4D PRINTING: AS AN ALTERNATIVE MANUFACTURING TECHNIQUE FOR COMPLEX GENERATIVE FORMS AND FORMWORKS IN BOTH SINGLE AND MASS-CUSTOMIZATION

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

4D PRINTING: AS AN ALTERNATIVE MANUFACTURING TECHNIQUE FOR COMPLEX GENERATIVE FORMS AND FORMWORKS IN BOTH SINGLE AND MASS-CUSTOMIZATION

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The advances of digital possibilities created an environment where fabrication of form and formwork techniques reconsidered with digital terms. As a new research field in digital fabrication, primarily additive manufacturing has particularly attracted the attention to fabricating complex generative form and formwork. Presently a new and promising technology, however, is not too far off that may take additive manufacturing to a new dimension. With the recent advancement in material sciences, new approaches to additive manufacturing have also drifted to material focused operations; therefore, programable material applications with 3D printing technology revealed the term of 4D printing.

As an alternative manufacturing technique, 4D printing implemented to fabricate complex forms to prove its potentials for single or mass-customized fabrications, especially in computational and generative systems. A fabrication process, including digital and physical phases, is experienced where several design disciplines are combined to generate a feasible fabrication process. For the computational form-finding process, the curved-crease folding technique utilized to create developable three-dimensional generative forms. A digital model also experimented by printing the active composites with different principles. Accordingly, self-transformation process of the printed active composite structures tested to prove the concept.

The results show that 4D printing of curved-crease active composite structures promising to be utilized as formwork and form as it is to fabricate complex generative surface structures for single or mass-customized architectural scenarios. The fabrication experiment has also provided a source to generate a 4D printing fabrication process.

Keywords: Formwork, Digital Fabrication, Additive Manufacturing, Curve-Crease Folding, 4D Printing

ÖZ

KARMAŞIK ÜRETİMLERİN TEKİL VE SERİ ÖZELLEŞTIRMEDE BİÇİM VE KALIP YAPIMINDA ALTERNATİF BİR YÖNTEM OLARAK 4B BASIM

Cangir, Fethi Can
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Dijital olasılıkların gelişmesi ile birlikte form ve kalıp yapım tekniklerinin dijital terimler ile yeniden değerlendirildiği bir ortam oluşmuştur. Dijital üretim alanındaki son araştırmalardaki eklemeli üretimlerin kompleks form ve kalıp üretimdeki kabiliyeti özellikle dikkatleri üzerine çekmiştir. Fakat eklemeli üretim tekniğini tamamen yeni bir boyuta taşıyacak yeni ve gelecek vaat eden bir üretim teknolojisi yakın zamanda ortaya çıkmıştır. Malzeme bilimdeki son gelişmeler ile birlikte eklemeli üretimlerindeki yeni yaklaşımları malzeme odaklı işlemlere yöneltmiştir, böylece 3B basım tekniği ile akıllı malzeme uygulamaları 4B basım terimini ortaya çıkarmıştır.

Alternatif bir üretim tekniği olarak özellikle sayısal ve üretken sistemlerde, tekil ve seri imalatlardaki potansiyellerini kanıtlamak amacıyla, karmaşık formları üretmek için 4B basım teknolojisi uygulanmıştır. Uygulanabilir bir üretim süreci oluşturmak için çeşitli tasarım disiplinlerinin bir araya geldiği dijital ve fiziksel fazları içeren bir üretim süreci deneyimlenmiştir. 4B baskı yapının form bulmasına dayanan dijital sürecin sayısal modellenmesi kıvrımlı katlama tekniği ile düzlemde açılabilen üç boyutlu karmaşık bir form oluşturulmuştur. Dijital olarak üretilmiş bir modelin aktif kompozit yapılarını farklı prensipler ile basmak suretiyle üretilen fiziksel modeller ayrıca test edilmiştir. Buna göre basılı aktif kompozit yapının kendiliğinden dönüşüm süreci kavramı kanıtlamak için test edilmiştir.

Sonuçlar, 4B basım tekniği ile üretilmiş kıvrımlı katlnan aktif kompozit yapıların tekil ve seri üretilen mimari senaryolar içinde karmaşık form ve kalıpların üretilmesinde kullanılabileceğini vaat etmektedir. Üretim deneyi ayrıca bir 4B baskı sürecini oluşturmak için bir kaynak oluşturmuştur.

Anahtar Kelimeler: Kalıp, Dijital Fabrikasyon, Eklemeli Üretim, Kıvrımlı Katlama, 4B Baskı

to my family

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ABBREVIATIONS	
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
AM	Additive Manufacturing
FFF	Fused Filament Fabrication
FDM	Fused Deposition Modeling
DIW	Direct Ink Writing
RP	Rapid Prototyping
3DP	3Dimensional Printing
4DP	4Dimensional Printing
PACs	Printed Active Composites
PM	Programmable Matter
SME	Shape Memory Effect
OWSME	One-Way Shape Memory Effect
TWSME	Two-Way Shape Memory Effect
SMAs	Shape Memory Alloys
SMPs	Shape Memory Polymers
PMS	Printing Management Software
CCF	Curved Crease Folding

CHAPTER 1

INTRODUCTION

1.1. Motivation

With the recent advancements of technology, digital terms have become a well-established research field in fabrication. By the dissolving of the divergence between the intellectual act of design and material act of making, digital fabrication techniques revealed completely new potentials for manufacturing techniques to fabricate form and formwork.

Manufacturing techniques with the digital terms have gained new perspectives. Understanding and fabrication techniques of form have been altered and advanced with digital possibilities, especially, Additive Manufacturing (AM) has created revolutionary approaches to physical fabrication directly from digital design data. Frequently known as 3D Printing (3DP), additive manufacturing has been existing on the market for decades yet just over the last recent years it has caught the imaginations of high numbers. Therefore, it has become a remarkable study field for many researchers and architects. Before long, additive manufacturing occupied an essential place in the fabrication of complex generative and computational forms with highly detailed surface finishing and an expanded degree of freedom. Particularly for complex generative formworks fabrication, that generally needs even more complex structural consideration than the form itself with conventional techniques, additive manufacturing promising high potentials for both single and mass customization. By all the advances, additive manufacturing became a general working area that we can encounter in various fields of fabrication processes, always changing, advancing, and enlarging its scale.

Additive manufacturing techniques for generative and computational forms have gained undeniable importance at various scale. With the fabrication possibilities of additive manufacturing, different discussions also conducting in terms of its material, precision, and size. Along with the evolution of architecture, where increasingly more complex forms of different scales coming together, it seems that these discussions about additive manufacturing will be on the agenda of fabrication at architectural scales.

Presently a new and promising technology, on the other hand, is not too far off that may take additive manufacturing to a new dimension with significant importance (Campbell, Tibbits, & Garrett, 2014). Fabrication technologies have been drifting from digital tools to material sciences since the past decade. Recent developments in robotics, biology, and material science have also created a reconditioned interest in materials (Papadopoulou, Laucks, & Tibbits, 2017). Therefore, new approaches about fabrication evolving by the context of material-based operations.

The time we are in has unprecedented capabilities cross the scales and disciplinary boundaries. Borders between disciplines is gradually blurring. New capabilities of the technology on materials sciences have been advancing in the natural and synthetic field that offering smart capabilities of life-like qualities such as shape and property chance, computation, programmability (Tibbits & Tomas, 2013). On top of that, smart materials have been introduced as switching technology that could alter all the classic understanding of existing production techniques with unique skills. Even an identified class of smart materials has been defined as one of the most promising technological developments by the Global Agenda Council for Emerging Technologies of the World Economic Forum. Programmable smart materials can be the key for fabrication advancement in future decades (Li, Shang, & Wang, 2017).

To get the advantages of programmable materials and to incorporate with them in fabrication processes, possibilities of additive manufacturing is one of the most promising techniques to process the material. With the advancement of additive manufacturing; therefore, smart material applications have also been advanced. In order to make "responsive" kinetic systems, additional components used to require that were difficult to assembly, expensive, and failure-prone. Recent advances in additive manufacturing, on the other hand, enable us to manipulate programable materials with folding, curling and bending surface mechanisms and material sensors, that defined as 4D Printing (4DP) in material science (Tibbits, 2014).

Figure 1.1. 4D Printed expanding strip material to create a sinusoidal strip (Tibbits et al., 2014)

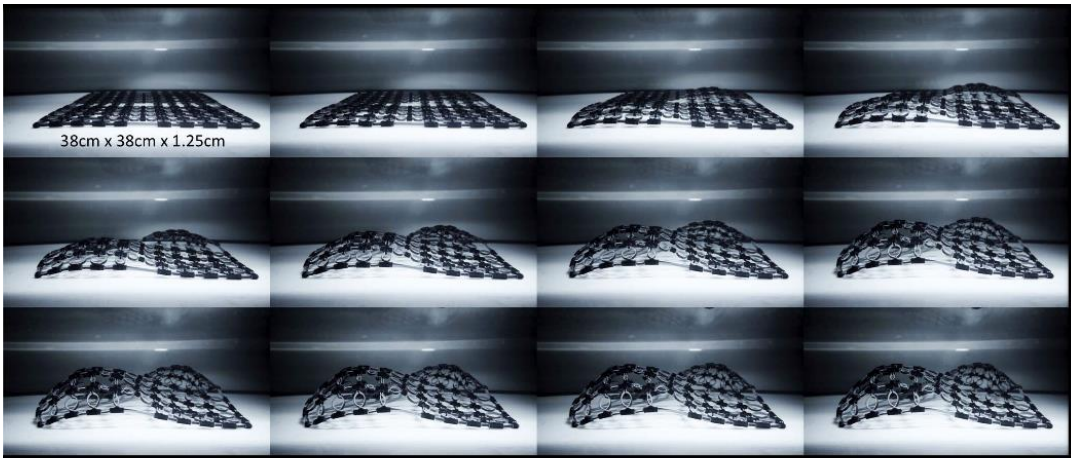


Figure 1.2. 4D print complex 2D multi-material component exhibiting a grid deformation (Raviv et al., 2014).

As the financial, ecological, geopolitical, and strategic consequences of additive manufacturing, 4D printing offering exceptional abilities by converting digital information of the virtual environment into material information of the physical world. The capability of objects to transform its shape and function after the fabrication, 4D printing providing extra capacities and performance-driven applications with its fourth dimension (Campbell et al., 2014). These advancements of the material processing have also brought a new concept and manifestations for fabrication of architecture. The interests in material science in different fields have gradually been growing. Researches on metamaterials, soft robotic materials, and biomaterials, therefore, enabled to produce responsive structures with dynamic abilities like change properties, shape, and structure at various scales (Correa et al., 2016).

Figure 1.3. 4D printed object with different water submersion phases (Tibbits, McKnelly, Olguin, Dikovsky, & Hirsch, 2014).

Searching an alternative formwork fabrication technique, 4D printing is a promising technique that enables us to utilized the fabricated structure as formwork and the form as it is with the same principles for repetitive/non-repetitive generative and computational systems. Due to the possibilities of fabricated objects, 4D printing is a potential manufacturing technique for both single and mass customization manufacturing processes of formwork and form as it can be united.

Proposing 4D printing as an alternative manufacturing technique lies in its potentials to print dynamic structures that can transform their structures depending on predefined environmental conditions. Because of the ability to transform its structure moreover, different instances of the same structure can be utilized to fabricate various surface configurations of the same formwork and the form as it is for single and mass customizations. Therefore, it is essential to discuss the potential roles of 4D printing in terms of form and formwork fabrication in architectural concerns.

1.2. Problem Statement

Designing and making as two primary concern of architecture, the gap between these two interests have always been a challenge for architects to design feasible forms. Since the invention of first primitive adobes, fabrication techniques and materials have experienced admired evolutionary processes. With the industrial revolution, advance technological and material developments have the most effects on manufacturing technology and created new approaches for fabrication. Especially, since the beginning of twentieth century, advancement of liquid composites materials enabled to implement complex architectural forms. By the usage of concrete composites, for example, various complex structural and non-structural forms have been experienced. In order to be able to form liquid building composites, however, another structural system requires to hold liquid material till its cure, therefore, formwork as a temporary structure occupies the most considerations for fabrication of liquid composites. The more complexities in forms, the more complex formwork fabrication have also required. Therefore, formwork fabrication has become essential to fabricate desired complexity in contemporary architecture.

In the fabrication of contemporary architecture, liquid composite materials have an exceptional role. The primary reason for the popularity of liquid building materials lies in their biomorphic characteristic to goes characteristically from a liquid to a solid form that is just like working with clay. As fusion composites, liquid building materials have no implicit shape which provides the required flexibility to flow and fill into any possible formwork. Therefore, they have been one of the main enablers of modern architecture to realize simple and complex forms. Fabrication of liquid composites materials, on the other hand, is not the only matter. Since it is the formwork determines the possibilities to fabrication that represent a noticeable ratio of the overall work (Wangler et al., 2016). The more complex geometrical forms even require the more costly and exceptional formwork fabrication that generally cannot be reused or even recycle. Eventually, existing possibilities for fabricating non-repetitive complex architectural formworks results neither ecologically sustainable nor economically feasible manufacturing processes for a broader scope of architectural typologies.

Concrete as such that was one of the main components of Roman construction, and that is undoubtedly the most widely used building material in modern architecture. Formwork fabrication for concrete, however, that could account for over 50% of the concrete structure's complete cost, and this account could rise with the geometric complexity of the structure. In figure 1.4, the average resource distribution of a concrete construction process demonstrated. These rations also have the same approximation for other liquid building composites.

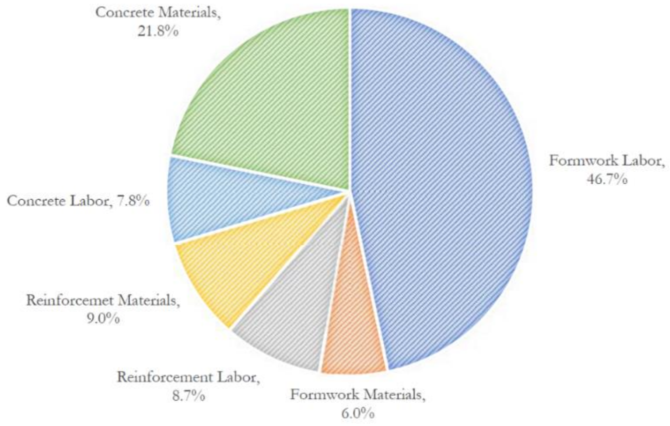


Figure 1.4. Average resource distribution of a concrete construction in terms of both labor and materials (Oesterle, Vansteenkiste, & Mirjan, 2010)

To form liquid composite materials that require a formwork to poured or mold to sprayed. In other words, geometric and structural potentials of these materials only obtainable by the ability to fabricate the required formwork. Most of the existing fabrication techniques rely on typical inelastic static formwork systems. These static systems are the most common techniques that refer to temporary structures to pour fluid composites. At the beginning of the twentieth century, static formwork systems generally customized with wooden frames. After the liquid composite has gained its strength, formwork is removed and generally discarded after a single use thus, fabrication accounts for a considerable amount of resources for both labor and material cost (Wangler et al., 2016). Therefore, to fabricate a static formwork system is feasible only as long as labor cost is relatively low compared to the material cost (Jipa, Bernhard, & Dillenburger, 2018).

With never-ending demands for precision, material, and different scales in the built environment, on the other hand, fabrication techniques have gained a new perspective. Manufacturing techniques in architecture have an interdisciplinary concern now. New inputs of digital fabrication technologies are becoming inevitable. Together with the new inputs of generative fabrications; however, new questions also arise during the process of fabrication. Questions like, what is going to be the relevant techniques to manufacture? Also, is it going to be flexible enough to adapt different assembly logics and different materials? (Gramazio, Kohler, & Oesterle, 2010).

The flexibility of liquid composite building materials has excellent advances in terms of material handling, and placement that can be poured into a suitable formwork, and any shape can be achieved. However, it has not yet to be fully taken advantage of in the world of digital fabrication (Wangler et al., 2016). In other words, a gap has emerged between the possibilities of recent digital advancement in architectural design and the reality of the fabrication industry where there is no efficient solution for the fabrication of complex forms particularly within computational and generative form and formwork systems (Kristensen, Gramazio, Kohler, & Langenberg, 2013).

With the most recent advances in digital fabrication techniques, manufacturing concerns of formwork have revealed the question; how can we utilize these recent technological and material advances to fabricate complex generative forms and formworks for single and mass customization. To fabricate various formwork related architectural applications; therefore, recent advances in additive manufacturing techniques providing high potentials to fabricate with highly detailed surfaces and an expanded degree of freedom. Despite all the potentials of additive manufacturing on the other hand, it is still challenging with scale limitations and static structural forms. Therefore, it is essential to search for an alternative and more advanced printing technique for generative and computational forms and formworks.

1.3. Hypothesis

In this research, it is hypothesized that 4D printing manufacturing technology can be utilized to fabricate feasible repetitive/non-repetitive complex generative and computational structures that can be used for formwork and form as it is in both single and mass-customized applications.

1.4. Research Questions

It is comparatively a new area of research that not many of 4D printing applications have accomplished yet. Increasing interest in material science, however, could extend the range of smart material. Therefore, the impressed structural characteristics of materials such as strength, durability, and surface quality could also improve. Accordingly, these advancements of programmability of materials could even change the prevailing trends of 4D printing that mainly focus on changes in the form of printed parts. With a broader range of printable responsive materials, however, not only the future of printed structures displays shape transformation. With the addition of functionalities in the printed structures, but they also may not just need to be designed for a particular operation. Instead, they can be intended to continuously reconfigure to suit the evolving environment, and satisfying more than one request along with the manner.

In the light of recent advancements, this study aims to research potentials of 4D printing technology as a new approach to fabricate repetitive/non-repetitive complex generative and computational form and formwork applications.

Therefore, this study investigates the following research questions:

- Is 4D printing an efficient fabrication technique for single and mass customization of repetitive/non-repetitive surfaces, particularly within computational and generative systems in architecture?

- Potentials of 4D printing as formwork in terms of how stable is it, how responsive is it, and how manageable its responsiveness.

CHAPTER 2

LITERATURE REVIEW

2.1. The Frame of the Literature

In order to develop a literature survey on the manufacturing techniques for single and mass customization, this literature research focuses on advanced manufacturing techniques in modern ages of fabrication. Because forming liquid composites plays an essential role in the modern ages of architecture as a mainstream fabrication. Consequently, formwork fabrication comes into prominence to form liquid composite materials. Manufacturing techniques of form and formwork, therefore, have always occupied the central place in the digital fabrication researches. In this respect, studying fabrication techniques of formwork in terms of classic and digital manufacturing manners plays an essentials role in this literature.

With the 21st century, a new era of transformation in manufacturing technology emerges along with digital technologies. Material based transformation of digital fabrication techniques especially arise with additive manufacturing in various fields at different scales. Although additive manufacturing is a new developing research field, that application scale generally restricted with prototyping, recent attempts proving that the application scale of additive manufacturing is gradually extending towards building scale with high precisions. Examining additive manufacturing technology, however, will guide us to a recent developing material-based fabrication approaches.

The disadvantages of static fabrication logic of additive manufacturing emerged as a new discussion topic. With the most recent technological advances of material science, more responsible and smarter dynamic structures are not too far off. Researches in the area of programmable matter and smart material structures in biological and physical realms have extensively increased. Additive manufacturing applications are not restricted with static objects anymore, but it is capable of fabricating smart and responsive materials. With the recent advancement in material sciences, new approaches on additive manufacturing have also drifted to material focused operations; therefore, smart material applications with 3D printing technology revealed the term of 4D printing. This new manufacturing technique is promising great potentials to fabricate complex and generative forms that can be utilized for formwork and form as it is. Therefore, a detailed study of this manufacturing technology has conducted in the literature. Afterward, a series of previous fabrication studies examined to understand the fabrication approaches of the technique. Various pieces of researches have been conducting on 4D printing to search for dynamic details. In this concern, the relation between form and material application, as a new fabrication approach examined in the literature.

2.2. Formwork to Fabricate Form

As the simplest definition, formwork can explain as a temporary structure whose purpose is to provide temporary support and containment for a liquid form of a material until it cured and support itself. To build a structural system building another temporary construction, however, means more cost of material, more labor, and more time. Especially fabrication of complex generative forms by conventional formwork systems are the most labor-intense, and it generally represents a significant portion of the total cost of construction (Bechthold, 2011). Repetitive and straightforward solutions thus become the most preferred fabrication ways. Avoiding from the complex formwork expenses, on the other hand, neglected the structural and aesthetic potential of liquid composite materials; consequently, monotonous built environments started to increase, especially noticeable in many Asian metropolises (Hack, 2015).

In the late 1940s, several fabrication techniques with alternative formwork applications have developed. In the Turin Exhibition Building for example, pre-fabricated formwork elements started to use by Pier Luigi Nervi in 1949. After that, he used the same technique in some of his dome shell structures, such as the Palazetto dello Sport in Rome in 1957 (Bechthold, 2011). Besides, to reduce the fabrication time and cost of built structures, pneumatic formwork technique has also developed in the 1940s. To provide temporary support by pressurized membrane used as a formwork system. Pneumatic systems have been using as formwork techniques, but constructed shell shapes with this technique typically restricted to synclastic forms. The construction industry has developed a modular and reusable formwork layout to lower the cost of formwork over the past. However, it was a troubled attempt when each formwork differs in shape (Kaftan & Stavric, 2013). Therefore, concerning repetitive and non-repetitive generative form applications, digital fabrication technology is expected to lead to more efficient and sustainable construction techniques (Wangler et al., 2016).

Since their advancements, pourable liquid composite materials have an exceptional role in the fabrication of architectural forms. Not only because of their properties in terms of structural performance, building physics, accessibility, and cost but also due to their fluidity characteristic that they can be molded into any possible shape regardless of geometric complexity. Because conventional construction techniques are not efficient enough to provide this complexity, however, digital manufacturing possibilities started to use more commonly to find a reasonable technique for complex repetitive/non-repetitive generative and computational forms. Thus, the gap between digital possibilities to design and physical feasibility to fabricate has been gradually closing.

While architects forced the limits of form with Computer-Aided Design (CAD) tools, conventional static formwork systems with restricted material capabilities become incapable of ensuring required complexity. Therefore, to overcome the necessity of complex repetitive or non-repetitive generative formwork fabrications, computer-aided manufacturing (CAM) tools has been started to use in construction and enabled the fabrication of formwork with high complexity.

Fabrication of repetitive and non-repetitive generative forms has been a challenging task for technical and economic reasons. When design consists of several complex and non-repetitive different forms, a unique mold for each is required to produce; thus, the cost of the building increased by maximizing the required cost of formwork. Also, production a unique mold for each different object concluded a high amount of waste which is unsustainable to operate. Therefore, it would be critical to developing systems that are practical to fabricate complex forms efficiently while reducing the number of waste products and the building cost (Aşut, Eigenraam, & Christidi, 2016). It is therefore essential to know how best to take advantage of the customizable features of formwork fabrication with economically viable means of manufacturing. This issue requires a better knowledge of the state-of-the-art, which is conducted by literature review and experimental design research.

2.2.1. Conventional Fabrication of Formwork

Throughout the 20th century, formwork advances have paralleled the growth of material possibilities. Increasing interest towards liquid moldable building materials as the primary building material displays the formwork fabrication a new scope of issues in the advancement of suitable sheathings and rigid resistance maintenance. The classic understanding of formwork as a temporary structure that is fabricated as fast as possible, exposed to a heavy load throughout the molding of liquid material for a few hours, and disassembled in a few days for future reuse. Because of its classic temporary nature, connections, braces, tie anchorages, and adjustment devices are also required to assembly a formwork system. The concept of "temporary structure" does not quite represent reality. Components of this structure should use more than once to gain a cost-effective advantage. Therefore, it is essential to select highly durable and straightforward to maintain materials. The design of the formwork should be such that it can be expertly assembled and disassembled to increase productivity.

Formwork is a structure that holds the liquid material to control its place and orientation according to the required size and shape. It is not just a mold to hold liquid material; however, formwork is a structure that not only supports its load, but also supports the load of freshly placed liquid material, and construction live-loads like materials, equipment or personal. Therefore, several primary objectives of formwork applications should satisfy: Quality, that is important for structures as strength, stiffness, position, and dimension of the desired structure. Safety that is necessarily essential for the employees as well as the concrete structure and the economy, the most reasonable cost considered with ideal demands for quality and safety.

Currently used techniques for fabrication of conventional formworks fabrication typically employ rigid timber components. This conventional formwork system is composed of a network of columns that carries an assembly of curved and straight timber beams. To form desired geometry, wooden boards bent over the beams, cut to shape and secured. This time-consuming formwork fabrication technique is feasible as long as the cost of labor reasonable enough compared to the material cost (Bechthold, 2011). However, during the past few decades, this cost division has been altered, the labor cost of formwork applications has increased approximately twice as fast as material cost (US Bureau of Labor Statistics, 2013). Even the use of timber and steel materials to build formwork systems discussed at the American Institute of Concrete in 1908. Therefore, the advancement of material technology to construct a temporary formwork structure has come into prominence in many fabrication research areas. Where different material possibilities like plywood, metal, plastic, and many other materials experienced to build formwork has enabled, and that has altered the classic understanding of formwork.

Timber still as a favorite material in formwork fabrication, on the other hand, has many advantages. It is a proper material in terms of the proportion of strength to weight, it can easily be shaped with simple hand tools, and it is considered as an aesthetically pleasing material. However, because of the complexity of bending wood in two axes, timber formwork surfaces have generally restricted with ruled surfaces like hyperbolic paraboloid (HP) shapes. These formworks can be fabricated from wooden boards, that can be bent in a single direction, and follows the set of perpendicular parabolas that define the hyperbolic paraboloid shape. In addition to that surface structure, a temporary support structure, consist of column-supported beams that follow the ruling lines of the hyperbolic paraboloid form, also needed for shaping the board layers.

