POINT TYPE	OUTCOMES
Type1	• Although there were no errors during the production-phase, the deployable effect observed in the digital environment was not replicated when the system was tested in the physical environment.
Type2	• The second designed joint encountered some errors during production; however, after several printing attempts, it was successfully fabricated without any issues. • Despite allowing the wooden bars to move due to the flexibility of the joint material, it does not exhibit deployable characteristics. The bars could flex but were unable to be securely fixed in different positions or return to their original positions. • Following the tests, it was found that 3D printing the entire system as a single unit was not successful, prompting the decision to produce parts separately.
Type3	• Upon examination of the physical prototype, it was observed that printing with TPU posed no issues. However, it was noted that the joints were too large, potentially affecting the aesthetic appearance and precision of the shape when pouring concrete. • It was determined that the pipe profiles were suitable for subsequent stages, but the other parts proved unsuitable.
Type4	• The system was exhibited deployable features, operated successfully. However, the potential to create a structure similar to the space truss system was questioned. In this context, it was found that a design principle used in space frame systems, which facilitates the convergence of multiple beams at a single point, could be adapted for this study.
Type5	• In all previous phases of 3D printing, all parts were printed using TPU. However, issues arose during the printing of the spheres with TPU due to the small size of the holes in the center. Consequently, while the tube profiles were reprinted with TPU, the central sphere was printed using the harder. • This method facilitated the production of all components using advanced fabrication technologies and demonstrated the best deployable features of the system.

Table 3: Outcomes obtained using different fabric molds.

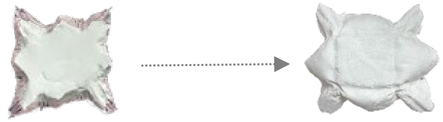
NO	FabrIc Type	MIxIng RatIo (Cement to water)	Is It suspended In the aIr?	Outcomes
1st	Type1	3:2	No	• The effect of dynamic factors during the drying process of concrete is reduced; therefore, a more static situation is observed. This revealed that the top part of the final product was flat, while only the side parts were curved. • It was observed that using stretch-film to contribute to the reusability and cleanliness of the mold had a positive effect. • Since no breakage was observed in the produced concrete mixture, it was concluded that the concrete mixture was successful. • It was determined that the desired performance could not be fully achieved due to the kitchen-cloth fabric being a bit stiff.
2nd	Type2	2.5:1.5	Yes	• The concrete was not spread adequately, resulting in a less pronounced curvature compared to the experiments with a higher weight. • Cracking occurred at the left edge of the concrete unit, and deformation was observed in the shape
3rd	Type2	3:2	Yes	• The use of a more flexible flannel fabric and an optimized concrete mix ratio facilitated more effective spreading of the concrete. • No cracking was observed along the edges of the concrete unit.
4th	Type2	3.5:2	Yes	• Due to excessive weight and the effects of gravity, a more pronounced bulge developed at the central region of the concrete unit compared to the other areas. •No deformation was observed in the produced concrete unit.

3.2 Fabric Experiment Results

In order to observe the behavior of concrete on fabric, a variety of fabrics were employed, including both rigid and flexible materials. Furthermore, in the second, third, and fourth experiments, dynamic factors were incorporated into the system to examine the concrete's behavior. The results of the four experiments are presented below **(Table 3).**

Different concrete mixtures were poured into fabric molds made of Fabric Type-1 and Fabric Type-2, and the resulting products are listed below **(Table 4).** The concrete dried in approximately twelve hours and was removed from the mold without sticking.

Table 4: Comparison of the resulting concrete outputs.

Order of experiment	Views
1st	
2nd	
3rd	
4th	

3.3 Comparing the Physical Model to Computational Model

Based on the data obtained from scanning the concrete unit, it was observed that the edges of the shape formed a longer profile compared to other sections, as the fabric mold was suspended from the fixed wooden formwork at its ends. This characteristic was successfully transferred to the digital environment.

However, when simulating the behavior of the concrete in a computational design environment, a shape with similarly curved edges, like the one created in the physical environment, could not be achieved, and the digital simulations did not fully align with the physical models. Further research is needed to investigate this inconsistency **(Figure 16)**.

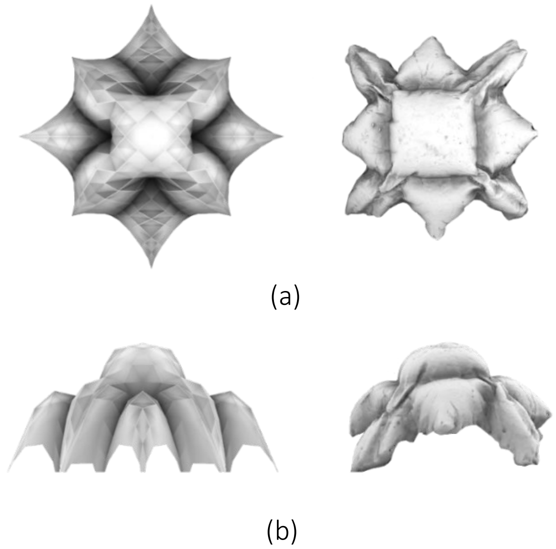


Figure 16: Comparison of computational model (left) and scanned digital model (right)
(a) Top view,
(b) Front view.