With conventional formwork fabrication, many complex modern architectural forms fabricated at various scales. Conventional approaches to formwork fabrications, however, generally restricted the design process with repetitive and geometrically dull forms that provide simple fabrication processes. Recent advances of digital design tools, on the other hand, push the limits of design and enables researchers to reimagine the fabrication terms of form and formwork. The fabrication challenge of repetitive and non-repetitive complex generative formwork structures is an excellently suited to exploiting digital design and fabrication techniques.

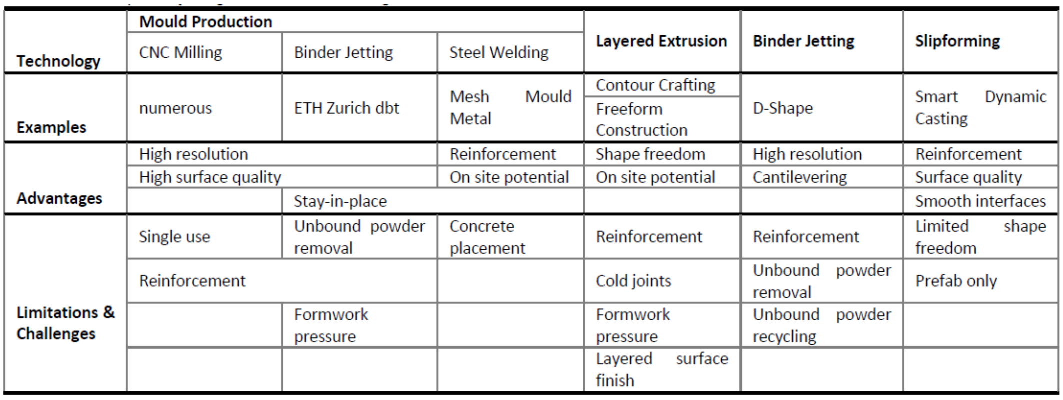
2.2.2. Digital Fabrication of Formwork

As Antoine Picon suggests, engineering, specifically civil engineering, split from the precepts of architecture in the mid-eighteenth century; thus, the tension between technology and architecture increased. By the advancing of digital design tools and fabrication technologies; however, architects have been taking more objective performance criteria on construction processes since the past decade. Therefore, the typical known architecture has abandoning notions of style and theory as progenitor and been taking parts as the impetus for initiating the design process into the physical world (Bell, 2012).

Encouraging by the new computational tools, interest in complex generative forms in architecture has significantly increased. Experiencing this interest in complexity has been practiced generally with superficially resemble shells, but their geometries are not the structural components. Instead, classic structural systems of curvilinear frames, beams, and columns also need to be constructed to support these digitally generated complex shell forms. These kinds of structural solutions are often bulky compared to the grace of the material-efficient structural surfaces. Increasing interest in complex repetitive or non-repetitive generative forms on the other, hand has also provided the challenges of their structural construction to overcome (Bechthold, 2011).

Accelerated advancement of Computer-Aided Design technology over the last decades have also increased the design potential of complicated generative forms. Construction of these complexities commonly generated by the application of custom-made inlays on conventional static formwork systems. Custom made inlays produced by using CNC methods to mill homogeneous blocks of foam or wood. Despite this extensive milling process cause a considerable cost and energy consumption, and a considerable amount of waste discarded after the first use, this costly and wasteful manufacturing method is the most effective way to fabricate custom formworks in order to construct forms with complex geometries (Kristensen et al., 2013). Spencer Dock Bridge by Amanda Levete Architects, for example, constructed in 2012 as an example, required more than 100 custom milled formworks layout for single use. Although its geometric possibilities of complexity, using CNC milling to fabricate single used complex formwork inlays is a slow and energy insensitive fabrication process, also considering its waste ratio it is an unsustainable manufacturing technique (Wangler et al., 2016).

On the other hand, digital fabrication is gradually becoming inevitable to lead to more efficient and sustainable construction techniques by placing material only where it is needed. As a result of more efficient construction techniques with digital fabrications tools, that can reduce waste generation, especially for formwork (Wangler et al., 2016).



Technology	Mould Production			Layered Extrusion	Binder Jetting	Slipforming
	CNC Milling	Binder Jetting	Steel Welding			
Examples	numerous	ETH Zurich dbt	Mesh Mould Metal	Contour Crafting Freeform Construction	D-Shape	Smart Dynamic Casting
Advantages	High resolution		Reinforcement	Shape freedom	High resolution	Reinforcement
	High surface quality		On site potential	On site potential	Cantilevering	Surface quality
		Stay-in-place				Smooth interfaces
Limitations & Challenges	Single use	Unbound powder removal	Concrete placement	Reinforcement	Reinforcement	Limited shape freedom
	Reinforcement			Cold joints	Unbound powder removal	Prefab only
		Formwork pressure		Formwork pressure	Unbound powder recycling	
				Layered surface finish		

Figure 2.1. Summary of major digital formwork technologies (Wangler et al., 2016)

Restrictions resulting from conventional manufacturing techniques remain the primary challenge for adaptive and non-conventional architectural forms to be constructible. Therefore, contemporary approaches toward geometrically complex architectural forms need new ideas for fabrication techniques. Evolutionary advances in computational design possibilities are heading toward new capabilities for manufacturing adaptive and non-conventional architectural forms. Architects are also becoming more active agents in processes of designing the construction systems as well as its products by being more included directly in physical prototyping (Mansoori, Kalantar, Creasy, & Rybkowski, 2018).

Materials have a catalytic role in the formative design by integrating from the beginning within a design-based process of form-finding. Because of the advanced technological advances in digital fabrications and material science, there have been many developments in the casting of complex and non-repetitive architectural forms that can now be expanded into generative computational processes (Dourtme, Ernst, Garcia, & Garcia, 2012). Advances in material sciences can now be explored, providing fundamental perspectives into contemporary digital design processes and their fabrications within architectural practices.

2.3. Digital Fabrication

By the growing population, the dependence for digital techniques of highly large, tiny, accurate and complicated structures we seek to fabricate with new instruments and procedures, our society is growing in complexity through all measures. Advancements in digital design and fabrication tools are pushing our capabilities (Tibbits, 2010). Meanwhile, the conflict between the design and fabrication, on the other hand, is struggling in conflicts of advancing design capacities with conventional fabrication techniques.

In order to push fabrication and design paradigms, architecture has always been inherited by new technologies from various disciplines by repurposing, reimagining, and challenging technologies. Architecture's interdependence on technological developments, therefore, has led to significant movements from prime examples like the development of the arch, to vaulted cathedral ceilings, the boom of high-rise structures, wrought-iron, steel, glass, concrete, and various other materials. At the Beginnings of the 1990s computing advancements have brought a revolutionary movement to architectural design by the graphical modeling of complex geometries and forms. Inevitably, to satisfy the construction needs of these complexities, digital fabrication terms has become an important market (Gramazio, Kohler, & Langenberg, 2014). Recent architectural approaches, therefore, have also formed by these new technological influences through digital environments of fabrication tools, and techniques. In other words, architecture fundamentally moves forward through cross-disciplinary advancement. Therefore, with this lineage of architecture's dependency on technological advancement, across different disciplinary scale-lengths with material programmability, new questions also arise such as: how will architecture be influenced from these digital possibilities of manufacturing? (Tibbits, 2012).

When subjected to complex design concerns, it is comprehensible to have a design approach that isolates construction processes from design. In conventional processes, even in parametric ones, the unity between construction and design systems can be lost the control if too many parameters and criteria included. Therefore, a new understanding of the design process is necessary that can stratify performances and conditions, and engages design by separate but parallel processes, provide control over many parameters (Ahlquist & Fleischmann, 2008).

With restricted possibilities of conventional fabrication techniques, architecture's design scenarios could not exceed existing physical feasibilities to fabricate so far. Since the official release of architectural design and manufacturing methods with digital possibilities, however, architects have got a chance to realize complex digital design data. Advancing digitally-driven fabrication technologies enabled to fabricate any possible geometries.

Over the last 20 years, it has become possible to produce non-standard components according to digital design data. Since then, architects integrated the fabrication as a generative criterion in the design process (Gramazio, Kohler, & Oesterle, 2010). Capability of digital fabrication tools have affected architects and researchers to put them as a generative factor in almost every conceivable tool for gluing, melting, drilling, winding, cutting, pouring, or painting. The announcement of digital design and fabrication techniques in architecture, architects have got a chance to realize complex digital design data. Just like in the industrial revolution, digital fabrication terms of information age had also experienced on specific examples. As an early monumental attempt to realize complex digital design data to a full physical scale, Guggenheim Museum in Bilbao, Spain by Frank Ghery demonstrated possibilities of digital possibilities.

Desires for free-form architecture and the promotion of high-performance building products and techniques have brought precise changes to the building sector. Notably, one of the significant achievements in implementing digital design and manufacturing instruments was the completion of the Bilbao Guggenheim Museum in 1997 (Ku & Chung, 2015). Therefore, free-form architectural projects have become more affordable with the accessibility and accuracy of 3D modeling instruments and direct fabrication control. Fabrication with digital possibilities, therefore, created a precise environment, where users can fabricate digital design data to physical objects economically, rapidly, and efficiently (Wang et al., 2018). The capabilities of the physical realization of sophisticated digital design data have also created an environment where architects are now more integrated with fabrication processes ever before, as architects create digital design data, digital fabrication tools directly driven by these data. Therefore, architects have started to be involved in the processes of construction as a leading role.

With the advancements of digital technologies, architects started to reimagine the existing fabrication techniques and develop new approaches to fabricate. Since their advancements, digital fabrication technologies began to take roles in fabrication processes in various tasks. Because of the capabilities of digital tools to operate a remarkable variety of non-repetitive operations, these tools demonstrated their flexibility. Remarkable amount of various sized sophisticated examples successfully experienced with entirely digital processes. Although recent applications of digital technologies promising great opportunities for the built environment, a general approach for digital fabrication technologies, however, is not the matter that we should fasten upon on it. It should be possibilities of digitalism that has the most opportunities to provide evolutionary possibilities for the fabrication (Abramovic, 2017).

In the architectural design process, the perception of responsiveness has been used as diagrammatic concepts, that could evolve by its regulations and in response to the environment. There is, however, a split between process and materiality as the material becomes a concrete moment and no longer responds as the process continues to evolve. By turning the conventional form into a computational form, however, digital design and fabrication tools could change the design process to break that split. This is how digital power makes it possible for architects to design dynamic items where the architectural object reacts instantly to the process changes and subsequently to programmatic problems (Dourtme et al., 2012). Because the system is conditioned not only by the nature of the material but also by the technological constraints, however, the movement of the components is restricted. In order to incorporate with such constraints in fabrication technology, it is essential realizing the potential of common material characteristics in a dynamic concept of machinic architectural form.

Developing an integrated design technique to simulate fabrication processes, a much more flexible relation provided between concepts and productions. It also advanced its potential public impact by adaptability, which could be much more customizable than any method ever done or even imagined before. (Baquero, Montas, & Giannopoulou, 2014). Contemporary design techniques and procedures are reshaping by the topics connected with the industry such as mechanics, materiality, and organic assembly. Intelligence systems are at the forefront of concerns for intelligence embedded, dynamic systems.

Recent advancements of design and fabrication with digital techniques promote a stream of design data from the digital to physical building environment, physical fabrication and assembly however still maintains mechanical, energy-intensive. Increasing the capability to design larger and stronger systems, that form, assemble, and build on the bases of the integrated computational knowledge of the material, representing a base movement to a smart methodology of fabrication. Materials now have the capacity to incorporate formative roles by incorporating building data and physical activity directly into a material system (Wood, Correa, Krieg, & Menges, 2016).

In order to manufacture smart material technology, digital fabrication technology has promoted by various fabrication techniques. However, among all techniques, some have significantly affected all the conventional fabrication approaches. Additive manufacturing is one of these crucial techniques, commonly known as three-dimensional printing (3DP). By providing direct interaction between digital design data and material, additive manufacturing created an environment to manipulate the material. Therefore, since its advancement, transforming design information directly from digital data to physical objects has been a favorite research field for researchers to investigate and for architects and designers to use the advantages of this revolutionary fabrication technique.

2.3.1. Additive Manufacturing

Since the invention of Additive Manufacturing (AM) in 1984 by Charles Hull, it has advanced at remarkable rates and received extensive recognition. Charles Hull, the founder of 3D systems, pioneered stereolithography as well, that was a new advance for visualizing and testing design data before putting resources into full creation. Today, countless industries across the globe are using these advances. Without generous increments in time, material or inefficiency, the capability to single and mass-produce customized components have been gained as one of additive manufacturing's revolutionary advances. Capabilities of our current realities of additive manufacturing, however, are a long way behind our visions and expectations (Tibbits, 2014).

Additive manufacturing, commonly recognized as 3D printing (3DP) or Rapid Prototyping (RP), has various fields of various applications. Additive manufacturing emerged as a sophisticated fabrication model that expecting as an effective fabrication method for future manufacturing technology. Applications of additive manufacturing, therefore, have spread significantly from conceptual models to engineering, high-performance metamaterials, and electronic devices (Wu et al., 2018). In countless industries, the ability of single and mass-customized components has gained from the revolutionary benefits of additive manufacturing. Meanwhile, considerable fast advancement in hardware technologies created an environment where anyone can easily access fabrication tools. Including the fabrication of physical prototypes, product design, health care products, and even living organic structures, additive manufacturing has utilized to fabricate a wide range of items. In addition to these applications, towards the various limitation of conventional methods in processing material, additive manufacturing also provides new approaches for manufacturing (Liu et al., 2015). Additive manufacturing, therefore, has become a popular fabrication research topic in various fields that publications about it significantly increase since the last decade.

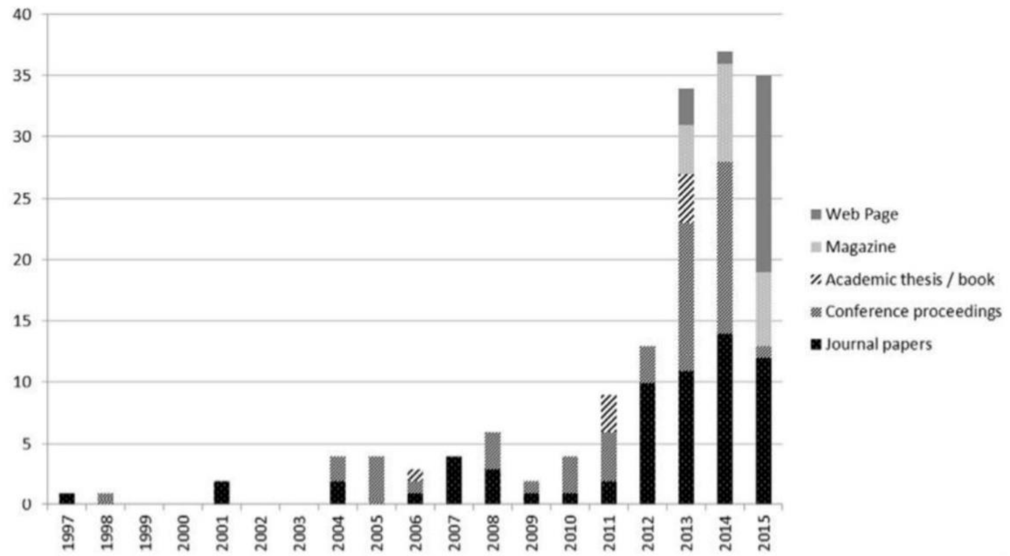


Figure 2.2. Publications relevant to architectural additive manufacturing since the last decades (Al Jassmi, Al Najjar, & Mourad, 2018)

Not only capabilities of printing various kind of hard and soft materials such as plastic, resin, metals, polymers, food, and biomaterials, with high an accuracy, but also decreasing the cost of technological equipment provided more people with access to 3D printing technology. This creates an environment where architects, engineers, even hobbyists focus more on the possibilities of the additive manufacturing sector.

According to the American Society for Testing and Materials, It is possible to order additive manufacturing systems in seven distinct classifications, which are binder jetting, material jetting, material extrusion, vat photopolymerization, powder bed fusion, energy deposition, and sheet lamination. Another way of classifying additive manufacturing based on how the raw material preserved. Most commonly preferred manufacturing techniques based on extrusion, including fused deposition modeling (FDM) and direct ink writing (DIW). The logic of both methods works as line-by-line then as layer-by-layer. While FDM melts a solid material in a heating nozzle, the distinction is that DIW stores liquid ink which can cure later. (Wu et al., 2018).

As an emerging class of manufacturing, additive manufacturing technology is revolutionary due to the advantages of fast prototyping, consistency usage of materials, and flexible design in form and structure. Additive manufacturing, therefore, developed as an exciting and significant architectural fabrication method. Meanwhile, additive manufacturing technology face some challenges at the same. Due to layer-by-layer operations, slow printing speed is a critical drawback. Moreover, although the consistency material usage, additive manufacturing still challenging with overuse raw material problems (Ding, Weeger, Qi, & Dunn, 2018). Because of the manufacturing logic of 3D printing, fabrication of hollow and slender structural forms requires temporary support structures, that in some cases the amount of materials used in support structure can surpass the material usage in the primary structure. The scale is also another essential for current industrial printers of additive manufacturing technology, that have limited printing bed sizes and generally cannot exceed the prototyping scale. Large scale additive manufacturing, on the other hand, is a comparatively new research field which investigating only by a few laboratories.

Recently increasing interest in programmability in the material world, on the other hand, revealed a new approach for 3D printing. The growing existence of computing in every daily routine has disclosed responsive environments, devices, and methods. Most of today's systems today have still been operating with a high mechanical paradigm and stay extremely energy-intensive, extremely susceptible to failure and costly processes. In the meanwhile, emerging advancements in material science revealed programmable smart material technologies. The printing of these smart materials has also emerged as a new term of manufacturing that is 4D printing. By advancing this technology of 4D printing, it is possible to exclude the necessities for complicated devices or conventional actuation forms, and create completely incorporate dynamic changes into structures of materials (Correa et al., 2016).

2.4. 4D Printing

"4D printing" as a term first identified by Skylar Tibbits at the 2013 TED Talk. Soon after the first introduction of the term, the first research paper published in 2013 by utilizing the idea of Printed Active Composites (PACs) a printed structure that can transform its shape by using the Shape Memory Effect (SME). From that day forward, 4D printing caught incredible attention both in public media and research communities of additive manufacturing and smart materials (Wu et al., 2018).

The concept of 4D printing explained as "3D+time, printing time", the time here defined as the fourth dimension, the idea also advanced in a previous couple of years. A common explanation of 4D printing nowadays is the evolution of the shape and functionality of a 3D printed structure overtime when a predetermined stimulus is exposed. The easiest way to accomplish 4D printing is to print a single, smart material that recently attracts noticeable attention from various research fields. Shape Memory Polymers (SMPs) are the most commonly used smart materials for making a shape-changing geometry. By printing SMPs with a one-way activator or two-way reversible activator, 4D printing can be achieved (Wu et al., 2018).

Almost all 4D printed structures' shape-shifting transformations based on one "relative expansion" phenomenon between active and passive materials. This "relative expansion" is the source of almost all complex 4D printing shape-shifting behaviors like folding, bending, twisting, coiling, or curling. These behaviors enabled by encoding different types of anisotropy between active and passive materials and fabricating different heterogeneous structures (Momeni & Ni, 2018).

As a new process, 4D printing demonstrates a radical change in additive manufacturing. It includes multi-material prints capable of changing over time, or a customized material system that can change its shape, straight off the printing bed. This approach provides a direct route from concept to physical reality with performance-driven features directly integrated into the material. The transformation over time that described as the fourth dimension here, strengthening that printed objects are not merely static, dead structures any longer, instead they are programmable active and have the ability to transform independently (Tibbits, 2014).

Since its advancement, additive manufacturing technology started to use in manly fabrication processes that provided an excellent manufacturing environment where three-dimensional static digital design data can directly be 3D printed from various types of materials. By adding the time factor to additive manufacturing, the 4D printing technique provides exceptional fabrication techniques for self-folding structures from micro to macro scale. Therefore, fabrication of self-folding intelligent structures provided great opportunities for diverse functional spectrum such as prototype, aerospace, or biomedicine.

4D printing responsive structures have the benefit of saving time and material. Fabrication of a smart structure with this technique can accelerate additive manufacturing by saving time for printing and material consumption up to 60-87%. Printing shape-changing structures also, that are responsive to a kind of external stimuli, can be used to save storage and transport space. It is possible to program a complicated form with smart components into a flat surface; thus, transformation and storage of these flat structure can easily be ensured (Wu et al., 2018). Due to the rapid developments and interdisciplinary study of digital fabrication, smart materials, and design, as a new concept "4D printing" derived by these advancements. Therefore, although 4D printing still in its early stages, it has already been an exciting subsection of additive manufacturing and attracts a tremendous academic and industrial interest.

As an active research topic, the number of publications about 4D printing has indicated an increasing growth in the past five years. Citations on this topic, however, increase more dramatically than the publications. As the most active country, the United States is leading by holding 42% of the total publications about 4D printing, following China and Singapore. 4D printing research, therefore, is beginning to be acknowledged in the academic globe, leading to hype and interest in the years to come (Wu et al., 2018).

Emerging technologies of 4D printing expecting to practice in many fabrication areas. Such major industrial areas as clothing, automobile, aviation, medicine, and the architecture, that 4D printing technology are expected to use in these and many other fields. Therefore, the market size of this technology estimated 0.55 billion dollars in 2025, beginning at 63 million and an average annual raise of 40% (Chung, Song, & Cho, 2017).

Mainly, studies carried out on 4D printing deals primarily with smart materials and their sensitivity to a stimulus over time. Due to its novelty and technical complexity; however, the immediate operation of 4D printing processes is difficult to operate. Because there is insufficient information about smart materials and processes, the technical capability of 4D printing is still unclear. Discovering or synthesizing smart materials that are responsive to stimuli and can easily self-transform, on the other hand, is quite demanding. In addition to that, software research of 4D printing technology is also an essential issue because it promotes advances in 4D printing technology. To simulate, model, design, and control, software solutions are essential in 4D printing. However, the possibilities of digital processes of 4D printing software, particularly for the entire 4D printing process, are presently not possible.

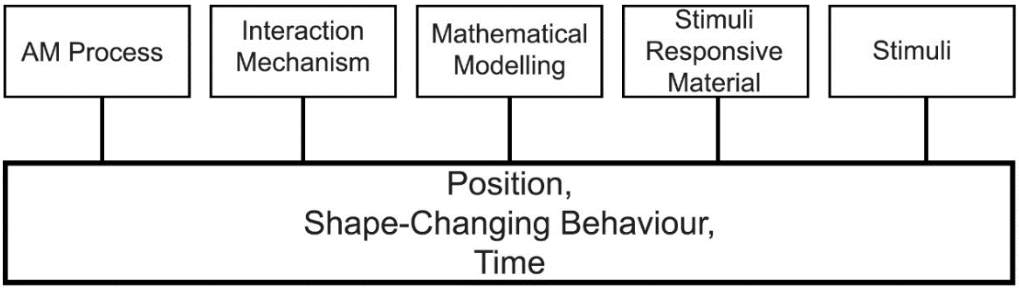


Figure 2.3. Fundamentals elements of 4D printing (Nam & Pei, 2019)

In order to manage the digital process of 4D printing, six significant steps of software solutions required, which are Simulation, Modeling, Slicer, Host/Firmware, Monitoring, and Printing Management Software. "Simulation software," as the first step software, has to be considered before the design and generation of a form production. A consistent simulation of a design scenario reduces the risks before actual product development. Subsequently, "modeling software" is the next software solution to generate required 3D object modeling data. Next, to obtain the G-code file, "slicer software" is required, that is the format printers can read, of 3D generated data. Slicer software is the one where 2D printing process patterns of 3D products determined. After the production of 3D processes, based on design data from the slicer software, a "host software" is necessary to laminate the actual object. While fists four operations to accomplish the 4D product target, a "monitoring software" observes the process of self-transformation, performs if needed. All the processes operated by a user through the printing management software (PMS), which is attached to the software of each stage to monitor all the procedures simultaneously (Chung et al., 2017).

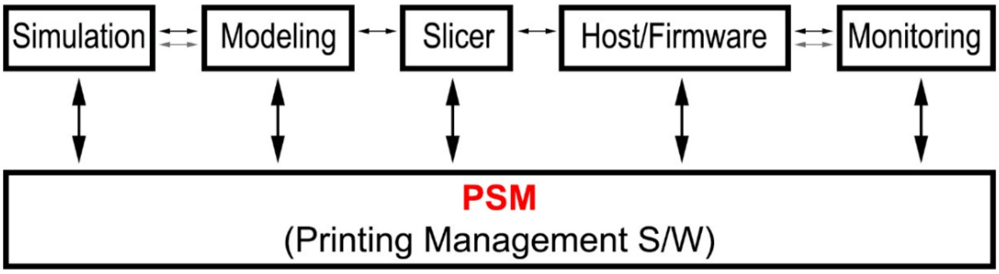


Figure 2.4. Software solution for 4D printing (Chung et al., 2017)

The gap between interdisciplinary concerns is getting closer, where programmability and computational mediums have discovered in every substance and at every scale. Chemically, inorganic protocells that act like living organisms, demonstrating replication and other cellular-like traits that can be programmed and manipulated either through environmental influence or directly through the substance's parameters (Tibbits, 2012). Besides, many different disciplines from synthetic biology, neuroscience, material science, chemistry, and physics to computer science have exploring fundamental abilities to programing the matter, build in inherent logic, and compute with Turing-complete functionality across scales. Therefore, computation is becoming not only the term for electronics and digital mediums anymore but also the term of programmability transforming as a fundamental capability by merely having the correct lens and an ability to communicate or manipulate collectively interacting components (Tibbits, 2012).

The integration of active components is a growing field of studies in architecture with the ability to calculate behavioral responses. Such a fabrication in which digitally managed devices is positioned by material systems, where the design and organization are based on the material itself. However, Only the capacity to design material systems with extremely particular responsive features produces the characteristics of the computational and physical strength of the material. The development of material-driven computation strategies relies on the programming of a material level system. These strategies include a variety of parameters such as design, manufacturing, and actuation, which are strongly affected by the capacity of the material to calculate a physical reaction itself (Wood et al., 2016).

Responsive materials are in the science, engineering, and design of physical matter that are capable of changing shape and function in an intentional, programmable manner such as shape, density, modulus, conductivity or color. Authors, Michael Hensel, Achim Menges, Skylar Tibbits, Dan Raviv, Manuel Costoya, Emilio Otero, Michael Fox, et al., seem to agree on the programmable design of architectural components straight from the characteristics of materials and the design of their internal structures. That evaluates a new field of work where unpredictable results are pointing a new level of relationship of humankind with matter and nature itself (Baquero et al., 2014).

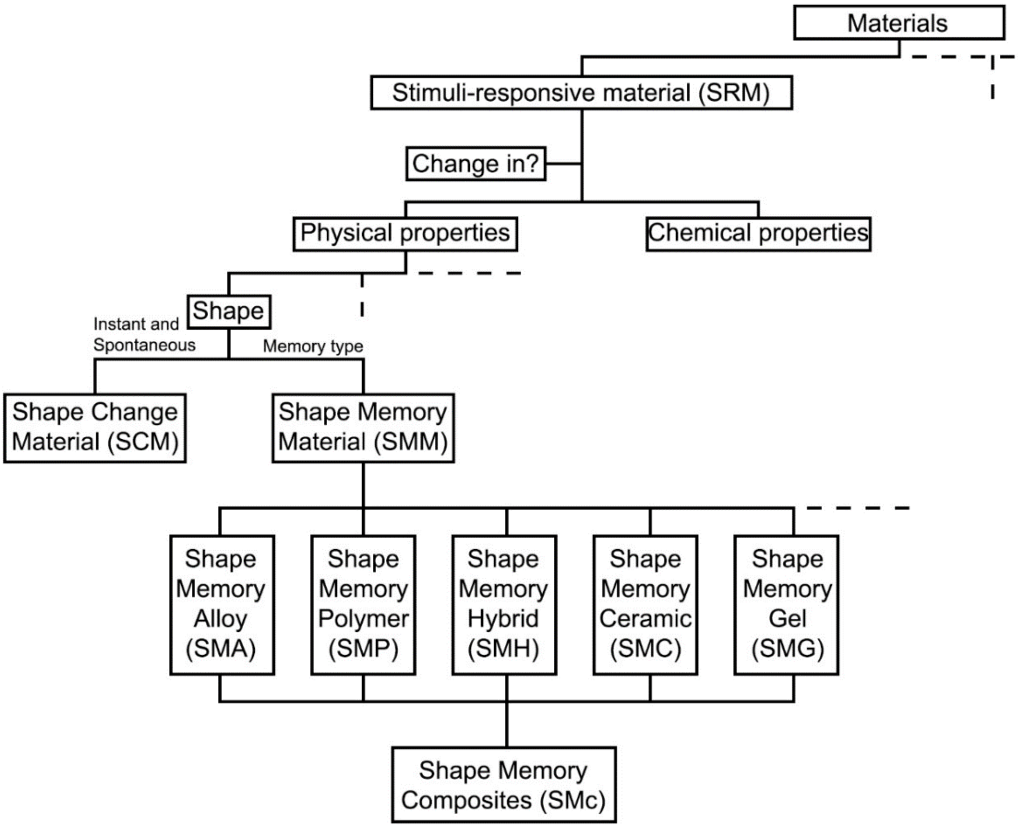


Figure 2.5. Stimuli-responsive materials (Nam & Pei, 2019)

Shape Memory Polymers (SMPs) as an evolving material class have shape-shifting capabilities. If an external stimulus such as heat, light, or electricity is exposed, they are able to undergo significant deformation. Because of their shape-changing abilities, SMPs can minimize reliance on motor activities to perform comparable kinetic tasks. The inherent characteristics and material behavior of SMPs have led to a broad spectrum of applications in the extremely advanced applications presently being produced in biomedicine and aerospace. Examples include smart fabrics, electronic heat-shrinkable tubes, self-deployable spacecraft reflectors, mobile phones self-disassembled, smart medical devices, and minimally invasive surgery implants (Steven, 2013). When the external stimulus is exposed, SMPs are capable of transformation that is known as the Shape Memory Effect (SME). Although it is widely researched and developed in biomedicine and aerospace industries, the potential of SME has not to be explored enough within an architectural framework (Steven, 2013).

When heated till it reaches its melt temperature, Shape memory polymers can be formed by extrusion or injection-molding processes. When cooled below its glass transition (Tg) it reaches its memorized shape. SMP can be deformed, and its temporary shape can be strained when heated over its Tg where it approaches its elastic state. SMP returns to its original form until it is heated again above its Tg, the temporary shape holds permanently. This process can be repeated forever with a distinct temporary form at each cycle (Steven, 2013).

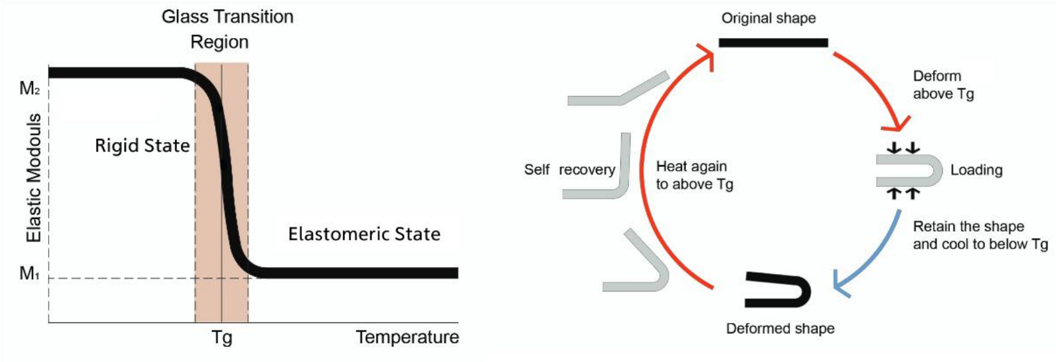


Figure 2.6. (Left) Temperature response pattern of SMP. (Right) shape-changing cycle of SMP (Mansoori et al., 2018)

Table 2.1. Comparison between SMPs and SMAs (Mansoori et al., 2018).

Property	*(SMPs)*	*(SMAs)*
Density (g/cm3)	0.9–1.2	6–8
Extent of deformation	Up to 800%	< 8%
Required stress for deformation (Mpa)	1–3	50–200
Stress generated upon recovery (MPa)	1–3	150–300
Transition temperature (°C)	− 10 to 100	− 10 to 100
Recovery speed	1 s to min	Less than 1 s
Processing condition	< 200 °C; low pressure	> 1000 °C; high pressure
Cost	< 10/lb (£7.5/lb)	Approx. $250/lb (£189/lb)

Shape Memory Effect (SME)

Constructing the physical environment depends on our manufacturing advances, which inevitably will need smarter materials and processes. By the unprecedented technological developments, expectations of what an object can and should do are coming into prominence. Thus, these expectations, in turn, drifting the search for material sciences to embed the information directly into objects in order to make them functional, and capable of responding to external stimuli (Abdel-Rahman & Michalatos, 2017). The transformation capability of an object, therefore, has become an important question for many researchers in various fields trying to accomplish.

Pointing to an inevitable revolution before us, instead of smarter devices, we should be able to embed the information into the matter (Tibbits, 2010). The development of smart materials is essential for 4D printing research; however, many smart materials are in growth, and it is not possible to print any smart material by additive manufacturing. Therefore, while more smart materials investigated, there will also be increased use of different kinds of 4D printing activation techniques (Leist & Zhou, 2016). Furthermore, rather than just shape-changing phenomena for a smart material to be critical to additive manufacturing research. The ability to transform color, hardness, or transparency in distinct techniques will also become critical in smart material fabrications.

Materials that can transform its shape or property under a specific external stimulus classified as "smart materials." A popular one is Shape Memory Alloy (SMA) that has two phases as martensite (low temperature), and austenite (high temperature). Under the influence of these two phases, SMAs are able to change shape between its deformed and original shape. Shape Memory Polymers (SMPs) as another class of smart materials is also gaining popularity recently. SMPs can remember a continuous shape under a number of external factors such as temperature, pressure, water, magnetism, or light (Leist & Zhou, 2016). Depending on temperature or magnetic field variations, responsive materials subjected to programming between two changing phases. This phenomenon of transformation named Shape Memory Effect (SME). Characteristics of shape memory effect classified in three, namely, one-way shape memory effect (OWSME), two-way shape memory effect (TWSME), and pseudoelasticity effect (PE) (Lee, An, & Chua, 2017).

One-way shape memory effect maintains its deformed state by an external force, and when heated, it recovers its initial shape. In addition, obtained from a suitable thermomechanical treatment, some exhibit two-way shape memory effect, known as the reversible shape memory effect. Unlike one-way that can remember only one permanent shape, two-way shape memory effect has the ability to remember various forms at low and high temperatures (Lee et al., 2017).

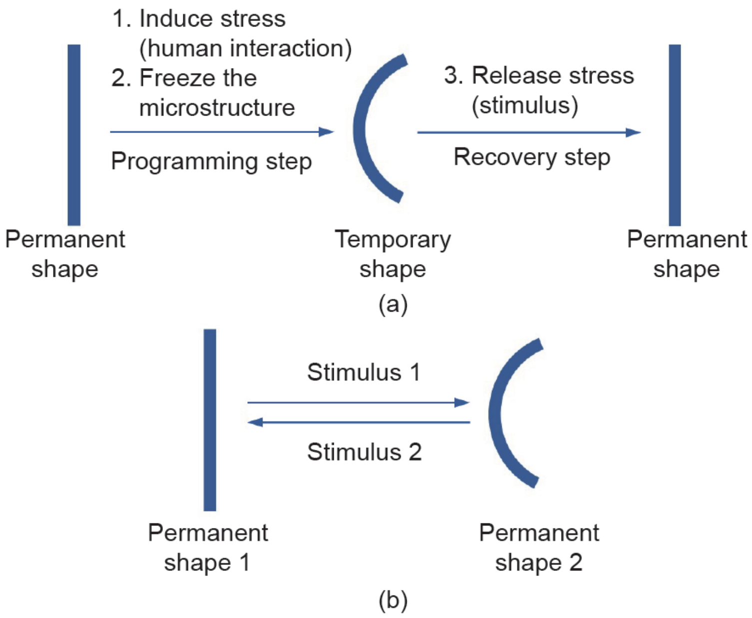


Figure 2.7. The process of one-way and two-way shape memory effect (Lee et al., 2017).

4D printing complex self-evolving structures first revealed by the Self-Assembly Lab (SAL) at MIT. SAL's one of the first examples was a 1D string made from plastic hinges and pins. These pins connected to for a log chain and each design to bend in a defined direction. These 1D plastic chains are able to transform into 3D forms when given random mechanical energy due to the embedded bending limitation of the material.

The plastic chain example as one of the first examples of 4D printing self-folding structure, SAL used a hygroscopic characteristic as smart materials that can expand when exposed to moisture. By putting rigid materials in specified fields to prevent the automatic reflex expansion of the hygroscopic material, it is possible to control the bending angle and direction of the expanding material. When subjected to water, hydrophilic polymer can expand up to 150%. Multi-material printing uses rigid material as a framework and the smart material as the actuator of the object — combination of rigid material and hygroscopic material use in specially designed to generate the transformation. The areas with hygroscopic materials will only actuate when the all object submerged in water.

Not only the 4D printing of plastic but also experiments are proceeding with various other printable materials to create responsive structures. This expansion of material possibilities paves the way for various opportunities for 4D printing in different industries. Therefore, SAL demonstrated that 4D printing eliminates the need for cables, engines, and on-board energy to change the shape of objects directly from the print bed. Due to the elimination, objects could become lighter and easier, reducing the risk of failure.

Although it is essential to use the structural characterization of materials that can respond to different environmental stimuli to demonstrate self-transformation, it is also essential to design a proper printing pattern and material combination to create desired shape deformation. Therefore, to generate a self-transformation of a 4D printing, structural characterization of materials and printing pattern, two primary concerns to operate a 4D printing process. It is possible to create the printing path using digital design tools and simulate the deformation mechanisms of the structure. With the various combination of printing paths, different deformations can be achieved. By printing different sequences such as linear and grid patterns folding, bending, rolling, twisting, helix, buckling, curving, topological change, expansion/contraction, waving and curling are some of the basic shape deformations that can be achieved.

By taking the advancements of additive manufacturing, materials can be deposited in precise grain patterns and regulate the anisotropic behavior of the material. It is possible by utilizing such advancements to fabricate custom grains specifically to enhance shape change. Therefore, different bending balance states can also be achieved through differential growth between the two grains (Correa et al., 2016). Programing the material to produce different curling or folding deformations by operating the pattern and orientation of layers, the layer height, and the interlayer interaction is possible under the controlled external stimuli like moisture or heating conditions. However, with this technique, transformation is achieved by the specific pattern of the grains only; the fundamental folding direction principle of the final object depends on the grain's direction.

A combination of a reactive and nonreactive material, multi-material printing expands on the previous method. The foundation for the responsive deformation conduct shapes the object through the difference in each layer's volumetric expansion, bending rigidity, and elasticity modulus. This method utilizes multi-material 3D printing as a means of manufacturing custom multi-layer composites. The mixture of a hygroscopic composite material with a stable polymer material; the different physical characteristics of the two distinct components generate various curling deformations.

Because of the potentials of 4D printing has been searching by many researchers and various applications with different techniques, materials, and scales. Even the most recent possibilities of digital design tools, material researches, and advancing capacity of additive manufacturing pave the way for individual researches. 4D printing fabrication, therefore, becoming more accessible for the ones who are willing to research both in the digital and physical environment. Since its emerging, 4D printing advanced a great deal in a short time. Researchers from different disciplines have experienced various digital and physical applications for different purposes in fabrication. Some of these examples examined in the following.

Table 2.2. 4D Printing, by Self-Assembly Lab (SAL), (Tibbits, 2014), (Tibbits et al., 2014)

4D printing is a novel manufacturing technique to generate a precise folding method that has various applications by radically new series of physical models. Here, some physical prototypes exhibit the progress of 4D printing, developed at the Massachusetts Institute of Technology (MIT).

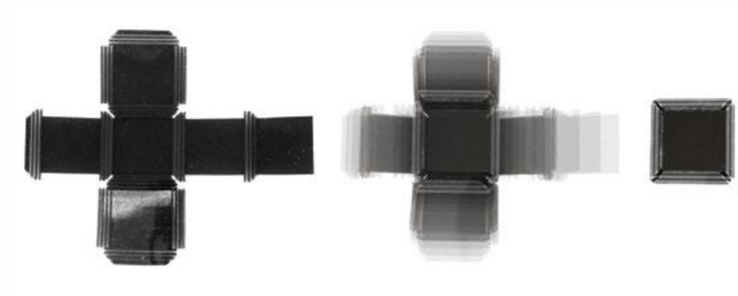


Figure 2.8. 4D-Printed three-dimensional cube

Figure 2.9. 4D Printed Truncated Octahedron

Figure 2.10. 4D Printed Curve-Crease Hyperbolic Paraboloid

Technique: Multi-Material Additive Manufacturing
Scale: Macro-Scale
Materials: Hydrophilic UV Curable Polymer

Table 2.3. Active printed materials by (Raviv et al., 2014)

Complex self-evolving structures unlike conventional 3D printing approaches where materials designed and fabricated as static objects but not as responsive models, here introduced a new approach to the simulation and fabrication of responsive structures that can transform their property into a predetermined form after fabrication.

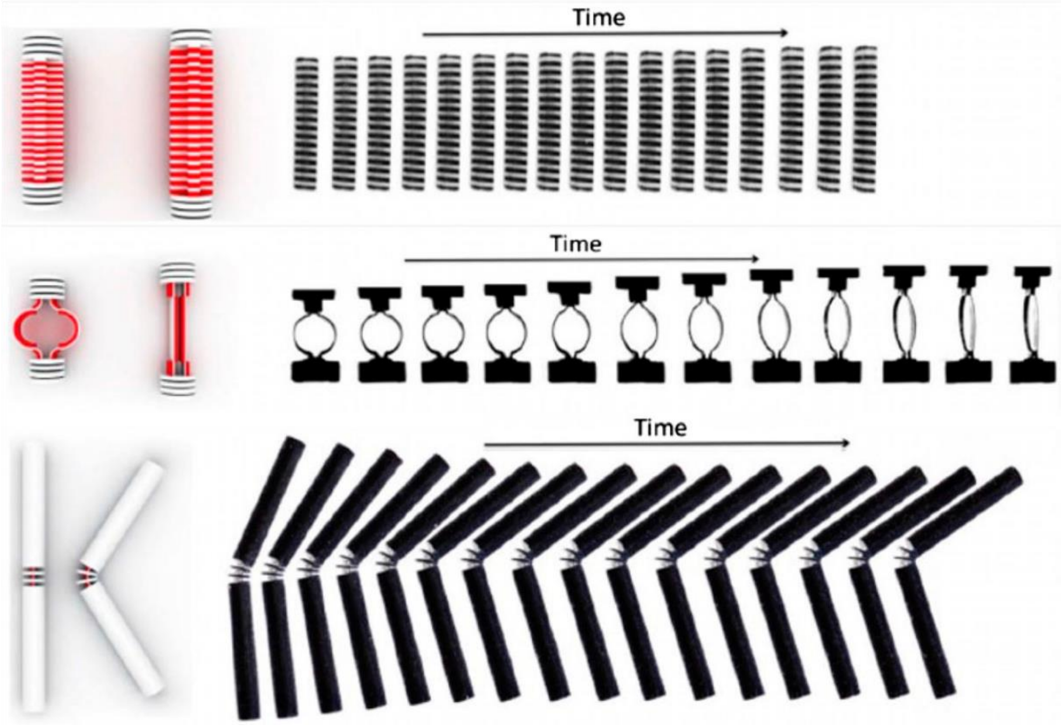


Figure 2.11. Self-evolving objects exhibiting linear stretching, ring stretching and folding

Technique: Multi-Material Additive Manufacturing
Scale: Macro-Scale
Materials: Hydrophilic UV Curable Polymer

Table 2.4. 3D Printed Wood by (Correa et al., 2016)

Wood, today's most prevalent construction product, is still primarily desired for industrial standardization without exploiting its intrinsic anisotropic characteristics. By the advances of additive manufacturing to encourage tunable self-transformation, anisotropic, and hygroscopic characteristics of wood could enhance by developing and printing custom wood grain structures. For programmable materials and responsive architectures, printed wood for self-transformation, suggesting a new strategy.

Figure 2.12. Self-transforms from of a flat sheet into curved surface

Figure 2.13. Multi-material printed self-transforms from a flat plate into a folded structure

Technique: Additive Manufacturing of Custom Grain Structure
Scale: Macro-Scale / Large-Scale
Materials: ‘‘Wood’’ FDM Filament (Laywood)

Table 2.5. Biomimetic 4D printing, by (Sydney Gladman, Matsumoto, Nuzzo, Mahadevan, & Lewis, 2016)

4D printing of biomimetic hydrogel composites that patterned bilayer architectures, programable in space and time, which localized swelling anisotropy encoded to induce complicated shape changes when exposed to water. The effectiveness of the method of biomimetic 4D printing depends on the capacity of local control of cellulose fibril orientation within the composite hydrogel to determine elastic and swelling anisotropies.

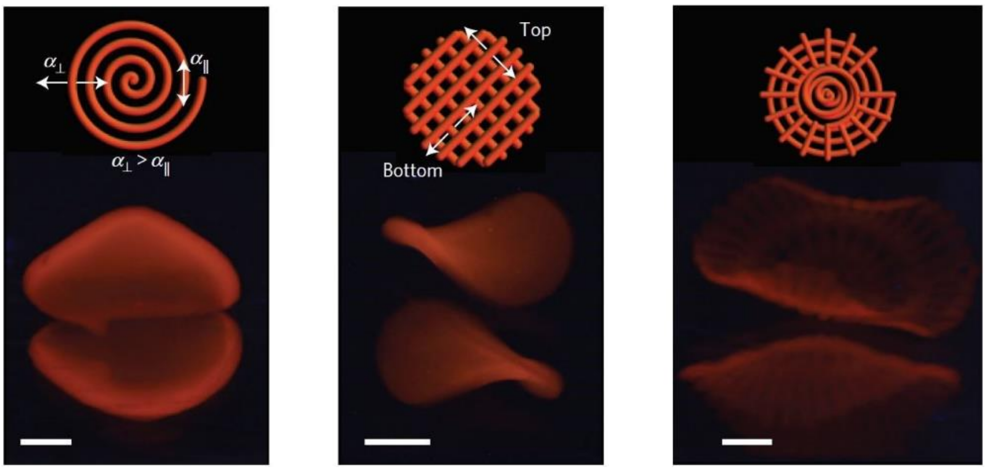


Figure 2.14. Printed biomimetic sample structures

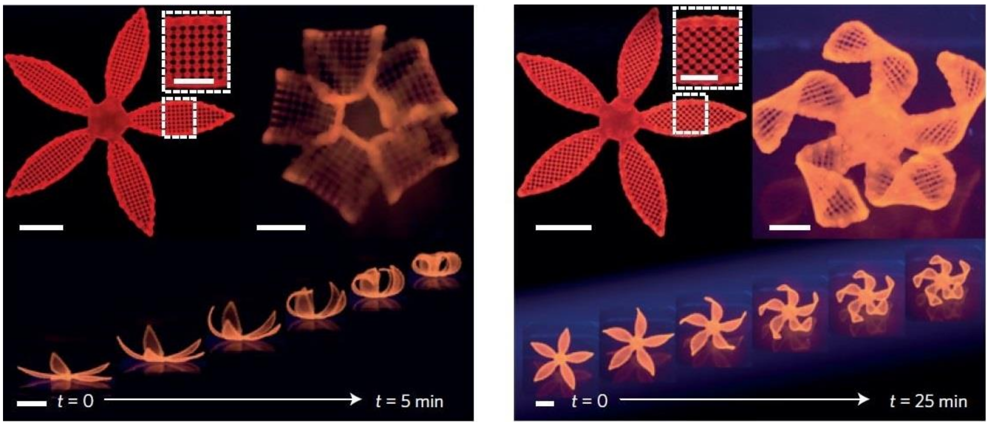


Figure 2.15. Printed biomimetic flower structures

Technique: Biomimetic Additive Manufacturing (bio-4DP)

Scale: Micro-Scale

Materials: Biomimetic Hydrogel Composite

Table 2.6. Smart three-dimensional lightweight structures, by (Quan Zhang, Zhang, & Hu, 2016)

Polymer material's shrinkable phenomena researched that the inner strain can be collected in printed objects and activated as heated. Here the advantage of the inner strain in fabricated objects took to make intelligent lightweight structures by self-folding flat plane under heat stimulation. This technique incorporates the advantages of 3D printing and the shape memory effect of the polymer, thus offering an effective method to achieve advanced lightweight, self-folding / unfolding performance structures.

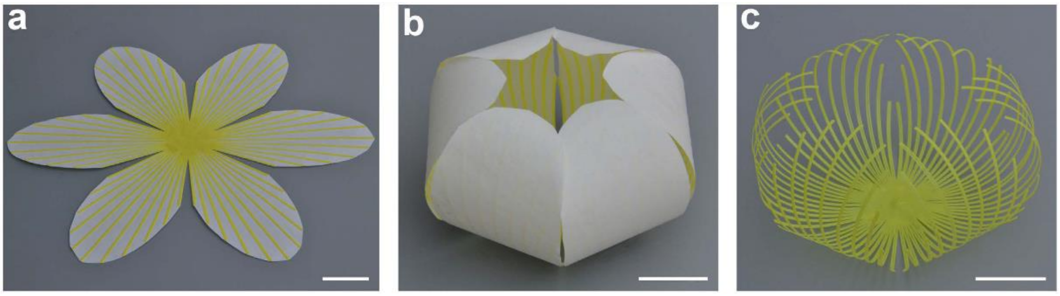


Figure 2.16. Formation of a planar flower structure

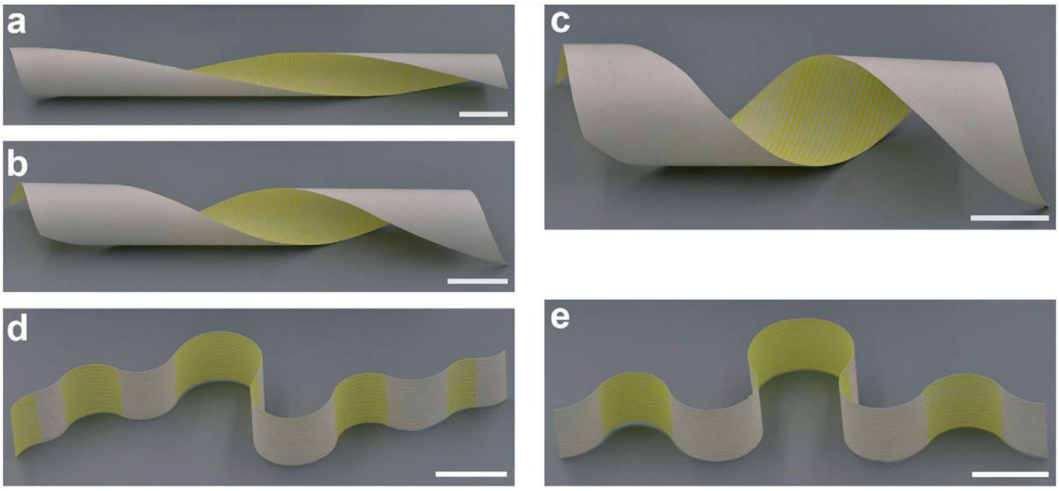


Figure 2.17. 3D structures by self-folding printed composites

Technique: Additive Manufacturing

Scale: Macro-Scale

Materials: PLA (Polylactic Acid)

Table 2.7. Multi-shape active composites, by (Wu et al., 2016)

Active multi-shaped composites that are design and fabrication approach of flat composites in rubber matrix composed of digital Shape Memory Polymer (SMP) fiber families. The printed composite can alter into various forms after programming into a temporary form through a straightforward program and then regain the flat continuous shape when stimulated by temperature.