4. MODULAR DESIGN OF MICRO-SCALE FABRIC-FORMWORK

In this study, a fabric-formwork was designed using a selected crease pattern, enabling the production and arrangement of concrete units. At this juncture, it is essential to consider the potential applications of these modular concrete units. Specifically, understanding *how this unit can be utilized to create modular designs and in what context these designs can be implemented* is crucial. In this regard, a concrete unit was defined in a computational design environment, and an algorithm was developed to generate configurations of this unit in a grid-based arrangement at various angles. Visual representations of these configurations at 30, 45, and 60 degrees were subsequently created **(Figure 17).** A configuration comprising two concrete units is shown in the physical environment below **(Figure 18).** It is hypothesized that the resulting modular design could be used in the future as an interior wall panel, an exhibit element in an art gallery, or as an architectural element on the facade of a building in larger-scale applications.

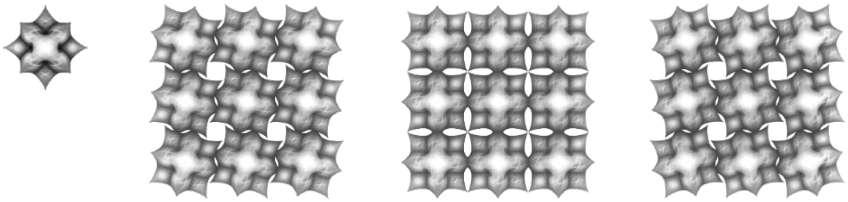


Figure 17: Modular state of the unit at 30, 45 and 60 degrees respectively.

Figure 18: A configuration consisting of two concrete units in the physical environment.

5. DISCUSSION

The shaping of concrete has evolved with the development of various construction methods over time. This evolution stems from the desire to eliminate the use of disposable, heavy, and bulky molds commonly employed in the construction industry. This study, conducted through the design of flexible fabric molds, introduces a mold system that, while differing in the materials used, aligns with the reusability aspect of systems developed by Meibodi & Tessmann (2014) and Szabo et al. (2019). On the other hand, although Lloret-Fritschi et al. (2023) demonstrated the successful production of concrete using wax-coated paper molds, which offered the potential for lightweight mold systems, their approach required the peeling of the mold to remove the concrete.

The most significant distinction of this study from existing concrete mold systems in the literature is the integration of a hinge mechanism into the dynamic mold system. This mechanism features a hinge system that allows five wooden rods to pass through a single joint, creating multiple degrees of freedom. This approach is analogous to the reconfigurable units with multiple degrees of freedom designed using metamaterials by Overvelde et al. (2016). In this context, while existing dynamic molds in the literature, such as the diagonal movement in Meibodi & Tessmann's (2014) mold or the two-state mold production in Lloret-Fritschi et al. (2023), exhibit limited movement, this study introduces a more versatile system.

There are also notable similarities between this study and other concrete mold systems. One such similarity is with the work titled "P_Wall" by Andrew Kudless, founder of MATSYS Design Studio, which employs computational methods to produce organic textures using flexible fabric molds. Additionally, the method of securing the fabric at specific points in Kudless's work parallels the construction approach in this study. However, unlike the MATSYS approach, which uses fixed wooden dowels for mold construction, this study integrates a movable hinge system into the fabric mold. Furthermore, this study bears resemblance to the works of Meibodi & Tessmann (2014), particularly in the inclusion of digital craftsmanship in the concrete mold production process.

6. CONCLUSION

This research evaluates the outcomes of applying the Fabrigami technique to flexible fabric formwork within the framework of fabric formwork, concrete, and digital craftsmanship. The study distinguishes itself from other works through the design of a multi-degree-of-freedom hinging system. Although the outcomes produced in this study focused on the single-target optimization of the form by fixing the foldable mold at specific points to a rigid wooden frame, the hinge system designed in this paper offers the potential to create unexplored form alternatives. By utilizing both fixed and movable elements, it is possible to explore different variations by securing the dynamic fabric mold at specific points during its movement and then pouring concrete.

Additionally, the repeated use of the same mold in three experiments conducted with fabric type-2, demonstrates the reusability of this mold. This offers a sustainable alternative to the heavy and single-use molds commonly used in the construction industry.

Due to limited access to resources, the dynamic fabric formwork designed and produced in this study was not fabricated on a large scale and was constrained by the build volume of the 3D printer. To advance this research, future studies could explore the application of dynamic formwork on a macro scale, potentially in combination with robotic fabrication techniques, to address the structural challenges of concrete structures that tend to collapse beyond a certain height in digital casting. Moreover, the assembly of the produced concrete units was beyond the scope of this study; therefore, future research could focus on developing a detailed assembly system to test its applicability at different scales.

When comparing the 3D-scanned model of the concrete unit produced in this paper with its digital simulation, a 100% match was not observed. In this context, future experimental work could focus on improving the accuracy of digital physical models by addressing production-related issues and incorporating more comprehensive datasets on the behavior of fabric and concrete into digital tools, thereby generating more precise predictive outcomes.

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Author Contributions

Writing—original draft preparation- Z.G.; Data Acquisition- Z.G.; Data Analysis/Interpretation- Z.G.; Critical Revision of Manuscript- Z.G., A.A.K., and L.F.G; Material and Technical Support- Z.G.; Supervision A.A.K., and L.F.G. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

The authors declare that there are no financial or other material conflicts of interest that could have influenced the results or interpretations presented in this study.

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