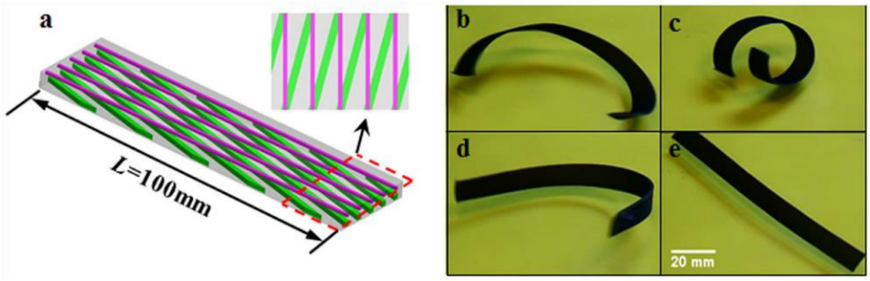


Figure 2.18. Active helix shape

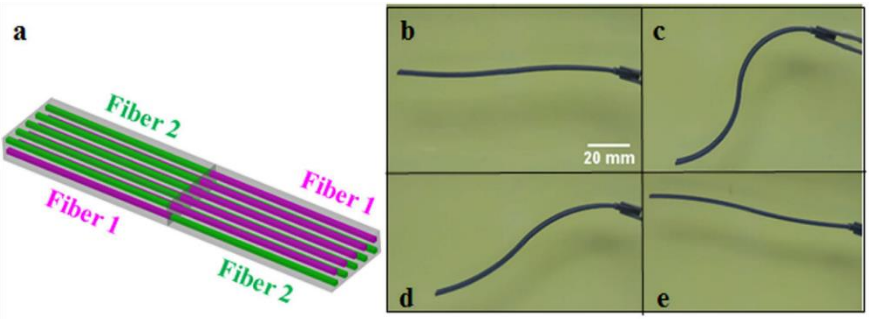


Figure 2.19. Active wave shape

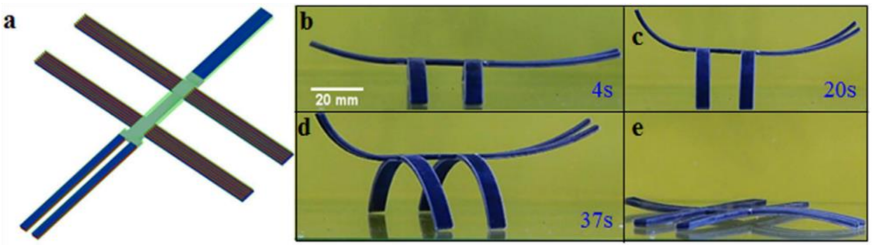


Figure 2.20. Mimicking an insect

Technique: Additive Manufacturing

Scale: Macro-Scale

Materials: Shape Memory Polymer (SMP) in a Rubbery Matrix

Table 2.8. Self-folding three-dimensional shape shifting of polymer sheets, by (Qiuting Zhang et al., 2017)

A thin sheet of pre-stressed polystyrene commercial paper, a kind of heat-activated Shape Memory Polymer, with black ink patterned lines. Depending on the printed side, mountain or valley of self-folding origami created by shrinking the black ink line to activate the localized folding after local near-infrared light absorption.

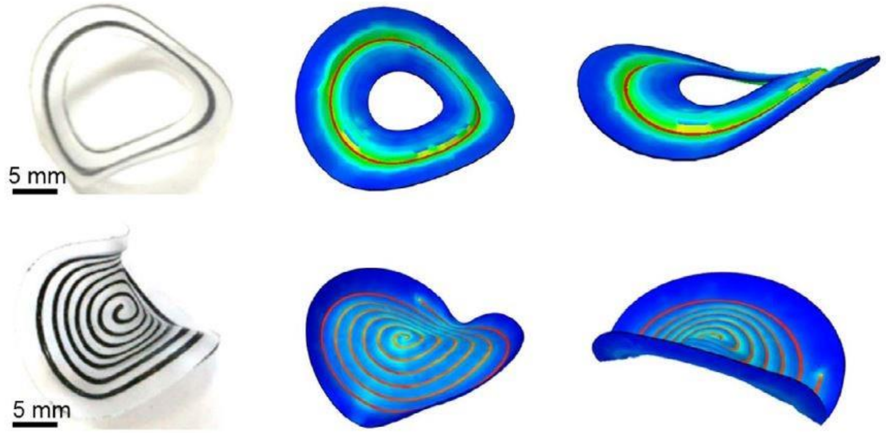


Figure 2.21. Self-folding formation of saddles

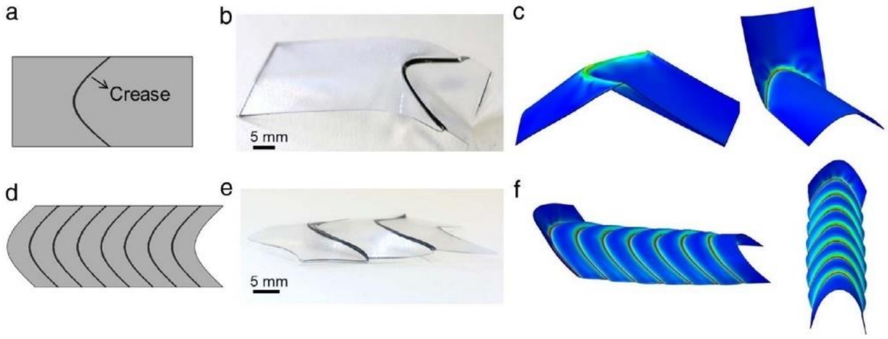


Figure 2.22. Self-folding via more generalized curved creases

Technique: Additive Manufacturing of Curved Crease Patterns

Scale: Macro-Scale

Materials: Shape Memory Polymer (SMP) Sheet

Table 2.9. Multi-State Structures by (Chen, Mueller, & Shea, 2017)

Here flat fabricated deployable structures that have activated predictable geometries. Structures have suggested bistable actuators act as a base block in a hierarchical framework. An appealing characteristic of bistability is that only transforming between states requires energy input, but not maintaining it.

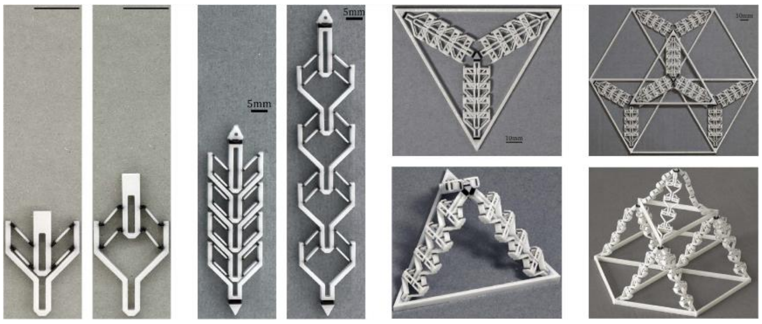


Figure 2.23. From a single system actuator to tetrahedral module tessellation

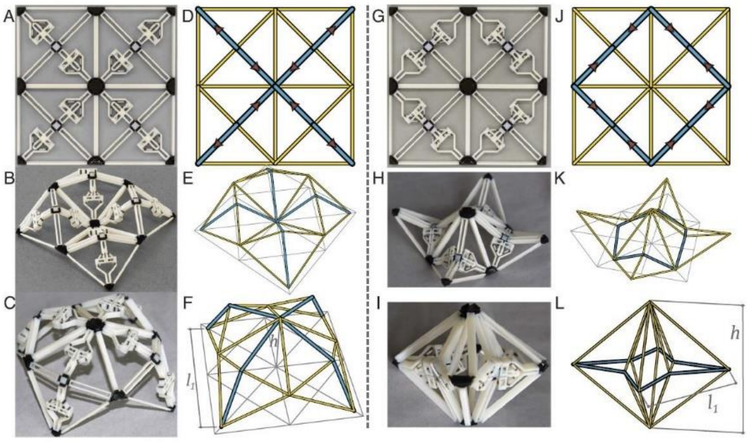


Figure 2.24. Retracted or the extended configuration of grid structures

Technique: Multi-material Additive Manufacturing

Scale: Macro-Scale

Materials: Elastomer-like and a Rigid-plastic Liquid Photopolymer

Table 2.10. Direct 4D printing by (Ding et al., 2017)

Printing composite polymers can reshape quickly into a new configuration by direct heating. A component's new shape resulted in the designed evolution of printed structure and process parameters. When heated shape memory polymer releases the strained elastomer and enables the object to change into a new form that can be reprogrammed in various sequences of forms.

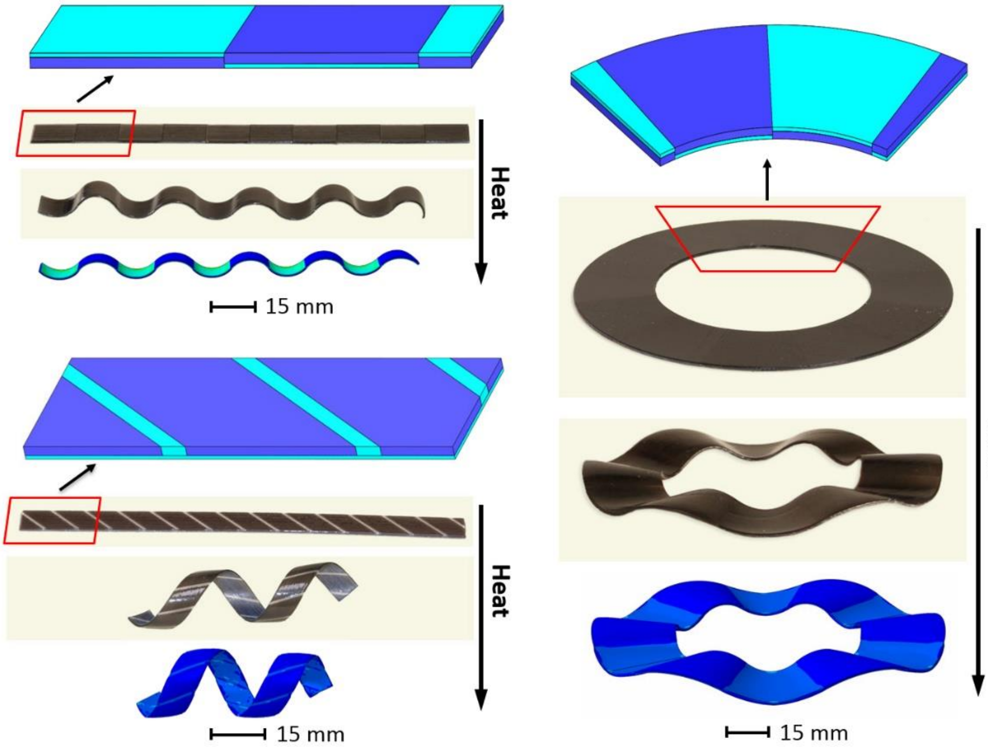


Figure 2.25. Structural elements by 4D printing

Technique: Additive Manufacturing
Scale: Macro-Scale
Materials: Shape Memory Polymer (SMP) and Elastomer

Table 2.11. 4D Mesh by (G. Wang et al., 2018)

By shrinking and bending the thermoplastic 4DMesh technique combines actuators with geometric algorithms to fabricate non-developable functional surfaces at centimeter to meter scale.

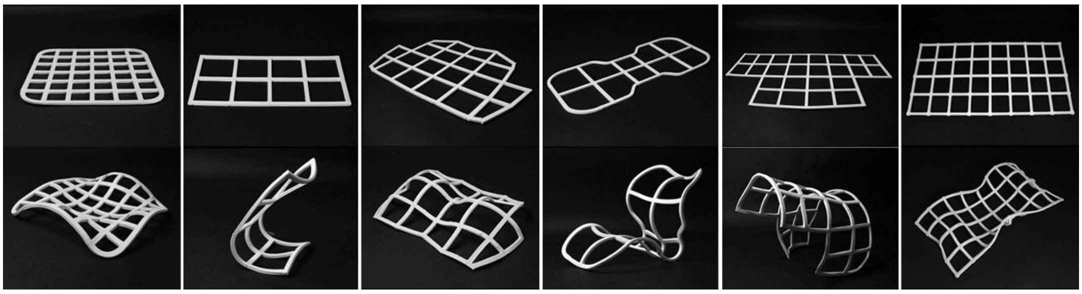


Figure 2.26. Before and after triggering of mesh structures

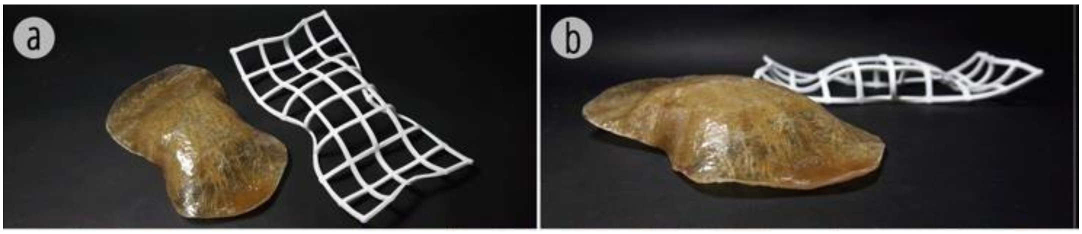


Figure 2.27. (a, b) Resin composite prototype

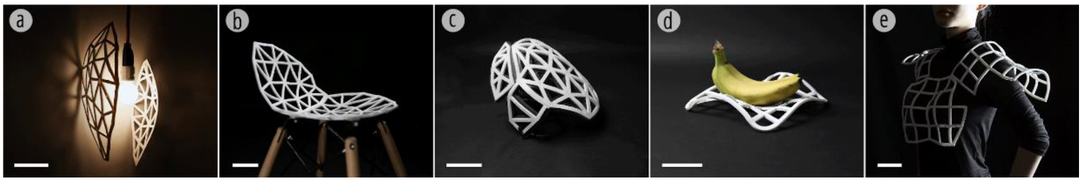


Figure 2.28. 4DMesh applications

Technique: Additive Manufacturing
Scale: Macro-Scale - Large-Scale
Materials: Thermoplastics

Table 2.12. 4D Rods by (Ding et al., 2018)

Slender structures are in architecture where they serve as building blocks for 3D structures. 3D printing allows such structures to manufactured with geometric complexity but has a price of lengthy construction time and the need to support structures during printing. Therefore, by manufacturing structures with programmable 1D composite rods that designed simply by heating into a predefined form, some of these constrain could be overcome.

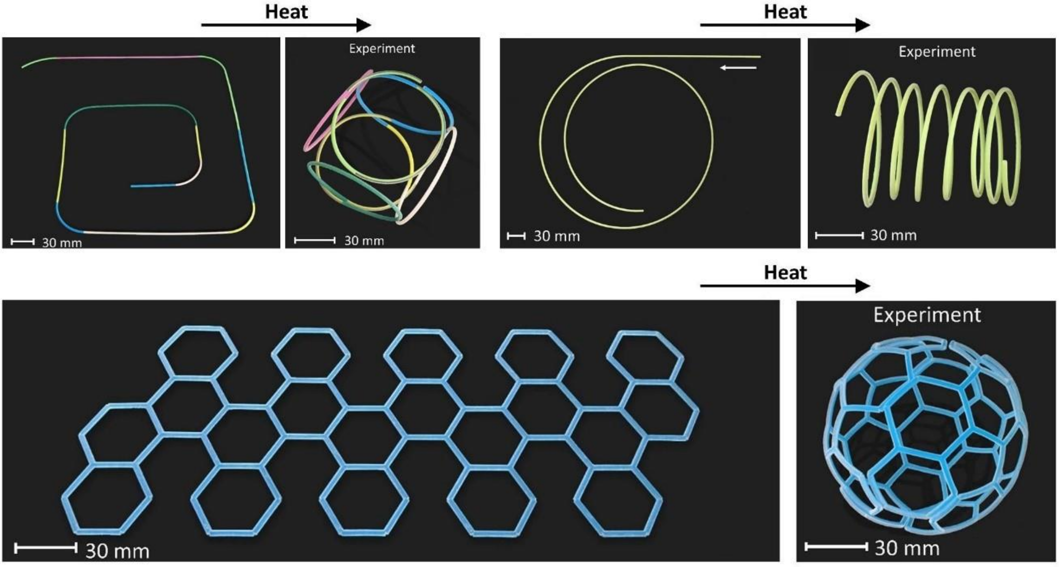


Figure 2.29. Transformed from a flat rod to a cubic frame, helix, and a buck ball

Technique: Additive Manufacturing

Scale: Macro-Scale

Materials: Glassy Polymer and Elastomer

Table 2.13. 4D Timber Construction by (Wood et al., 2016)

4D timber construction presents a technique for the use of self-constructing surfaces with hygroscopically actuated timber-based systems. With the recent computational design and methods of digital fabrication, the embedded hygroscopic features of the timber enable the design of discrete wood parts to be processed and reassembled into large multi-element surfaces. The methodology of material assembly allows the design and control at an extended scale of the encoded moisture response curvature direction and magnitude.

Figure 2.30. Responsive composite timber

Technique: Computer Numerically Controlled (CNC) fabrication
Scale: Large-Scale
Materials: Beech and Maple timber

Table 2.14. Programmable Morphing Composites by 4D Printing, by (Q. Wang et al., 2018)

Programable morphing is a printing technique of composite integrated continuous fibers, and the bilayer production realizes a high deformation accuracy of programmable deformation. The composite structure deformed by triggering the distinction between continuous fibers and the flexible matrix of thermal expansion coefficients.

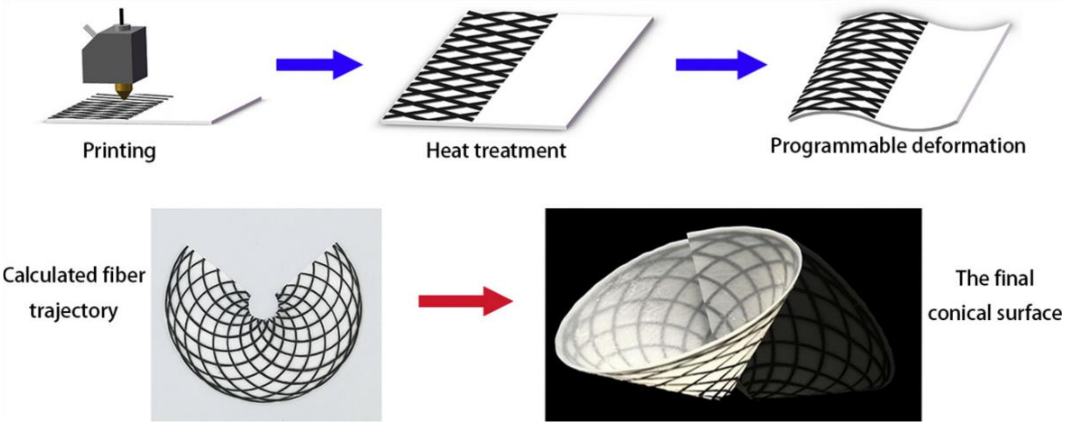


Figure 2.31. Graphical abstraction of pprogrammable morphing composites

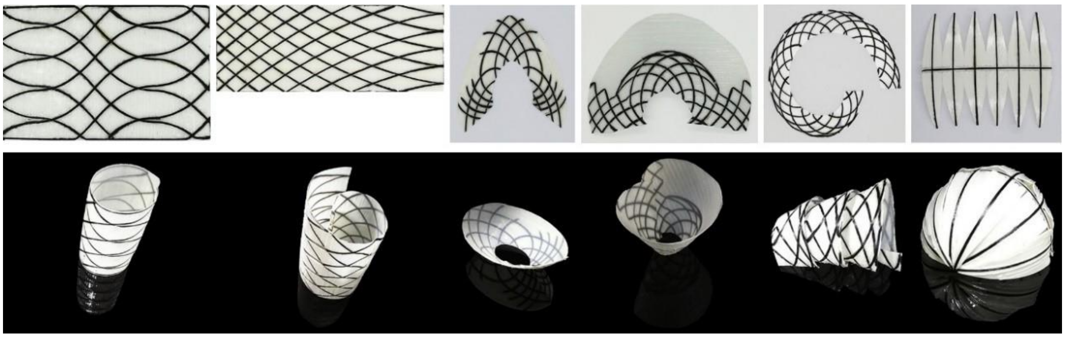


Figure 2.32. The required and actual shape of different geometries

Technique: Additive Manufacturing

Scale: Macro-Scale

Materials: Polyamide66 as flexible matrix material, and the carbon fiber as continuous fiber material.

Table 2.15. Adaptive Architectural Skins, by (Mansoori et al., 2018)

The goal of this method is to take wooden surfaces, that are commonly-used architectural material, and re-conceptualize it for the use in digital design. As a result of this laminating a shape memory polymer onto a kerfed wooden plane, a reversible deformation process of wooden surface successfully developed and tested. The composite obtains its responsiveness and curvature orientation, structural strength.

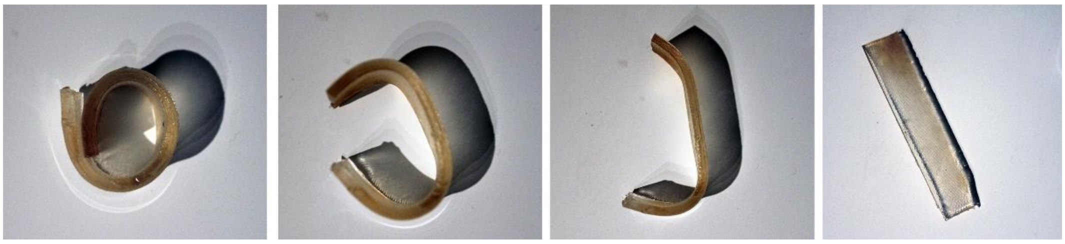


Figure 2.33. Initial test of SMP responsiveness

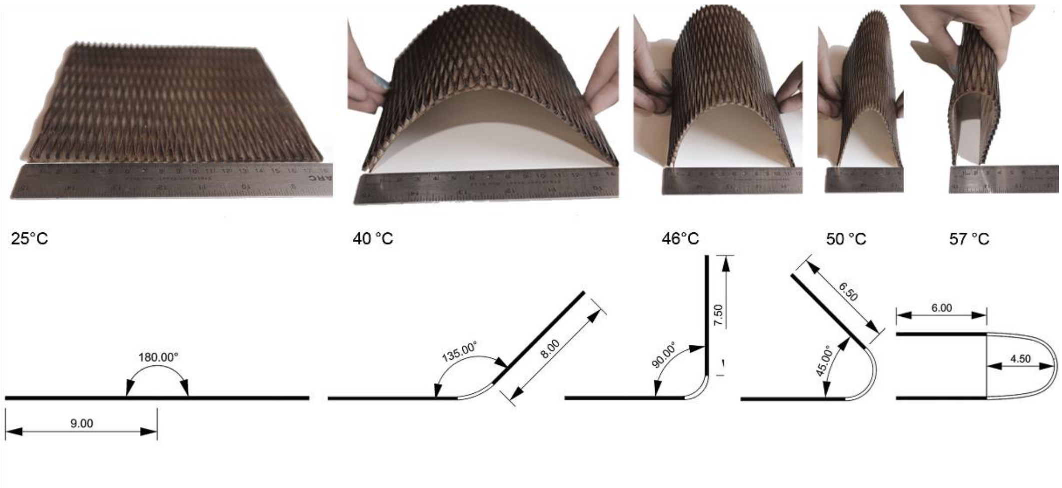


Figure 2.34. From the shape-memory polymer, the composite obtains its responsiveness and its curvature direction and structural stability from the kerfed wood

Technique: Kerfing

Scale: Macro-Scale

Materials: Shape Memory Polymer (SMP) and Kerfed Wood

Table 2.16. Thermorph: Democratizing 4D Printing of Self-Folding Materials and Interfaces, by (An et al., 2018)

As a novel printing method of fabricating self-folding complex geometries, Thermorph demonstrating a 4D printing example with an FDM 3D printer, off-the-shelf, low-cost filaments, and design editor. It is practicable to print and trigger flat thermoplastic composites into 3D with arbitrary angles of bending.

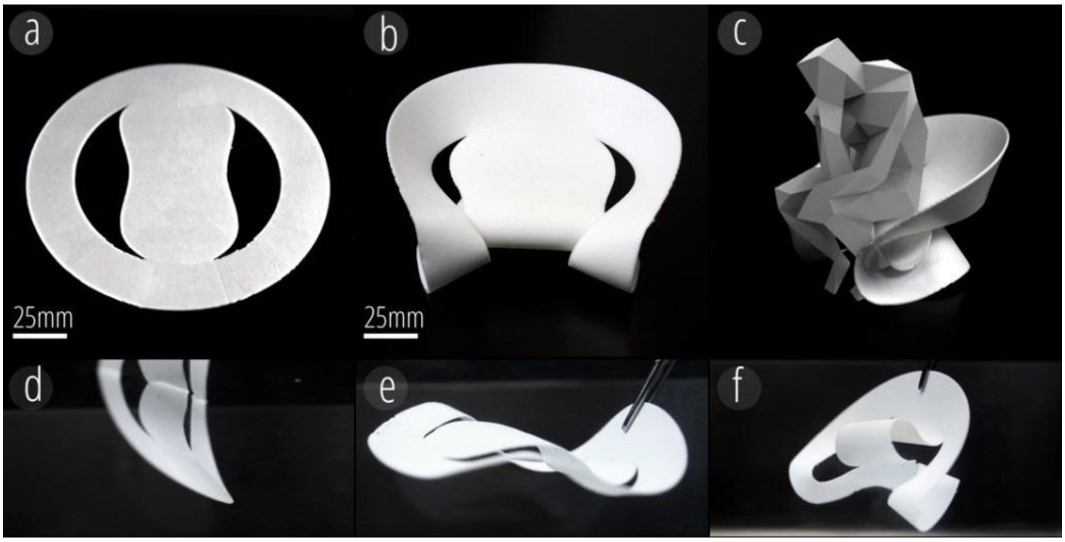


Figure 2.35. Self-folding chair

Figure 2.36. Self-folding boat

Technique: Additive Manufacturing
Scale: Macro-Scale
Materials: PLA (Polylactic Acid) and TPU (Thermoplastic Polyurethane)

Each of these researches provides different shape transformation and different techniques with different explanations and description; thus, types of responsive behaviors that can be performed with 4 D printing procedures have become hard to obtain an overview. In addition, the current literature understanding is not only scarce but fragmented as well. The purpose of this literature, therefore, is an effort to explore the different shape-change researches.

2.5. Advantages, Disadvantages, and Potentials of 4D Printing

With existing additive manufacturing technology, the ability to fabricate 3D physical objects with limited smart materials promises excellent potential. In order to take advantage of this technology, several interdisciplinary manufacturing studies have already started to fabricate their prototypes. Although, restrictions of current industrial additive manufacturing technology, diversity of 4D printing in application covered a wide range of spectrum since its advance.

4D printing techniques have many advantages to research that can increase fabrication speed, reduce costs for labor, and increase worker safety. In addition to these, with respect to complex generative forms and formworks fabrication 4D printing is expected to lead to more sustainable construction due to more efficient structural design, as well as reduced waste generation due to more efficient construction techniques. 4D printing does not require additional needs to create a responsive shape change straight from the print bed. Thus, because of eliminated hardware, objects become simpler that decreases the number of chances to fail.

Obtaining design information directly from the active printed structure creates an organic and constant information flow between digital design data and physical fabrication processes. Therefore, rather than following classic top-down architectural design strategies, 4D print fabrication techniques create an environment where simultaneously both top-down and bottom-up design approaches used.

As an evolutionary manufacturing technique, self-folding materials cited as one of the promising technological manners for fabrication. Because previous attempts to manufacture self-folding mechanisms required advanced stacking and post-assemblies. By the recent advancement of additive manufacturing and smart material technology, researchers have been exploring the possibilities of printing processes and coined 4D printing techniques to automate self-folding and responsive products. Difficulties however still exist for their overall accessibility of printable responsive products that either material synthesized responsive systems need someone with material science expertise, or to produce specific arbitrary 3D geometries the material is not generalized enough.

Although it is rather a recent field of research, various examples of 4D printing and smart material applications proved that using the opportunities of responsive, self-transforming structures promising significant advantages. Because it is a recent developing research area, on the other hand, it is not an easy process to operate. In addition, there is not a standard treatment or particular defined material for the process.

Considering the disadvantages of current conventional manufacturing techniques, fabricating with 4D printing technology could take an important role in manufacturing repetitive/non-repetitive complex generative and computational forms and formworks for single and mass customization. Because 4D printing technology directly related to additive manufacturing, on the other hand, there are some restrictions to be exceeded. By the recent advancements, additive manufacturing has evolved from a niche industry to mainstream technology. It is now available various range of commercial 3D printers in the market, from do-it-yourself desktop machines to industrial machines. Since its advancing, additive manufacturing has been experimenting in various research fields. Readily available 3D printers on the market, on the other hand, have restricted printing bed size; therefore, scale becomes one of the main limitation for 4D printing application.

Due to limited printing bed size and resolution capacity of FDM desktop printers, appropriate forms of 3D mesh simplified into a limited amount of faces without missing essential characteristics. In addition to that, the simulation tool of the digital environment does not take into account the material's weight and gravity, therefore, a material currently folds in the air, but it is not possible to simulate the conversion precisely with the software.

Because current possibilities of industrial additive manufacturing allow us to print restricted sized applications, the adaptation of this technology to actual sized fabrication scale is feasible only in specific scale applications. Therefore, to take the advantages of 4D printing technology in the actual construction scale, this study aims to contribute fabrication process for repetitive/non-repetitive complex generative form and formworks for single and mass customization with 4D printing technology as an interdisciplinary manufacturing technique. In order to make a consistent investigation, several primary methods are followed to make a feasible fabrication process. These methods and how they utilized during this study are epitomized in this section and elaborated in the following sections.

CHAPTER 3

DEVELOPMENT OF THE IMPLEMENTATION

3.1. Hypothesis

This research, it is hypothesized that 4D printing manufacturing technology can be utilized to fabricate feasible repetitive/non-repetitive complex generative structures that can be used for formwork and form as it is in both single and mass-customized applications.

3.2. Research Questions

The primary purpose of this study is to research potentials of 4D printing technology as a new approach to fabricate generative formwork applications; this study investigates the following research questions:

- Is 4D printing an efficient fabrication technique for single and mass customization of repetitive/non-repetitive surfaces, particularly within computational and generative systems in architecture?

- Potentials of 4D printing as formwork in terms of how stable is it, how responsive is it, and how manageable its responsiveness.

3.3. Contributions

In the scope of this research, it is proposed that 4D printed responsive structures can be utilized to fabricate both formwork and form as it is for complex generative and computational design, and can be an alternative fabrication technique for single and mass customization.

This study focuses on the 4D printing manufacturing technique as an alternative to enhance the fabrication of complex and generative formwork and form for single or mass customizations. Based on the literature review, research questions, and preliminary studies of author, implementation, and integration of a framework is established on how 4D print manufacturing technology can be utilized for repetitive/non-repetitive complex generative and computational forms. The framework of this study emerges from the reciprocal analysis of conventional and digital formwork fabrication techniques. Identifying the possibilities of digital fabrication, additive manufacturing, and 4D printing, further research at this point is needed to discuss the possibilities of the 4D printing manufacturing technique to generate a more intelligent fabrication process.

Fabrication of complex, repetitive/non-repetitive generative forms is an ongoing research field in architecture that many researchers working on to advance a more intelligent manufacturing technique. 4D printing is a recent developing research field that may take manufacturing to a new dimension to generate more intelligence manufacturing to fabricate complex generative form and formworks for both single and mass customization. Therefore, this study aims to contribute a 4D printing fabrication technique as a novel way of fabrication responsive complex generative and computational structures. That can be utilized as formwork and form as it is in both single and mass-customized applications with readily available FDM printers and thermoplastic filaments on the market. While many other previous studies have mainly experienced an arbitrary 3D geometry pipeline with sharp folds, this research also contributes a design and printing technique that allows for a programmable bending by creating new modules within a curved crease self-folding geometry design algorithm. In order to generate tangible research, various methods are used to operate a rational fabrication process. These techniques and how they used in the research elucidated and explained under this chapter in the following parts.

3.4. Form Finding

The question is how to deal with the complexities of form and reduce it down to a physical prototype? That is where reverse thinking is essential, which is an often-used strategy in computer science to break down complexities. This process of the research, therefore, defines the complexity and reduces it to its base parts until each part can be dealt with given the knowledge. In the process of reverse engineering, complex form connected with descriptive geometry so that it can be broken down to its simplest parts. Therefore, the design process of reduction and reverse engineering can lead architects to take a more systematic approach for theoretical ideas that creating complex forms while pragmatically attacking the issues of construct able forms (Parê, Loving, Hill & Parê, 1984).

Computation is one of a promising field that offers new potentials of exploring complexities in form. While the processing of complexity to its purest form, designers gain an insight into how to work through design issues. Before the fundamental discussion of computation language, however, it is essential to begin with simple physical elements to understand the behavior of the material. Therefore, introducing a simple plane manipulation by the folding material like paper, it is the simplest way to how basic physical moves create geometry. Afterward, using a Computation language, it is possible to use the transformation of points and curves to input the geometries of these translations into the digital environment (Parê et al., 1984).

In order to understand the fundamental physical behavior of plane manipulation, a folding technique is used in this research as one of the simplest ways to achieve certain complexities of developable surfaces. As a prominent example of folding, origami art is a fascinating technique to create spatial geometries from a planar sheet without stretching or tearing — conventional straight crease paper folding of prismatic origami that framed with planar facets and created polyhedral surfaces. Here, to create a complex three-dimensional form, altering the straight crease into a curved folding create a complexity that cannot be easily defined as vertex coordinates by accessible parameters. As a hybrid technique of folding and bending, curved creasing surfaces composed of developable smooth surface patches. Curved crease technique can be referred to classic origami resulting from pure folding and evolving surfaces by pure bending (Demaine, Demaine, Koschitz, & Tachi, 2015)

3.4.1. Curved-Crease Folding Technique

To form 3D complex surfaces from a flat configuration advantage, the hybrid property of the curved-crease origami technique used in the research. The pure bending surfaces restricted to simple geometries such as cones, tangent surfaces, and cylinders, prismatic geometry more flexible in design. However, it is not able to depict a curved surface without an excessive number of creases that are increasing the resolution. In such cases, creases form a set of vertices in which the material deforms mainly in the plane. Curved folds, on the other hand, forms a range of surfaces with a tiny number of creases, mostly separated. (Demaine et al., 2015).

Notable elegance of curved folded models not only demonstrates fascinating visual forms, but they also inherit structural characteristics and allow various parts from a folded sheet to be created that can save material, fabrication process, and costs of construction. Therefore, folded structures become an optimal candidate for lightweight deployable architectural and engineering systems (Hemmerling & Mazzucchi, 2016). In the process of form-finding by curved crease folding, the material resists the folding, and thus physical stress can guide design choices. A designer may begin to manipulate paper and let the material fold as it wishes to fold.

Therefore, the material-driven method needs little mathematical knowledge but strongly depends on tactile understanding that transmitted through repeated physical manipulation or folding. That can also be defined as a material logic-based bottom-up strategy (Koschitz, 2016).

As a part of the challenge is that the three-dimensional forms of curved-crease origami are usually not mathematically determined: the models are treated mechanically and have many degrees of freedom. Nevertheless, physical paper prefers to rest in one or some stable balance. These balances locally minimize the system's elastic energy where the paper is not creased, it attempts to return to its original flat form, and where the paper creased, it attempts to return to the set crease angle. Physics balances between these forces often result in surprising three-dimensional forms (Koschitz, Demaine, & Demaine, 2008).

3.5. Modeling of Curved-Crease Folding

The fundamental way of achieving curved crease folding models is to generate the folding lines as junctions of a developable surface with a cutting plane, resulting in one of the two sides' reflected geometry. In this situation, utterly digital simulation is feasible without feedback from a physical model, but the spectrum of design can be somewhat restricted (Raducanu, Cojocaru, & Raducanu, 2015). Therefore, the following techniques of virtual simulation of curved folding used to model more complex forms.

- By using physical models such as paper models, a design solution searched.
- The development digitally reproduced once a plausible idea emerges, preferably algorithmically, so that the folding pattern can be easily altered to optimize the solution.

- The simulation of the folding method is carried out by rationalizing the initial growth as a rigid model of origami, however rather than rigid origami curved-crease transformation requires the ruling lines of the folded form. A specific development does not describe a single result of folding; it relies on how the various strips are bent. However, the result is a ruled surface that can be developed and therefore has ruling lines. Various configurations of the same development show ruling lines with different orientations. That means the pattern of rulings determines how the design digitally folded. Rather than manual reproduction from scanned flattened models, by defining an algorithm based on the physical model examination, these ruling patterns can be digitally generated.

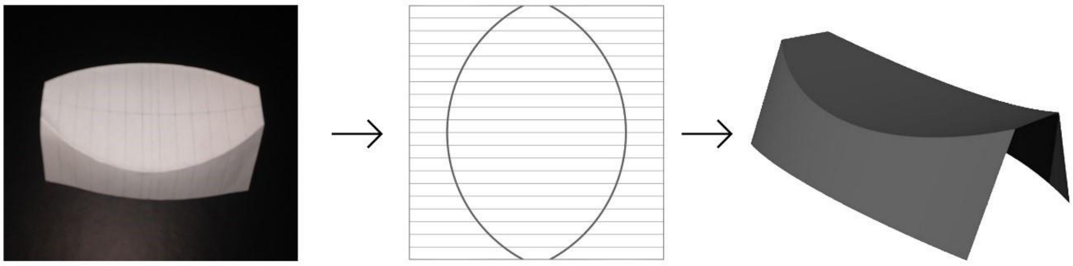


Figure 3.1. Modeling process of a curved-crease folding geometry (drawn by author)

Therefore, first of all, in order to be able to make a digital model, it is crucial to understand the geometric nature of curved folding modeling. It is considered a paper as a zero-thickness that can sustain bending without tearing or stretching. That means, from a mathematical perspective, a paper sheet acts as a developable surface. A developable surface is characterized simply by its ability to unfold into a flat surface as securing its lengths and angles; it is a ruled surface that the tangent plane fallows the surface throughout the entire line. A developable surface has no Gaussian curvature, and the rulings are either parallel or are tangent to a curve, respectively, that describe the surface (Vergauwen, Laet, & Temmerman, 2017).

It remains developable to transform a planar sheet by folding it along a curved crease. When spatial objects created, developable surfaces naturally appear without stretching or tearing from planar sheets. In other words, a three-dimensional shape can be described as a structure of interconnected components of developable surfaces after folding a sheet throughout a curved-crease pattern. For on unique curved-crease, an infinitive number of developable surfaces exist by folding of the curved-crease. Developable surfaces on both sides of the creases and rulings created for each variety of each basic shape, that describe them are unique. Therefore, the directions of the rulings play a significant part in geometric modeling on curved crease structures (Vergauwen et al., 2017).

Besides, it is also possible to unfold developable surfaces in the plane while keeping the length of all surface curves. Consisting of flat patches and ruled surface patches with the unique property of getting the same tangent plane for all points of the ruling. There are different methods for unrolling a 3D-geometry based on curved folding, which is composed of planar elements by single curved surfaces. However, it is still quietly challenging to ensure the unfolding into a single developable sheet without the need to cut or glue the different parts (Hemmerling & Mazzucchi, 2016).

In order to achieve an overall kinetic transforming structure, a geometric technique, that needs no or only a few material deformations, is essential. Some conventional geometric approaches to achieve kinetic transforming structural applications to create a polyhedral surface connection with a synchronized movement, are to use bars and rotational hinges to be able to generate scissors mechanism or to use plates and hinges. Curved folding, on the other hand, forms a planar sheet by folding along curved creases that can create complex surface forms just by both folding and bending, while comprising of developable surfaces generalized by simple forms like cylinders, tangent surfaces, and cones. Although each of these soft patches produces only comparatively fundamental shapes, a freely configurable surface, that enabling globally non-developable complex surfaces can be achieved by the existence of creases (Tachi & Epps, 2011).

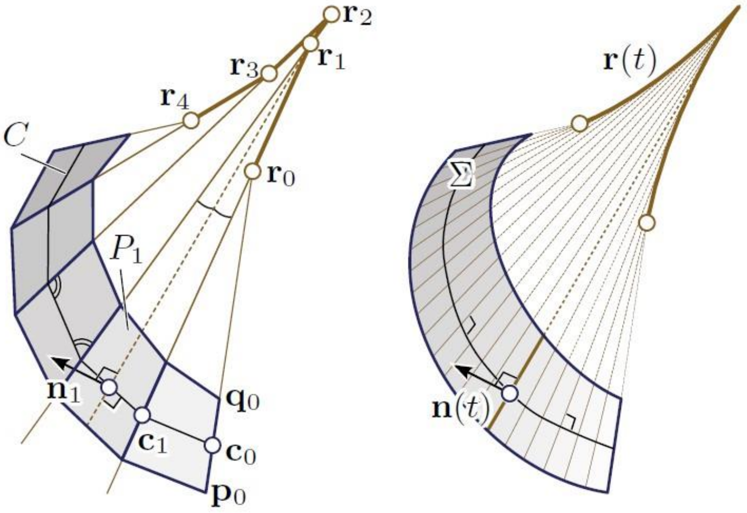


Figure 3.2. PQ lines of a developable surface (Kilian et al., 2008)

Representing a developable surface with PQ lines offers several benefits over the creation of triangular meshes by facial planarity. Subdivision by PQ lines offers a multi-scale approach that simple and computationally effective. The regression of the curves presents a separate form that is unique on the surface and thus must be controlled, and it is easy to estimate the curvature behavior.

A ruled surface model of a torsal discrete by lines of planar quadrilaterals (PQ). These planar quadrilaterals can be unfolded trivially into the plane without distortion. Joined edges by successive quads offer us the separate rulings. They usually form the borderlines of the regression polyline, specifically where the separate rulings are parallel or cross a fixed point. A process of refinement that maintains quad planarity produces a torsal-ruled surface in the limit. The rulings are the boundaries that are generally tangent to the regression curve, and in particular, cases are parallel or pass through a fixed point.

Since paper folding art is strongly associated with the geometric principles of origami, there has been a significant amount of mathematical studies. The mathematical literature includes an analytical understanding of how to fold locally curved creases. However, as opposed to the wealth of algorithms for straight creases, there was mainly no algorithmic understanding of how to design origami using curved creases (Koschitz et al., 2008).

3.6. Digital Modeling

Approaches for curved crease modeling and design tools based on the idea that folds are creased. Straight-line segments of these folds split the surface into faces that maintain only zero-order geometric continuity between faces. Throughout the years, this idealization of physically folded fabrications effectively used in the assessment and design of many origami-inspired designs algorithms. However, idealization like this might not be suitable for designs that Have non-negligible folding volume or maximum bending in limited material folds. In this case, folds are accurately represented as bent surface areas with geometric continuity of higher-order rather than as straight creases (Peraza Hernandez, Hartl, Akleman, & Lagoudas, 2016).

Moreover, on the contrary to the well-known straight folded structures, curved folding opens up more spatial options. It provides more performative structural effects at the same time because the curved surfaces derived from the curved folding of the crease improve the overall rigidity of the structure. Therefore, curved folding addresses more complex mathematical topics such as differential geometry and algorithms for optimization that require a thorough understanding of the underlying principles (Hemmerling & Mazzucchi, 2016).

Modeling and simulation solutions for the 4D printing operation of curved crease developable surfaces is an essential factor in the entire process. However, because it is a new developing research field, there is not a specific software solution for the 4D printing process. Also, classic digital platforms for additive manufacturing mainly deal with specific functions, while 4D printing operation of curved crease folding developable surfaces requires much more complex functionalities. Classic software solutions of modeling and simulation generally deal with static printing operations to preview the final output. Modeling and simulating of a 4D printing operation, on the other hand, should contain both previews the printing path and the shape-changing process of the final structure by the different stimuli like humidity, temperature, or light. For the development of the 4D printing techniques, therefore, 4D printing curved crease folding developable surfaces processes serves as a crucial part, not only within the boundaries of one material characteristic, but also the design of more complex surface transformation behaviors in multi-material printing.

3.6.1. Software

Digital opportunities of Grasshopper and Rhinoceros provide designers a working environment where they are exploring distinct design parameters and implementing modeling and rendering simulation outcomes. Therefore, digital possibilities in the conceptual design stage, the geometric modeling technique, become quite helpful. The digital environment of simulation, however, does not adequately represent reality (Vergauwen et al., 2017).

Recently Robofold introduced a Grasshopper plugin called 'Kingkong' that allowed the simulation of curved crease models in the parametric design environment. In modeling objects based on simple patterns is very easy to use Kingkong; however, it is less suitable for complicated patterns with numerous curved creases. Origami component of the Kangaroo, on the other hand, can be the best modeling tool for these complicated models (Vergauwen et al., 2017).

3.7. Geometric Fabrication Principles of Curved Crease

In order to create a self-transformation phenomenon of a curved-crease complex 3D geometries, the geometric principle of printing is essential. A programmable transformation is strongly related to the principles of the printing path. According to the printing direction of the active material, the orientation of bending can be controlled. Programming printing path of curved-crease developable complex geometries, on the other hand, do not represent lines of planar quadrilaterals (PQ). It requires a different principle of printing to programming the bending direction. Therefore, it is essential to understand the bending principles of printed active composite structures. Fundamental principles of self-transformation depended on the printing direction. In order to create such simple surface manipulations as folding, bending, rolling, or twisting, printing patters of active material also represents the moving pattern. This principle is quite useful for basic surface manipulations, and the 4D printing test samples that are experimented in the research, become quite instructive practices to understand the fundamental geometric principles of 4D printing technique.

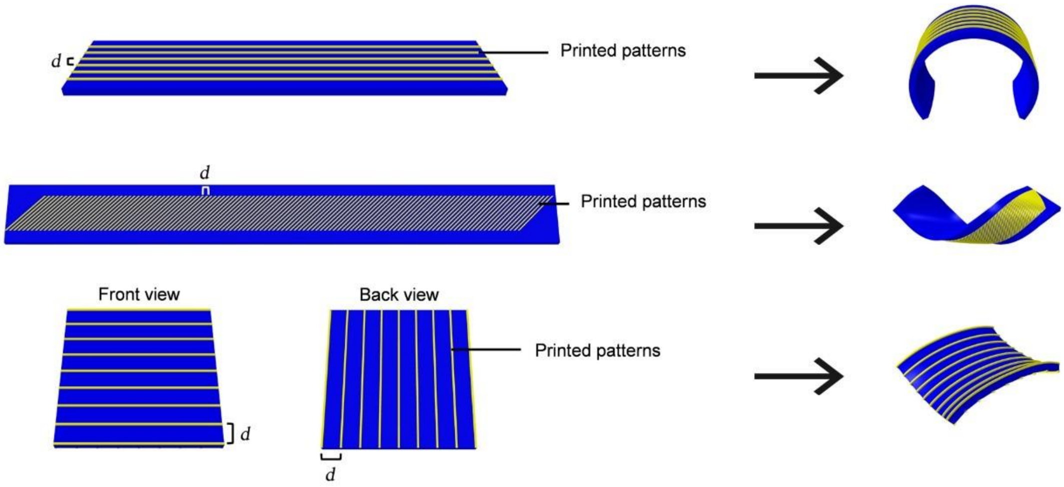
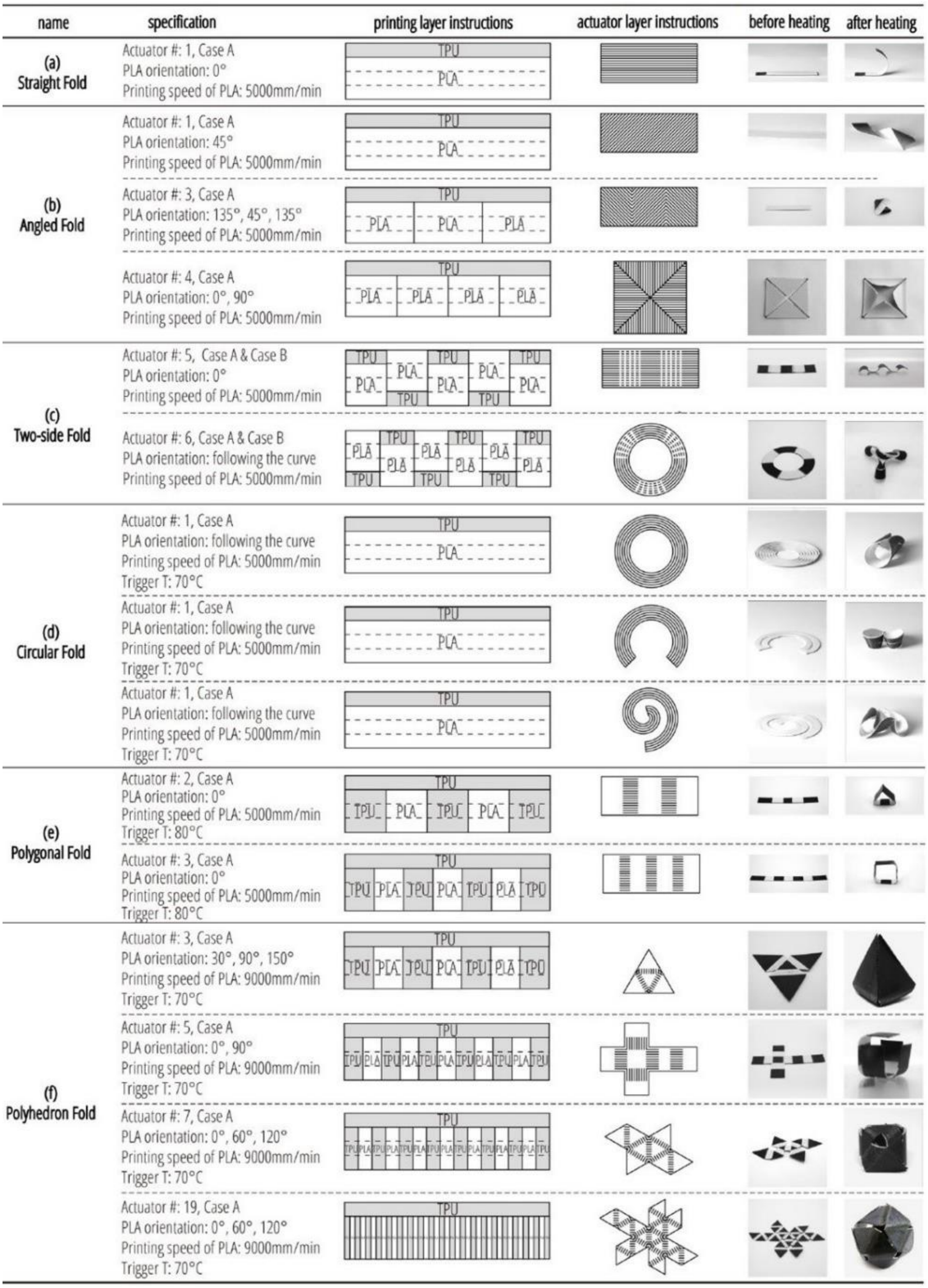


Figure 3.3. Geometric principles of printing directions (Liu, Zhao, Wu, & Lu, 2018)

Table 3.1. Analysis of basic shape deformations in 4D printing (Nam & Pei, 2019)

	Folding	The stress mismatch between rigid and active materials causes deformation.
	Bending	In response to activation stimuli, deformation is the swelling / shrinkage mismatch between both layers.
	Rolling	standardized curvature deformation that varies according to mismatch of expansion and thickness.
	Twisting	To cause twisting deformation, the fibers printed at certain angles.
	Helixing	A uniaxial expansion/shrinks of active layer at a non-zero angle between the active layer's main press direction and the bilayer strip's main axis.
	Buckling	By the compressive stress to buckle the flat frame out of the plane above a certain critical value.
	Curving	A developed stress gradient could cause the structure to curve spontaneously after release from the substrate.
	Topological change	In the presence of a suitable stimulus, mountain and valley characteristics produced from concentration circles.
	Expansion/contraction	This mechanism is driven by a spectrum of expansion ratios between active and rigid parts.
	Waving	In bilayers with similar rigidity and layer density, deformation could happen through swelling/shrinking mismatch in reaction to activation stimuli.
	Curling	Deformation with separate swelling features due to the stress mismatch between rigid and active materials.



name	specification	printing layer instructions	actuator layer instructions	before heating	after heating
(a) Straight Fold	Actuator #: 1, Case A PLA orientation: 0° Printing speed of PLA: 5000mm/min				
(b) Angled Fold	Actuator #: 1, Case A PLA orientation: 45° Printing speed of PLA: 5000mm/min				
	Actuator #: 3, Case A PLA orientation: 135°, 45°, 135° Printing speed of PLA: 5000mm/min				
	Actuator #: 4, Case A PLA orientation: 0°, 90° Printing speed of PLA: 5000mm/min				
(c) Two-side Fold	Actuator #: 5, Case A & Case B PLA orientation: 0° Printing speed of PLA: 5000mm/min				
	Actuator #: 6, Case A & Case B PLA orientation: following the curve Printing speed of PLA: 5000mm/min				
(d) Circular Fold	Actuator #: 1, Case A PLA orientation: following the curve Printing speed of PLA: 5000mm/min Trigger T: 70°C				
	Actuator #: 1, Case A PLA orientation: following the curve Printing speed of PLA: 5000mm/min Trigger T: 70°C				
	Actuator #: 1, Case A PLA orientation: following the curve Printing speed of PLA: 5000mm/min Trigger T: 70°C				
(e) Polygonal Fold	Actuator #: 2, Case A PLA orientation: 0° Printing speed of PLA: 5000mm/min Trigger T: 80°C				
	Actuator #: 3, Case A PLA orientation: 0° Printing speed of PLA: 5000mm/min Trigger T: 80°C				
(f) Polyhedron Fold	Actuator #: 3, Case A PLA orientation: 30°, 90°, 150° Printing speed of PLA: 9000mm/min Trigger T: 70°C				
	Actuator #: 5, Case A PLA orientation: 0°, 90° Printing speed of PLA: 9000mm/min Trigger T: 70°C				
	Actuator #: 7, Case A PLA orientation: 0°, 60°, 120° Printing speed of PLA: 9000mm/min Trigger T: 70°C				
	Actuator #: 19, Case A PLA orientation: 0°, 60°, 120° Printing speed of PLA: 9000mm/min Trigger T: 70°C				

Figure 3.4. Geometric principles of different self-folding scenarios (An et al., 2018)

3.8. Fabrication

Fabrication of curved-crease developable surfaces by 4D printed active composite structures represent an essential part of the research. In this part of the study, material and printing processes and how these are generated is covered. Fabrication processes of a 4D printing flat configuration of a curved crease complex geometry require material knowledge and manufacturing technology. 4D printing fabrication processes in previous researches generally generated with highly sophisticated material science and manufacturing technology. However, to create a feasible and quotable fabrication process for further researches, selection of the material and printing technology in this research based on the idea that any researcher can practice the process with easily accessible material and manufacturing technology on the market. Therefore, the choice of the materials and the FDM printer generated with this idea.

Fundamental understanding of the fabrication process of 4D printing is not different from standard static 3D object printing. In order to create the self-transformation phenomena over a solid printed 3D object, on the other hand, it is essential to know the physical advances of the material. Therefore, is it the base to know under what condition and how the material reacts. After identifying the material properties, to use the physical reaction, it is also essential to use the geometric principle to control the physical reaction. Curved-crease folding is a fascinating geometric principle to create sophisticated, complex developable geometries. In order to generate a 4D printing with the principles of curved-crease folding, the physical reaction of the material used to create the self-transformation phenomena.

With the material information and geometric principles of curved-crease folding, the theory of 4D printing is possible to model a digital simulation. The physical fabrication practice of 4D printing, on the other hand, requires a manufacturing process that generated with an FDM desktop 3D printer in this research. Therefore, to manage an overall 4D printing fabrication process material and manufacturing information practiced in the physical environment.

3.8.1. Choice of the Material

Because of a wide range of polymer material choices, simple shape manipulation, simple processing, and programming, polymer-based materials are highly preferred materials for 4D printing operations. Even a shape-memory polymer resin filament for 3D printers is available on the market. In order to manage shape-memory phenomena, polymers have two significant temperature parameters: glass transition temperature (Tg) and melting temperature (Tm) to control transitions in the plastic stage. In order to make it elastic and self-folding, the temperature should heat above its Tg and below its Tm.

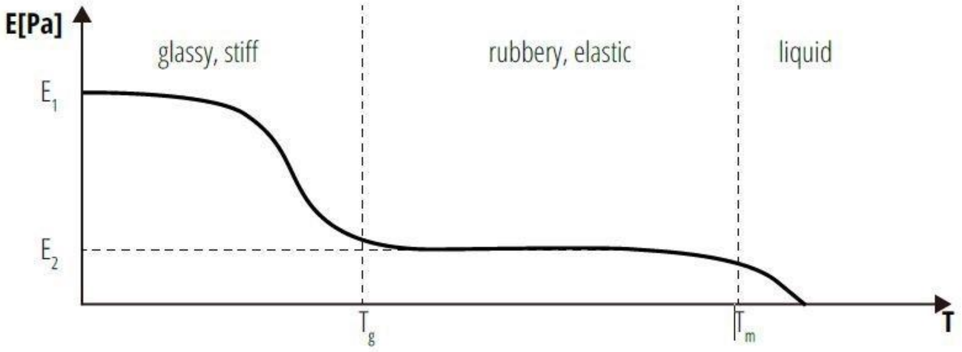


Figure 3.5. State transitions of thermoplastics (An et al., 2018)

In order to simulate the self-folding structure by controlling the transition temperature of the material, a bi-layer structure proposed. Thermo Polyurethane (TPU) as the constraining layer and layer of Polylactic Acid (PLA), together of these layers form a printed active composite (PAC).

The shape memory effect of a printed active composite consists of two steps:

Step 1 - shape programming: heating above its Tg and below its Tm to temporarily mold it from its original shape and keep it in its temporary shape by reducing the temperature below Tg.

Step 2 - shape recovery: reheating the material above Tg, the temporary shape can come back to its permanent form.

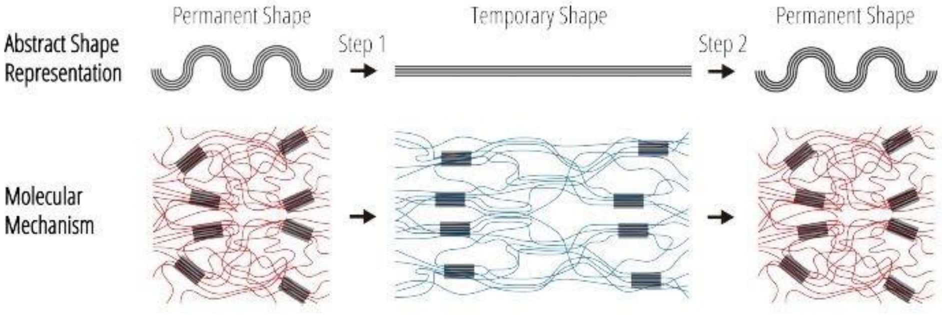


Figure 3.6. Molecular mechanism of shape memory effect (An et al., 2018)

- The polymer chain rearranged during the printing process, and residual stress can be built. When PLA extruded, the polymer chain is pulled and straight; after it cools and solidifies quickly, it will be forced to maintain the straight state (Temporary shape after step 1).

- Reheating the solidified PLA, releases residual stress, returns its polymer chain to a messy or low-energy mode, and shortens the printing process (Permanent shape after step 2).

3.8.2. Printing

Many curved lines folded paper models have studied over the years, but their implementation in modern design or architecture limited due to the complexity of the concept. Also, the implementation of this idea in fabrication leads to static objects that plastic crease deformation is permanent, and objects cannot return to their original flat state. Curved-crease-folding used in this research, on the other hand, shows a well combined and intuitive application with the flexible materials of the advanced forming technique as well as the hidden structural principles of active-bending.

Compared to the more standard solution of rigid components linked by kinematic joints, flexible structures that obtain movement from the limited elastic deformation of the structural elements can advance essential benefits. Also, due to the restricted properties of geometry and material, their design could become far more complex. However, not all curved-crease patterns produce a folding movement to generate a dynamic structure. The challenge is to create a printing pattern so that the balance is maintained and the elastic deformation is restricted and controlled throughout the folding process (Vergauwen et al., 2017).

Fundamental criteria of the printing process used in the research:

- An automated process carried out without pre- or post-processing.
- An FDM printer used to make this 4D printing method readily available to researchers.
- Off-shelf, low-cost, and available printing filaments used.
- Arbitrary 3D geometries handled. Unlike most self-folding and 4D printing operates with a set of primitives pre-designed and their combinations.

Printing principles in the previous 4D printing operations experimented that folding values of the printed structure can be affected by different parameters. Different printing order of the Printed Active Composites results in different bending directions and angles. As seen in the figure, two cases experienced with different printing orders between active PLA and TPU and obtained different bending values. Printing speed is also another valid parameter that the printing velocity of the active material increased; the angle of folding also increases. By this assumption, it is intuitively understood that the faster the active filament is printed, the larger the residual stress is formed within the active printing material. Another very efficient parameter can be the length of the actuator to adjust the bending angle. As seen in the figure, the more extended actuator, the more bending angle experienced. These parameters are essential to generate a bending value of a 4D printing process. However, it is the printing orientation that determines the folding direction and the desired form, as well. Therefore, it can be fundamentally defined that, by controlling the printing principles such as orientation, order, speed, and length, it is possible to generate a broad range of geometric forms to fold from flat patterns. In order to generate a reasonable 4D printing operation, some of these parameters that Thermorph experimented, utilized in this research.

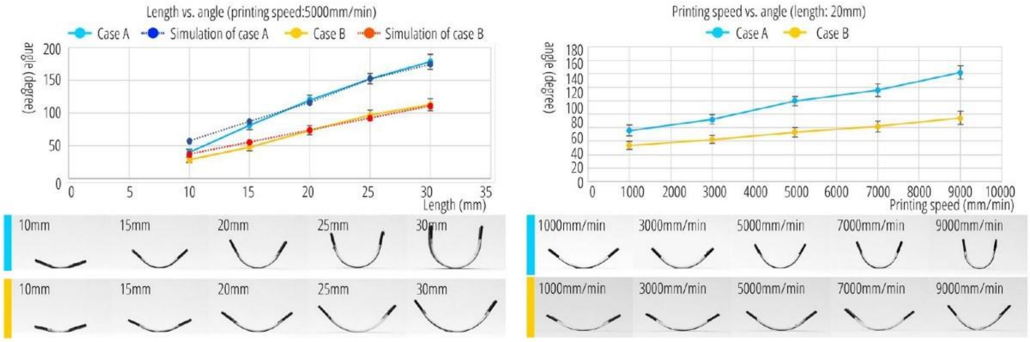


Figure 3.7. The fold angle as a function of the printing speed and the actuator length (An et al., 2018)

CHAPTER 4

MATERIAL AND METHOD

4.1. Focus of the Experiment

This chapter of the research focuses on the fabrication processes of the experiment in order to prove the potentials of 4D printing manufacturing technique to fabricate responsive structures. In order to utilize the 4D printing manufacturing technique to fabricate a feasible complex generative and computational surface, an experiment protocol consists of several processes is applied. Depending on former modeling with paper mockups and digital productions, a generative curved-crease surface selected as a base model to test the self-folding phenomena of 4D printing. The base model composed of three main surfaces works as active composites so that testing the fundamental principles of the 4D printing can measure with more consistent feedbacks. According to the base model, three different physical case scenarios generated with different printing principles. These principles designed variable as printing pattern, printing order, and the number of layers. Therefore, under different circumstances, different self-transforming characteristics planned to measured. How three experiment cases of 4D printed curved-crease active composite structures generated will be covered under this chapter.

4.2. Form Finding

In order to create a programmable self-transformation process by 4D printing, it is essential to take the advantages of a geometric principle. Therefore, the principles of the curved-crease folding technique utilized to fabricate 4D printed active composite structures. The hybrid property of the curved-crease technique used in the research to generate 3D complex surfaces from a flat configuration.

4.3. Paper Mockups

First of all, it is essential to understand the geometric essence of curved folding modeling in order to be able to create a digital model. Therefore, before the digital production of surfaces, a form-finding process generated with paper mockups. Form performance of curved-crease developable surface geometries experienced with paper models. In order to produce a digital model, form performances of paper mockups considered as a zero-thickness that can bend without tearing or stretching. It means that a paper sheet behaves as a developable layer from a mathematical point of view. Therefore, paper mockups provided proper physical data for the final productions. These paper mockups are not only performed a preview of the curved-crease forms but also provided geometric information to produce digital and physical printed of the desired curved-crease forms.

Figure 4.1. Paper mockups of different curved-crease folding geometries (taken by author)

4.4. Digital Model

Modeling and designing techniques for curved crease approaches based on the fundamental idea of making folds. Unlike the well-known straight folded structures; however, more spatial options are opened by curved-crease folding. Therefore, digital production of curved-crease developable surface structures addressed more complex mathematical subjects such as geometry differentials and optimization algorithms that required a comprehensive understanding of the fundamental principles. Modeling and simulation solutions are an essential factor in the entire 4D printing process of curved crease developable surface geometries. Since this is a new research area, however, there is no specific software solution for the process.

4.4.1. Software

As a software solution, using generative algorithms, Grasshopper is used. Grasshopper tightly integrated with the graphical algorithm editor of Rhino's modeling tools. Kangaroo is a Live Physics engine component for Grasshopper written by Daniel Piker for interactive simulation, form-finding, optimization, and constraint solving and known as a program as a basis for the producing of folding structure. In order to create curved-crease, developable surfaces KangaFold component in Kangaroo used for the case experiments.

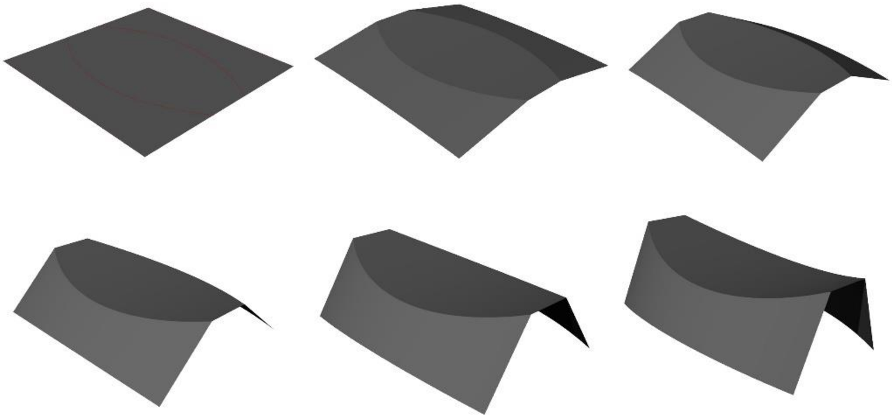


Figure 4.2. Digital process of the selected curved-crease (drawn by author)

4.5. Physical Model

Physical fabrication of 4D printed curved-crease active composite structures experimented with three models in the scope of this research. These models fabricated with different principles in terms of printing pattern, printing order, and the number of layers.

A bi-layer structure proposed to mimic the self-folding structure by regulating the material's transition temperature. Together with constrain and active layers, printed active composites (PAC) generated.

4.6. Experiment Setup

A form of curved-crease model is selected to generate the 4D printing process. The form composed of two curved-creases and three surfaces. This form of curved-crease geometry experimented in three different scenarios.

In the first case, printing operations generated as four layers of the active composite structure. Three layers of active material printed firstly and one layer of constraining material printed above them. In this first case printing pattern of the composite generated according to the lines of planar quadrilaterals (PQ) of the model.

In the second case, printing operations of the active composite structure generated as four layers. One layer of constraining material printed firstly and three layers of active material printed above it. In this second case, different that first case, constrain layer printed firstly and printed pattern of the composite generated according to the bending direction of the curved-crease form. Unlike the first case, in this case, only the center surface of the form printed with active material. The bending movement of the active surface expected to guide the side surfaces by following the creases.

In the third case, the printing operation of the active composite structure generated as five layers. Two layers of active material printed firstly for side surfaces, one layer of constraining material printed above them, and two layers of active material printed for the center surface. In this third case printed pattern of the composite also generated according to the bending directions. Unlike first and second cases, in this case, center and side surfaces printed with the active material to generated desired curved-crease form. While the center surface expected to bend one direction, side surfaces expected to bend other direction and the constraining layer at the middle expected to keep active surfaces together to form intended curved-crease geometry.

Three cases of different printing experiment setup to prove the potentials of 4D printed active composite structures. Printing pattern, orders, and adjustments of the cases presented in the following figures and tables.

4.6.1. Physical Case Curved-Crease Sample 1

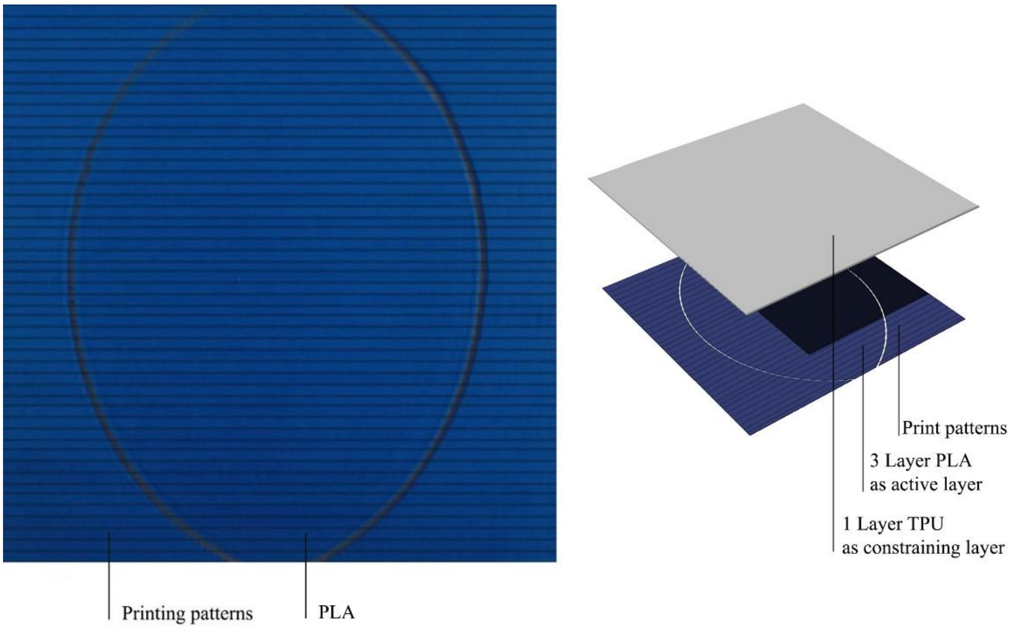


Figure 4.3. Printing pattern and the order of the 10x10cm curved-crease active composite structure (drawn by author)

Figure 4.4. Printing order of active composite structure (drawn by author)

Table 4.1. Printing adjustments (drawn by author)

PLA orientation	0°
Printing speed of PLA	5000 mm/min
PLA filament flow	105%
Printing speed of TPU	2000 mm/min
TPU filament flow	100%
Cooling fan (TPU)	Off

4.6.2. Physical Case Curved-Crease Sample 2

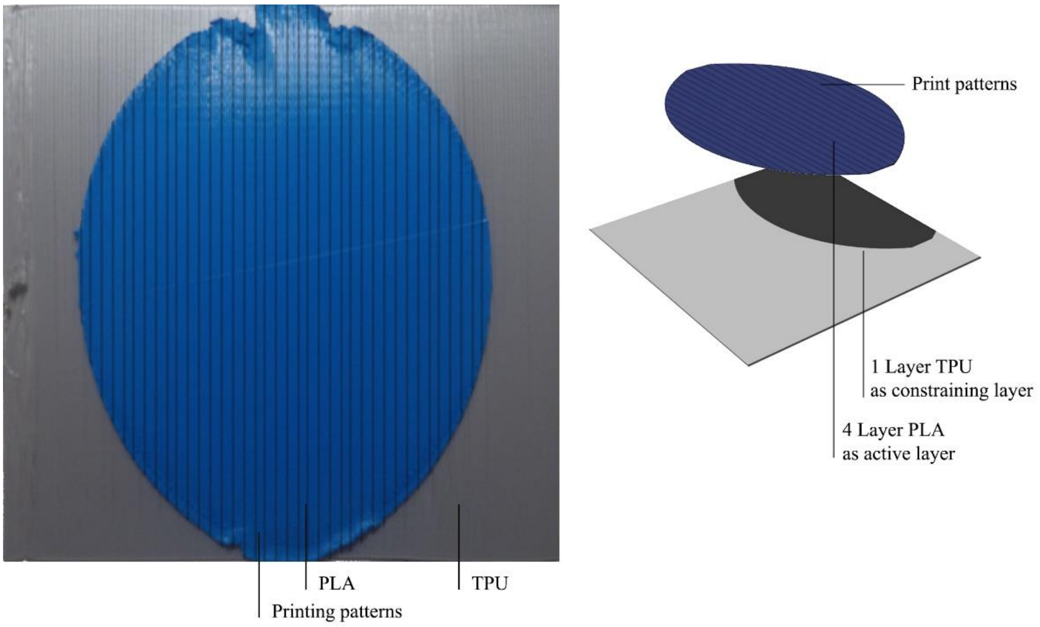


Figure 4.5. Printing pattern and the order of the 10x10cm curved-crease active composite structure (drawn by author)

Figure 4.6. Printing order of active composite structure (drawn by author)

Table 4.2. Printing adjustments (drawn by author)

PLA orientation	90°
Printing speed of PLA	5000 mm/min
PLA filament flow	105%
Printing speed of TPU	2000 mm/min
TPU filament flow	105%
Cooling fan (TPU)	Off

4.6.3. Physical Case Curved-Crease Sample 3

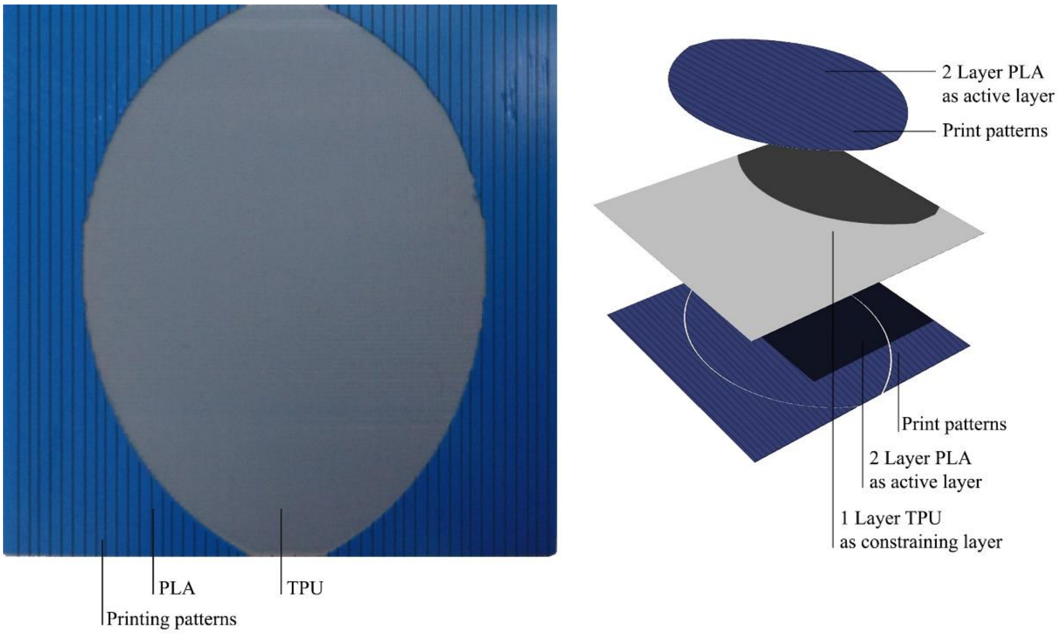


Figure 4.7. Printing pattern and the order of the 10x10cm curved-crease active composite structure (drawn by author)

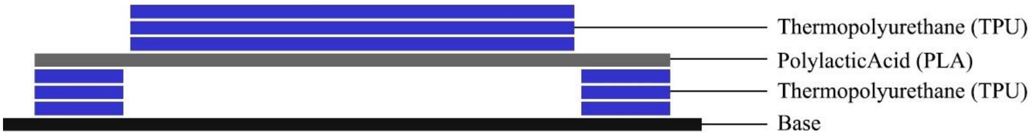


Figure 4.8. Printing order of active composite structure (drawn by author)

Table 4.3. Printing adjustments (drawn by author)

PLA orientation	90°
Printing speed of PLA	5000 mm/min
PLA filament flow	105%
Printing speed of TPU	2000 mm/min
TPU filament flow	100%
Cooling fan (TPU)	Off

4.7. Material

Bi-layer structure of the printed active composite (PAC) structures generated with two different materials. As constraining layers filament form of Thermo Polyurethane (TPU), and as active layers filament form of Polylactic Acid (PLA) is used.

Table 4.4. Mechanical and Thermal Properties of PLA

Mechanical Properties	Thermal Properties
Young’s Modulus: 1879 ± 109 Mpa	Glass Transition Temperature:61˚C
Tensile Strength: 28.1 ± 1.3 Mpa	Vicat Softening Temperature:62˚C
Bending Strength: 48.0 ± 1.9 Mpa	Vicat Softening Temperature:62˚C
Charpy Impact Strength: 12.2 ± 1.03 kJ/m2	

Table 4.5. Mechanical and Thermal Properties of TPU

Mechanical Properties	Thermal Properties
100% Modulus: 9.4 ± 0.3 Mpa	Melting Temperature:210˚C
Tensile Strength: 29 ± 2.8 Mpa	
Elongation at Break: 330.1 ± 14.9 Mpa	
Shore Hardness: 95A	

4.8. Fabrication

A desktop Fused Deposition Modeling (FDM) printer used to generate a 4D printing process. Desktop FDM printers are readily available for all researchers and provide great possibilities. In this research, because of its high-quality printing capabilities, the Original PrusaI3 MK3S Printer used to fabricate curved-crease printed active composite structures.

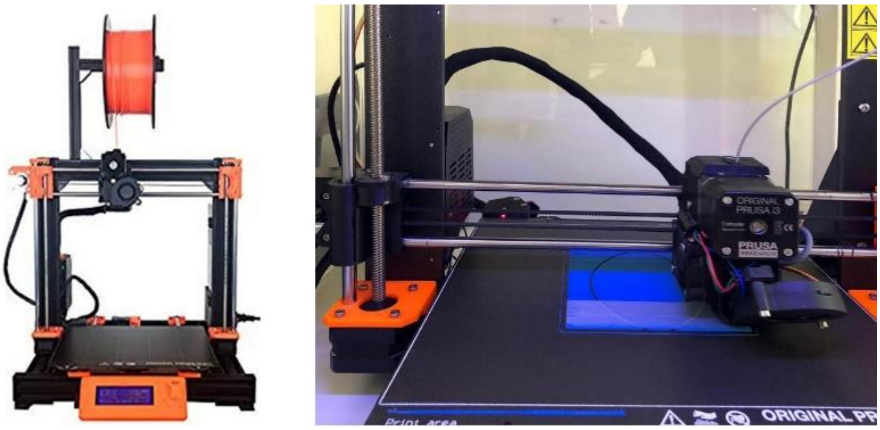


Figure 4.9. Original PrusaI3 MK3S Printer (taken by author)

4.9. Processing

Processing of the printed structures to their programmed geometries by self-transformation, heat in this case used to trigger programmed surface manipulation. Printed active composites exposed to controlled heat treatment between the temperatures of glass transition temperature (Tg) and melting temperature (Tm) to control transitions in the plastic stage of the polymer-based material.

4.9.1. Environment

After the fabrication process, in order to trigger the active material, a heat treatment process, in this case, is necessary to generate shape transformation by heating printed PLA above its transition temperature (Tg) and below melting temperature (Tm) to mold temporarily. Therefore, to obtain a desired programmed transformation, it is essential to control environmental parameters. Controlling the heat in an atmospheric environment is challenging to obtain for the evenly distributed heated environment. A water tank system, therefore, assembled with a heater and heat controller. Here, the working logic of the system is quite simple and effective, heater (on the back surface of the tank) heat the water in the tank, and heat controller (on the front surface of the tank) continuously measures the heat of the water in the tank. A constant relation between the heater and the heat controller keeps the water's intended degree.

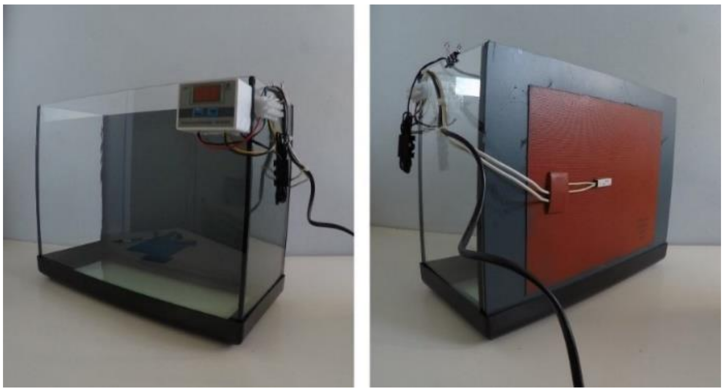


Figure 4.10. A water tank system with a heater and heat controller (taken by author)

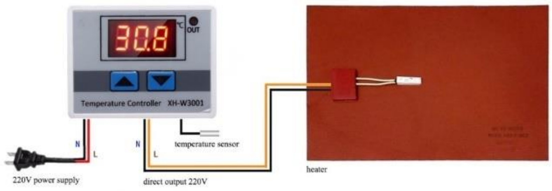


Figure 4.11. Connection diagram of heater and temperature controller (drawn by author)

CHAPTER 5

RESULTS AND DISCUSSION

5.1. Digital Model

After physical mockups, digital production of curved-crease developable surface geometries covers an essential part of the entire 4D printing process. Production before printed active composite structures, digital processes underlay the printing principles of curved-crease forms. Produced digital forms contributed to its potentials and several drawbacks that resulted in noticeable consideration in the process of 4D printing. Information obtained from the digital modeling process created fundamental printing principles. Therefore, examining the digital process of 4D printing contributed valuable information for this research and future studies.

5.1.1. Potentials

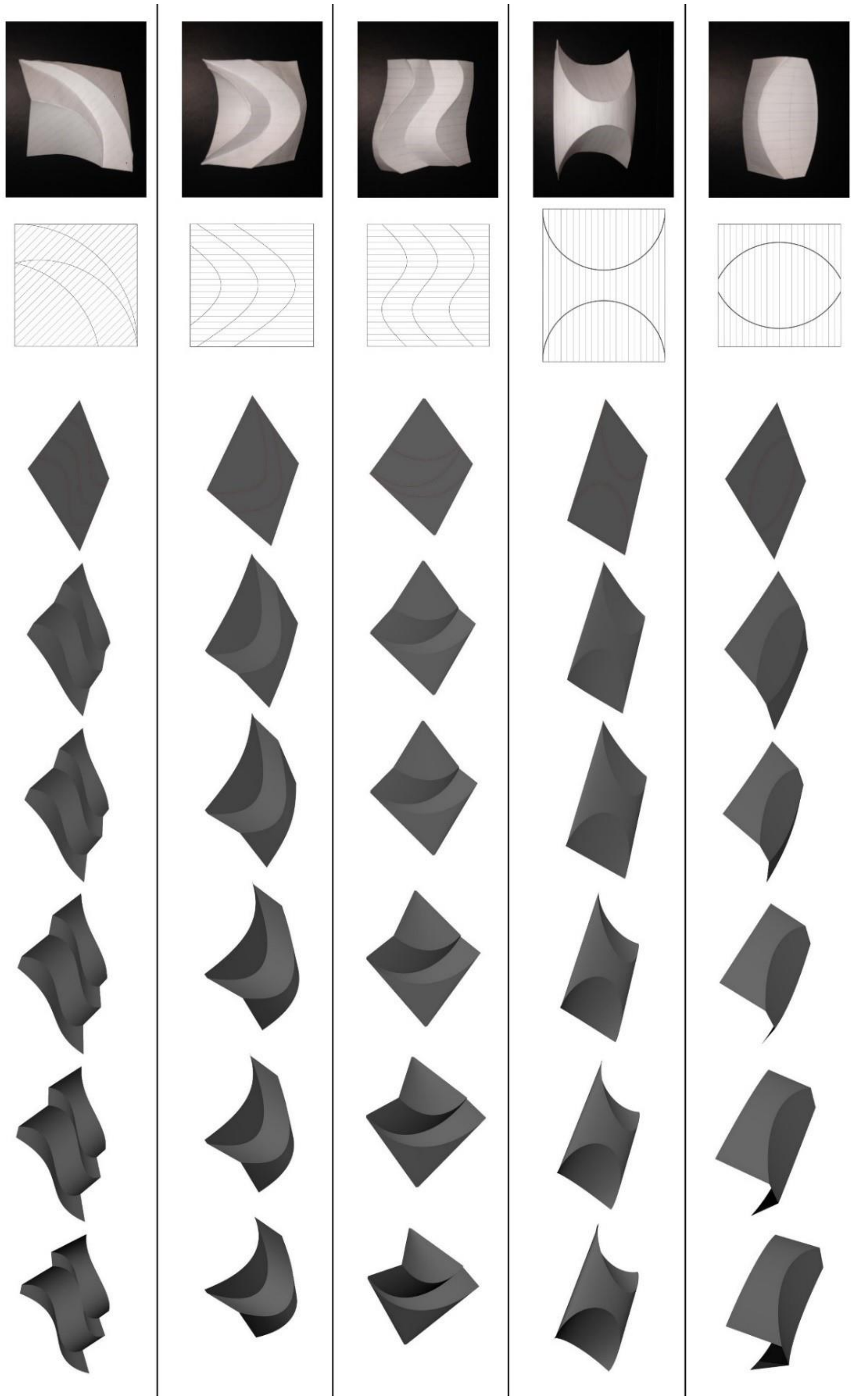
Production of forms in a digital environment revealed the potentials of the curved-crease developable surface geometries. Simulation of paths of the crease, surfaces folded by these creases, also applied force to transform the curved-crease surface geometry draw out the underlying self-transformation phenomena. Observing the potential movement of the forms generated the printing patterns of physical production. According to the bending directions of surfaces, physical printing patterns generated. Generation the digital production processes of the curved-crease forms in this research also contributed as an alternative digital process for 4D printing that has already no standard software and digital process solutions. Therefore, the potentials of the digital modeling process in this research exhibited an alternative production process with existing solutions.

5.1.2. Drawbacks

It has the potentials to generate the forms of curved-crease developable surface geometries in a digital environment; however, production in the digital environment revealed several drawbacks that are essential factors to be considered before physical production. One of the main drawbacks of digital production faced in this research is that in the digital environment, surfaces had no material information, so that movement of the curved-crease forms did not represent physical conditions. Due to the lack of material information in digital forms, shape transforming simulations did not refer to the physical printed active composite structure. Another significant drawback of the digital model is thickness. Digital production of curved-crease surface geometries has no material and layer thickness information, therefore folding is not limited. Printing of active composite structure samples fabricated in this research composed of different material configurations with variable layer numbers. Therefore, simulating these different fabrication scenarios with the same digital surface that has zero thickness could not reflect the physical conditions. External stimulus is another factor that did not simulate in the digital environment. Because material information and printing principles are directly related to the reaction of active composite structure towards external stimuli, folding values according to the external stimuli did not represent the physical conditions. Folding values of the curved-crease surface geometries restricted only by the digital force applied in the digital environment.

Therefore, because simulating a digital model of the entire 4D printing process needs a specialized software solution that is not available yet, the entire digital process of 4D printing could not be generated in this research. Simulation of the curved-crease forms and force to transform flat curved-crease developable surface configurations remained limited with basic surface geometries without material and external force information.

Figure 5.1. Digital cases of curved-crease developable surface geometries (drawn by author)



5.2. Physical Model

Physical models of the 4D printed active composite structures fabricated with different principles. Before the production of curved-crease samples, in order to observe the potentials of printed active composites, primary rectangular test samples fabricated with different dimensions to measure the effect of the scale. In this respect, 1x10 cm, 2x5 cm, and 5x5 cm test samples printed with three layers of active and one layer of constraining material. Shape transformation reflexes of these test samples processed in different temperatures. The information obtained from these test samples was essential to understand the movement principles of the printed active composite structures before the actual curved-crease samples.

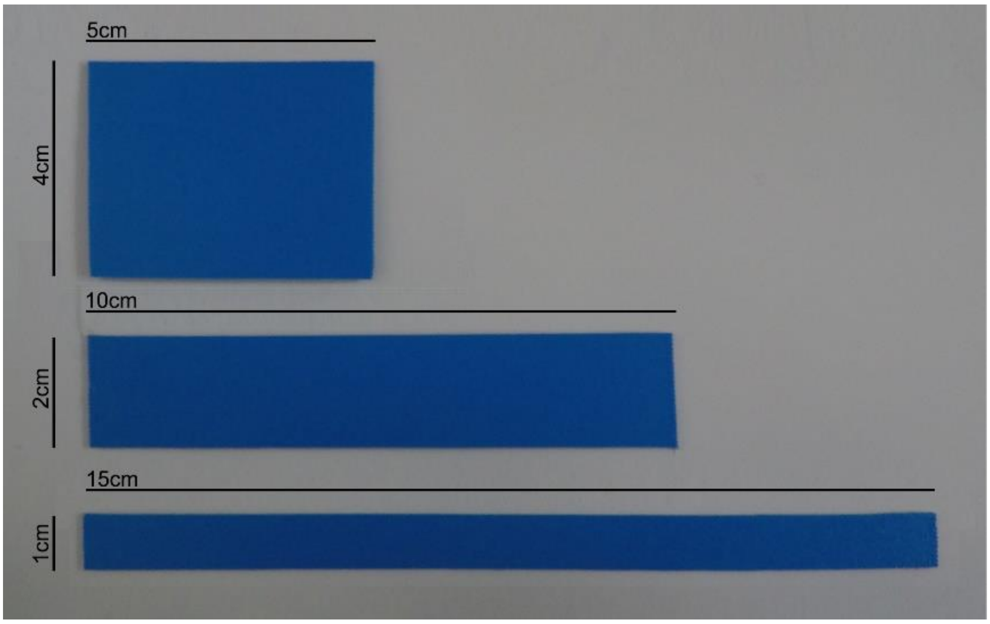


Figure 5.2. Printed active composite test samples (taken by author)

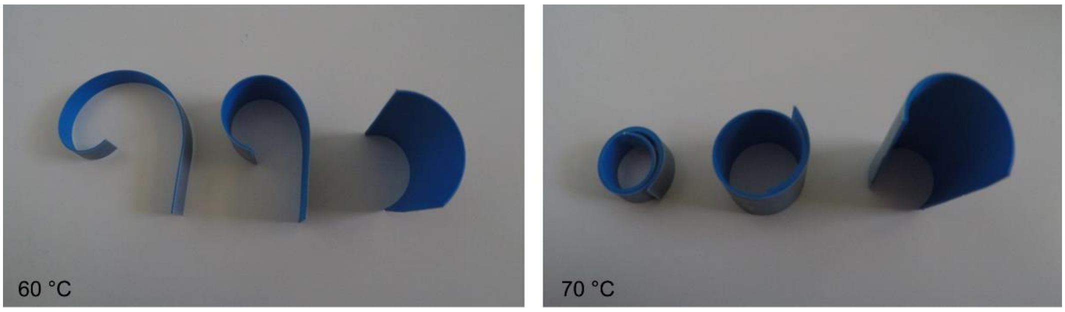


Figure 5.3. Self-transformation of test samples at different temperatures (taken by author)

The shape transformation process of physical curved-crease active composite structures fabricated in the scope of this research examined in terms of several feedbacks over the material, layer, heat, and form-finding. Processing of the printed active composite structures resulted in various shape-changing reflexes at different temperatures, depending on their printing patterns, printing order, and the number of layers. Therefore, it is essential to observe the responsiveness of the active composite structures in terms of practical factors.

5.2.1. Material

The filament form of polymer-based materials used to fabricate curved-crease active composite structures. As active composite structures, Polylactic Acid (PLA) as active material and Thermo Polyurethane (TPU) as constraining material, responded promising self-transformation reflexes. According to the printing principles, fabricated samples exhibited different self-transformation reflexes. Printing configurations with these two materials performed different results. Interaction between active and constrain materials in sample 2 resulted in the constrain layer as surface forms by the guidance of the active surface. In sample 3, on the other hand, constrain material used as a binder layer between active layers. These two samples with different printing principles demonstrated the potentials of Polylactic Acid (PLA) and Thermo Polyurethane (TPU) filaments in the physical process of proofed the potentials to be used as 4D printing.

5.2.2. Layer

Fabricated samples of curved-crease printed active composite structures resulted that form-finding reflexes of 4D printing are directly related to the number of layers printed on top of each other. Processed active composite structures resulted in the more layers printed to fabricate, the more resistance they react under the effect of heat. Curved-crease test sample 2 fabricated with three active layers started to react at 70 degrees, while curved-crease test sample 3 fabricated with two active layers started to react at 60 degrees. Therefore, it is proved the importance of considering layer numbers in a 4D printing operation to generate the desired self-transformation process.

5.2.3. Heat

Heat is the external stimuli that expose the mechanical changes of active composite structures fabricated in the scope of this research. As an external factor, changes in the temperature provided in a water tank with a heater and a temperature controller. Changes in the temperature resulted in different responses in each fabricated sample. Because of the printing principles of the test samples, the heat reaction of each sample demonstrated different reflexes at different temperatures. Active material used to fabricate printed composites that have its thermal properties of glass transition temperature (61˚C); however, not in every case, this glass transition temperature limit triggered shape transformation. According to the number of layers, the glass transition temperature of the printed active composites resulted in different temperatures. Therefore, although thermal properties of the materials used to fabricate 4D printed structures, printing principles of active structures such as the number of layers and the scale are can be the main decisive factors.

5.3. Shape-Transformation Processes of the Physical Samples

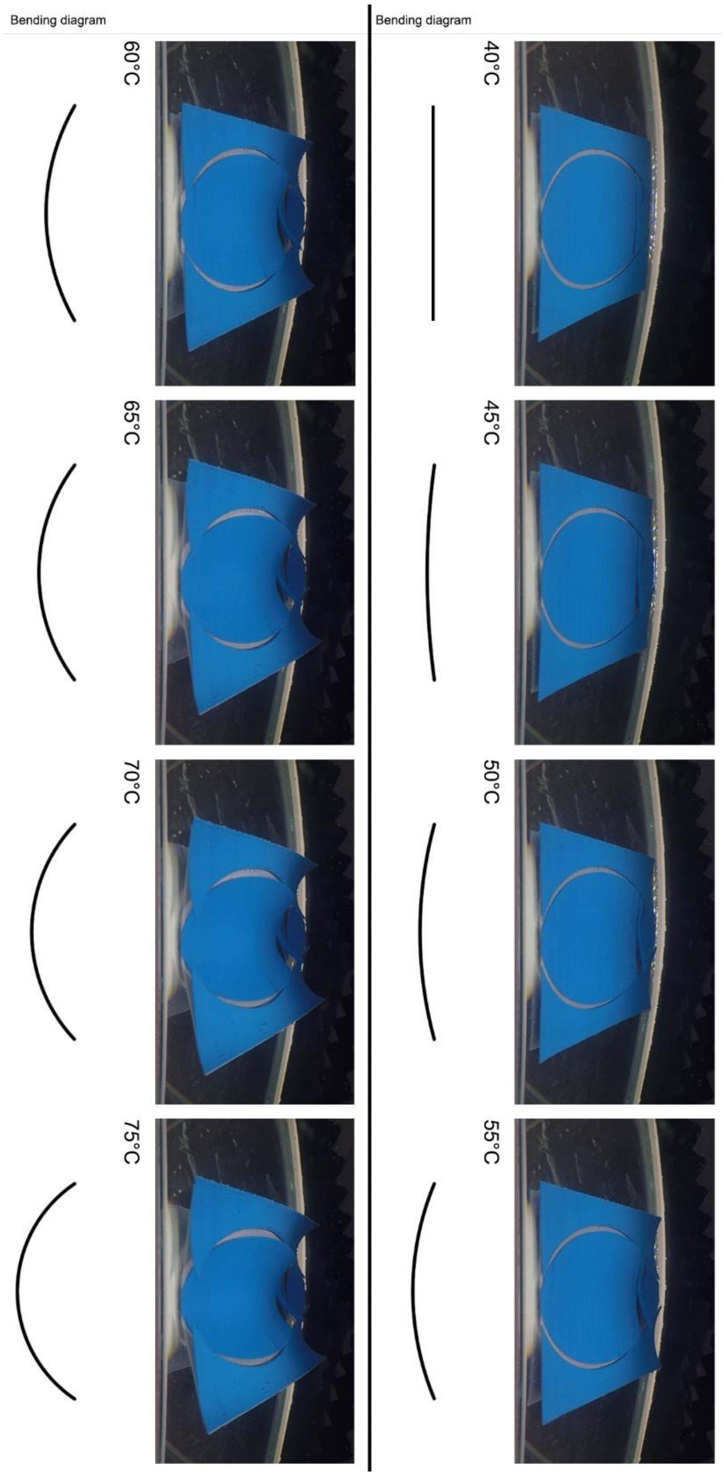


Figure 5.4. Shape-transformation process of the sample 1 (drawn by author)

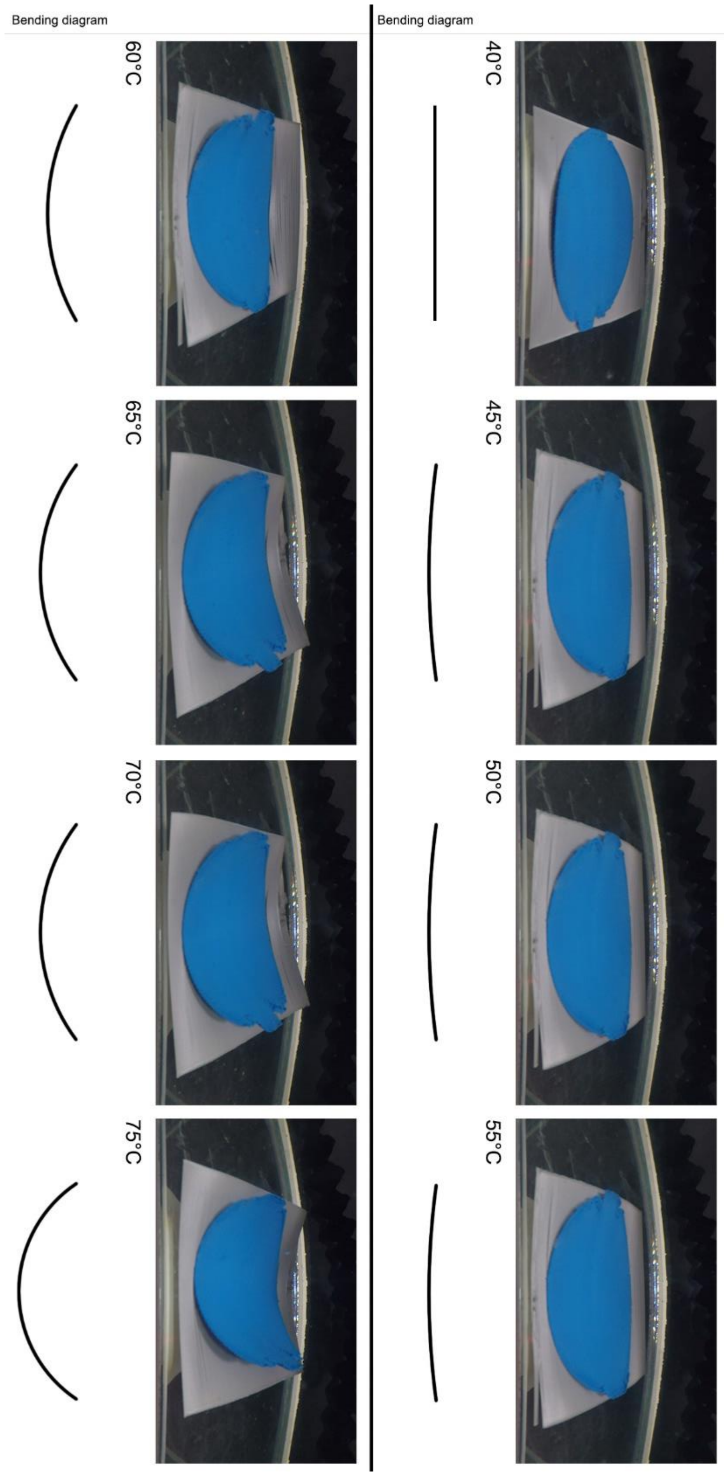


Figure 5.5. Shape-transformation process of the sample 2 *(drawn by author)*

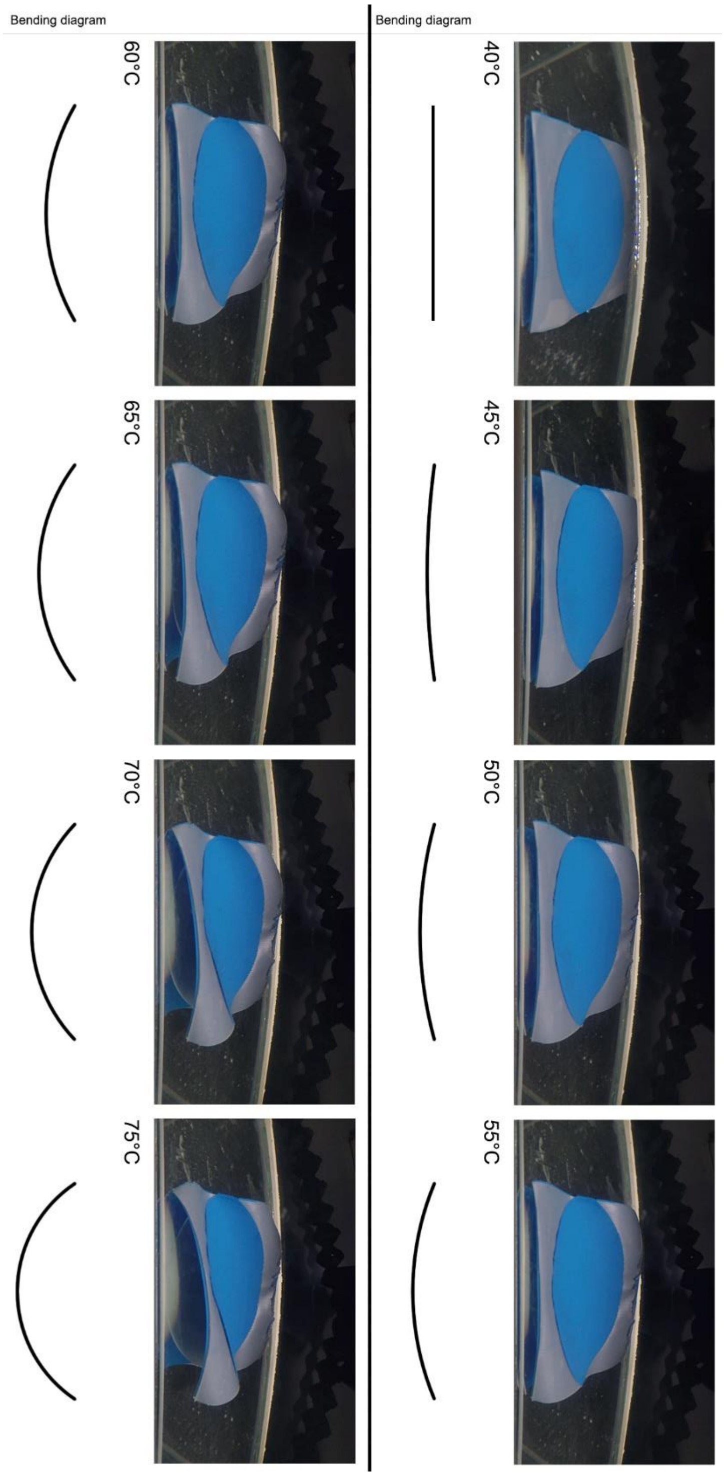


Figure 5.6. Shape-transformation process of the sample 1 (drawn by author)

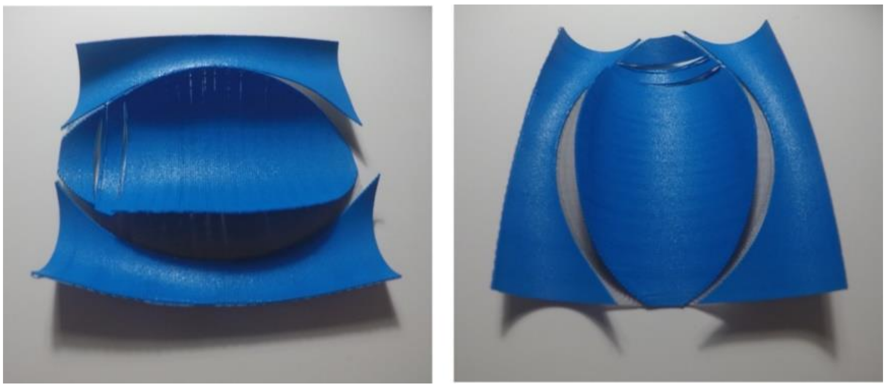


Figure 5.7. Transformed form of physical case curved-crease sample 1 (taken by author)

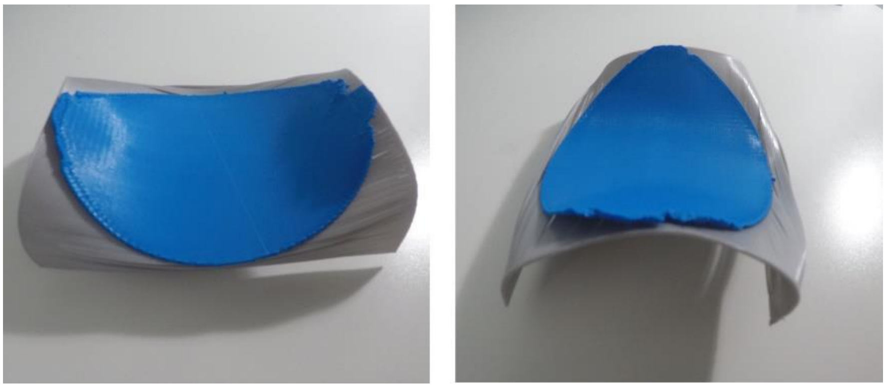


Figure 5.8. Transformed form of physical case curved-crease sample 2 (taken by author)

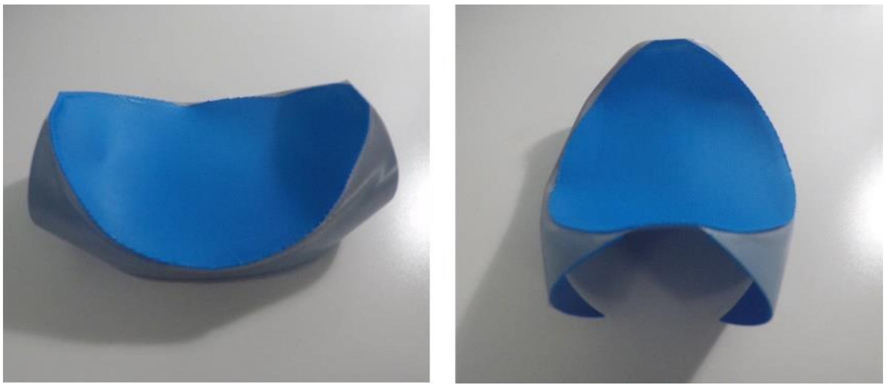


Figure 5.9. Transformed form of physical case curved-crease sample 3 (taken by author)

5.4. Diversity of Forms for a Given Performance as Form and Formwork

Shape changing process of 4D printed active composite, curved-crease developable surface structures fabricated in the scope of this research, performed a diversity of form instances. Processing the shape-changing phenomena of 4D printed curved-crease surface geometries in a predefined environment resulted in a programmable self-transformation motion until they reach their final form. The transformation process of the samples tested under the effect of heat that the temperature changes triggered the molecular changes of the active composites. Heating processes of printed active composite samples in the research performed different instances by the different temperatures according to their printing principles. They preserved their transformed form when the temperature cools down to the glass transition temperature (Tg) of the active material. Therefore, it is proved that it is possible to control the performance of the active printed composite structure by the environmental conditions. Controlling of the transformation process, it is also possible to perform each instance of the same structure as different diversities.

Performances of 4D printed active composite structures by the self-folding process can be utilized for various operations in a wide range of application fields where self-transformation can be proposed for different motion processes in dynamic structures. In this case, utilizing 4D printed active composite structures evaluated for architectural purposes as formwork and form as it is. According to the given performance parameter, 4D printed active composite structures are promising form finders that perform complex generative and computational surfaces by the geometric possibilities of the curved-crease folding technique. Therefore, it is essential to analyze the performance of these printed active structures in terms of architectural concerns of formwork and form.

Utilizing the diverse possibilities of 4D printed active composite structures is an effective way to construct a dynamic surface configuration. In order to create a dynamic surface form without any additional mechanical requirements, 4D printed active structures perform a dynamic shape-transformation process according to the given environmental parameters. A dynamic shape-transformation process with 4D printing also eliminates the energy consumption for the required movement that material itself performs the desired movement by the molecular mechanism of shape memory effect. 4D printed active composite structures eliminate not only additional mechanical requirements for a dynamic movement and the energy consumption but also curved-crease surface structures offer a wide range of geometrical diversities for dynamic shape-transformation processes. Therefore, it is essential to examine the possibilities of 4D printing as a form-finding fabrication technique in architectural concerns.

Performance of 4D printed active composite structures demonstrated complex generative and computational curved-crease surface geometries. Form performance of the printed active structures examined in a predefined environment where containable temperature implemented to the printed active composites. The self-transformation processes of printed active composite structures under the effect of heat treatment resulted in a wide range of diversities in the limits of the curved-crease surface. Exposing the 4D printed active composite structures to heat experimented with the temperatures between above glass transition temperature (Tg) and under melting temperature (Tm). As the temperature increase, the folding value of the printed active composite also demonstrated a more folding instance until it reaches its final value. Therefore, examining 4D printing manufacturing to fabricate form promising performance as dynamic surface configurations.

As a promising dynamic form of complex generative and computational curved-crease surface geometries, 4D printing of curved-crease active composite structures experimented in this research performing promising potentials as formwork to fabricate liquid building composites. Because of the possible diversities of a 4D printed curved-crease active composite that are performing various surface instances and eliminates the fabrication of different formwork surfaces for different instances of the same form. Therefore, utilizing 4D printing manufacturing technology as formwork to fabricate complex generative and computational surface geometries with liquid building composites is an essential performance of the printed active composite structures in this research.

5.5. Potentials as Formworks

4D printed active composite curved-crease surface structures promising undeniable potentials for complex generative and computational surface geometries. Because of the fundamental fabrication understanding, complex surface geometries by liquid composites generally composed of complex fabrication processes with single used materials. Potentials of the 4D printed active composite structures examined in this research, on the other hand, provided not only geometrical diversities as form but also has several advantages in terms of material, fabrication, and design approach. Therefore, examining these potentials provides a better perspective to compare this alternative fabrication process with the existing conventional techniques.

Potentials as form

Form performance of the 4D printed curved-crease active composite developable surface structures as formwork is a promising alternative solution towards restricted form performances of conventional formwork surface systems. The curved-crease folding is a fascinating technique to create complex surface geometries that also exhibit structural characteristics. In order to create complex 3D surfaces, curved-crease geometries provided developable but contain regions with non-zero principal curvature. Fabricated samples in the scope of this research demonstrated the potentials of a curved-crease active composite structure in terms of form-finding. Curved-crease active composite structures not only provided complex generative and computational surface geometries, but the active transformation process of these structures also provided different form potentials of the same structures in each instance by the shape-changing.

Potentials as materials

Printed active composite structures in this research fabricated with the filament forms of Polylactic Acid (PLA) as active layers and Thermo Polyurethane (TPU) as constraining layers. These polymer-based materials are quite advantages in terms of processing, fabrication, maintenance, and recyclability. Therefore, the potentials of the printed active composite structures in terms of material performance provides a better alternative for complex formwork fabrication towards the most used custom-made inlays produced with blocks of foam or wood. Material performance of the printed active structures as formwork also exhibited maintenance that the structures performed reversible self-transformation processes and proved the potential of these printed active composites as reusable structures. Unlike most preferred custom-made inlays formwork techniques, the performance of the 4D printed active composites demonstrates promising potentials of reusability as both for the same and different instances of the same form.

Potentials as fabrication

Fabrication of 4D printed active composites mainly based on additive manufacturing technology. The potentials of this technology continually changing and advancing. Fabrication processes with this technology degrading simpler operations, complex geometries with additive manufacturing; on the other hand, still challenge with some problems. Generating complex computational geometries from a flat composite structure of curved-crease geometries performing undeniable potentials. Because of the developability characteristic of curved-crease surface geometries that complex geometric forms can be generated form a flat composite structure. Therefore, complex fabrication processes of generative and computational curved-crease geometric forms can be degraded as a flat configuration of printed active composite structures.

Potentials as design

Potentials of 4D printed curved-crease active composite structures as formwork represented several advantages as form, material, and fabrication. In addition to these advantages, utilizing curved-crease developable surface geometries as a design idea also represent the design approaches based on the performance of a surface and its ability to form a geometry without any distortion. Based on this "bottom-up" design approach, the understanding of surface geometry generated within the capacity of developable surface geometries. Therefore, any complexities performed with curved-crease folding technique can be described and fabricated.

5.6. Maintenance of Fabricated Models

Curved-crease printed active composite structures fabricated with polymer-based materials performed regenerative shape transformation processes. By exposing heat between transition temperature and melting temperature of the active material, printed active composites has been subjected to several shape-changing processes. Because of the material advances, 4D printed active composite structures demonstrated advanced structural characteristics. Unlike conventional surface fabrication techniques with classic material principles, curved-crease models performed a reversible shape transformation process that provides multiple utilization of the same structure.

Printed active composite models fabricated in the scope of this research demonstrated promising shape-changing processes and proved the reusability of the printed active composite structures. Because of material properties and printing principles, on the other hand, several drawbacks also experienced during the shape transformation processes that are important to consider for further researches.

One of the main drawbacks experienced in physical cases of 4D printed curved-crease is adhesion between active and constrain layers. Because of the mechanical and thermal differences of these materials, the adhesion of active and constrain materials could not exhibit enough strength to hold the composite structures during the shape-changing process — especially joints at endpoints where initial splits observed first. However, not only the mechanical and thermal differences of the materials but printing patters also affected the splitting between active and constrain layers. Because bending direction is directly related to the printing patterns of the active composites, contradictive bending movements between active and constrain layers of curved-crease printed active composite structures also forced the adhesion of the layers to split. Therefore, adhesion problems in the printed physical models emerged mainly emerged because of mechanical and thermal differences and contradictive bending movements of the active and constrain layers. In three cases, adhesion of the different layers observed with different forms, especially case1 and case2, this problem distinguished more than case3.

Another main drawback experienced in physical cases of 4D printed curved-crease is breaking of the surfaces by the printing patterns. The durability of the curved-crease surfaces directly related to the printing principles of active composites; therefore, it is essential to print consistent surface structures in terms of its scale and thickness. The shape transformation process of 4D printed curved-crease active composite structures provided by the structures' scale, the thickness of active material, and the intensity of external stimuli. Therefore, dissonances between these parameters force to break active surfaces by the printing patters. In the physical cases of 4D printed curved-crease active composites in the scope of this research, surface breaks mainly experienced in case1 printed with two layers of active materials.

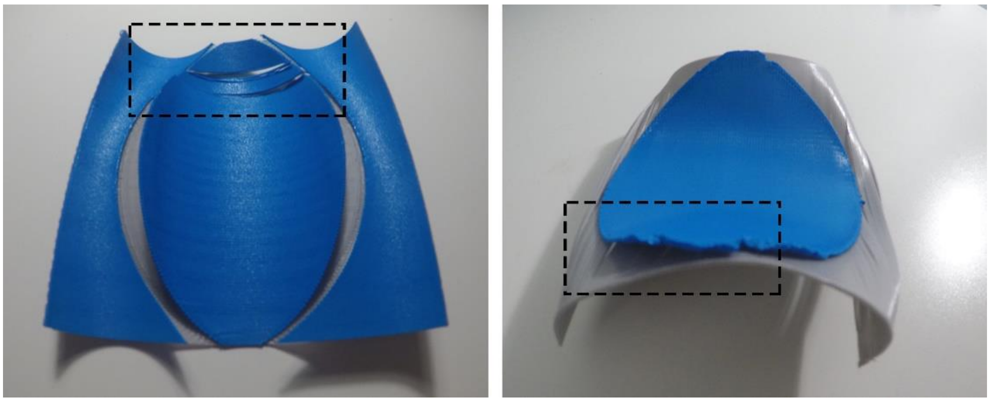


Figure 5.10. breaking and adhesion problems of physical cases 1 (left) and 2 (right) (taken by author)

5.7. Fabrication and Simulation Relationship

Analyzing the relationship between fabricated and simulated self-transformation of curved-crease printed active composites is a critical process to pave the way for further studies. In order to create an exact information flow between digital design data and physical prototype, it is essential to describe the material and geometrical information in the digital environment. Therefore, differences between digital and physical shape transformation in this research contribute to the 4D printing fabrication process that provides material information to calibrate digital simulation processes.

Because digital simulation processes of the curved-crease folding developable surface have no material information, folding values of a digital prototype have no material resistance. Therefore, folding instances of digital processes demonstrate only the folding limits of a developable surface. With the fabrication of physical prototypes, folding information of the printed structure can be defined as parameters for digital processes so that a more consistent relation between digital simulation and physical fabrication can provide.

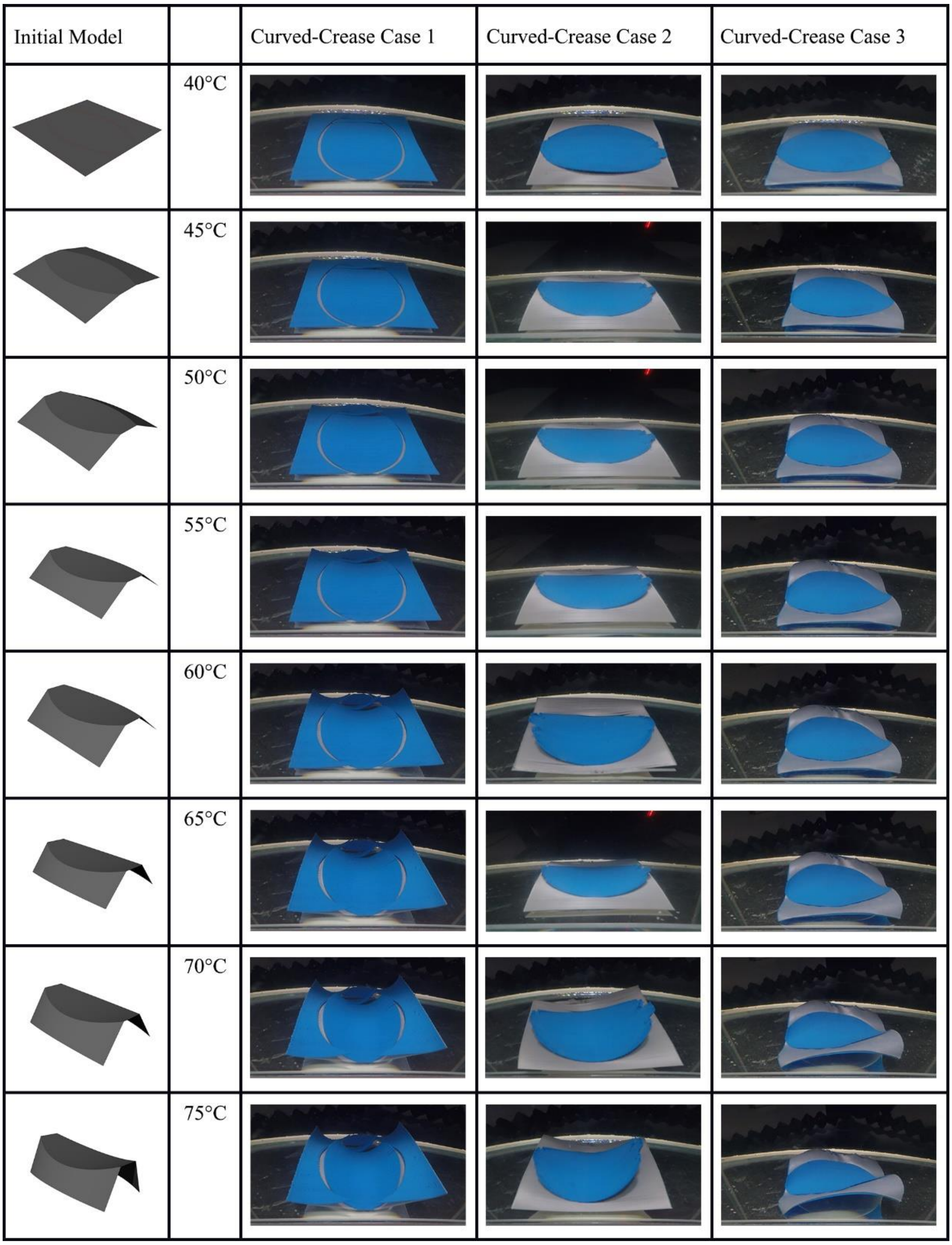


Figure 5.11. Shape-transformation process of the samples comparing with initial model (drawn by author)

Physical cases of 4D printed curved-crease active composites in the scope of this research fabricated with different printing principles in order to achieve desired 3D geometry. Three cases examined in a predefined environment to observe shape-changing processes. Differences between the digital model and physical cases and differences between each physical case provided contrastive examples. In order to obtain desired curved-crease geometry modeled in the digital environment, three physical 4D printed active composite structures with different principles processed to simulate the digital process of the curved-crease model. According to the printing pattern, printing order, and the number of layers, physical cases of curved-crease models demonstrated different shape-changing reflexes. Shape transformation reflexes of these three physical models examined comparatively in figure 5.11 to better understand the fundamental bending principles of 4D printed curved-crease active composite structures.

5.8. Proof of the Concept

Fabrication of 4D printed curved-crease active composite surface structures in the scope of this research generated with digital and physical processes. The purpose of the study is to prove the concept of 4D printing as an alternative fabrication technique for complex and generative forms and formworks. By the digital and physical experiments, the ability to transform its surface, different instances of the same printed active composite structures also aimed to be proofed to fabricate various surface configurations of the same formwork and the form as it is. In this respect, various digital curved-crease modeling generated in the digital environment and to proof the potentials of these digital surfaces several physical experiments conducted with different printing principles.

Digital modeling of curved-crease surface structures produced in the research resulted various surface configurations. The digital process of the 4D printing proved the surface potentials of the curved-crease folding technique. According to the digital curved-crease surface structures, the setup of an experiment generated in order to fabricate 4D printed active composite structures. Before curved-crease cases, test experiments printed with various scales, as seen in figure 5.2. That proved the potential self-transformation of printed active composite structures at different temperatures, as seen in figure 5.3. In this respect, 4D printing of curved-crease samples generated with three different printing principles. Fabricated samples exhibited different self-transformation processes under the effect of heat where the samples exposed to different temperatures resulted various surface instances, as seen in figures 5.4., 5.5., and 5.6. That preserved when the temperature cools down. Therefore, various instances of the same curved-crease printed active composite structure can be utilized to fabricate different surface configurations as formwork and form as it is.

Self-transformation phenomena of 4D printing generated in the scope of this research proved the potentials of curved-crease printed active composite surface structures as an alternative manufacturing technique for complex generative and computational surface structures. Utilizing the transformation process by the instances of the 4D printed active composites also providing remarkable surface alternatives that could be a promising fabrication technique for future researches.

CHAPTER 6

CONCLUSION

The intention of this research started with the idea of contributing 4D print manufacturing technology as an alternative fabrication technique for generative and computational structures that can be utilized as formwork and form as it is in both single and mass customization. In addition to that, how these structures utilized in architectural applications and the understanding of how to evaluate such utilization approached as an interdisciplinary discipline where such various fields as, digital design, digital fabrication, and material science are intersecting, thus leading us to a tangible and meaningful integration.

Accordingly, the hypothesis that "4D printing manufacturing technology can be utilized to fabricate feasible complex generative and computational structures that can be used for formwork and form as it is in both single and mass-customized applications" is emerged. By deriving from the proposed research questions, the frame of the literature, and preliminary researches of the author, the study is developed upon fabrication of formwork, digital fabrication possibilities of additive manufacturing, and unique utilization provided by 4D printing technology. Consequently, the main focus of the study is to fabricate complex generative and computational formworks for single and mass customization. In that sense, the 4D printing technique conceived as an alternative fabrication technology, whereby printed structures have the capacity to fabricate both responsive formworks and form as it is with the same printed structure. In addition to that, because of the potentials of self-folding printed active composite structures that can transform their form depending on predefined environmental conditions, it is possible to utilize different instances of the same structure that can fabricate various surface configurations.

Together with comprehensive research on digital fabrication technologies, a physical design problem also aimed. By the context of digital fabrication technology, the design problem of a 4D printing process and how these processes operated is critical to generate an alternative fabrication technique for generative and computational responsive structures as formwork and form as it is. An appropriate design and fabrication process build by utilizing particular types of design and fabrication exercises. The process of the experiment involves several digital and physical practices.

The digital process of the experiment starts with form-finding of the intended 4D print structure, where a sophisticated form derived from a flat configuration. A developable form, in other words, generated from a flat structure. In order to create a sophisticated developable form, a curved-crease technique, a variant form of origami, used. Curved creasing is a combined technique of fold and bend; the surface here consists of curved creases and soft surface patches, which allowed to create a complex generative form. After that, modeling and simulation of the curved-crease structure generated by using generative algorithms, using Grasshopper as graphical algorithm editor of Rhino's modeling tools and Kangaroo as a Live Physics engine component that enabled to simulate curved patterns in the parametric design environment. The physical processes of the experiment, on the other hand, involves more concerns such as scale, material, and printer. In order to generate a 4D printing fabrication experiment, within available opportunities, a feasible physical process operated with readily available desktop FDM printer and off-the-shelf and available thermoplastic filaments used.

Overview of the research suggests 4D printing as an alternative manufacturing technique for single and mass customization with the ability to fabricate responsive printed active composite structures that can be utilized as formwork and form as it is, for complex generative and computational forms. It is provided with a 4D printing fabrication process, including digital and physical practice. Therefore, the results confirm this study's initial hypothesis to utilize the potentials of 4D printing as an alternative formwork fabrication technique. It is one of the most promising fabrication techniques that researches and practices on 4D printing may not be realized for architectural scale applications soon. Findings for future research, on the other hand, are promising and encouraging for the fabrication of self-responsive structures.

Future Works and Application Areas

4D printing indicating to the future of science and education in which it is possible to use physical and tangibly dynamic structures to understand mathematically, biologically, chemically, physically, and other dynamic phenomena. Likewise, in order to explore new material properties and behaviors, researchers can also utilize 4D printed self-transforming structures and dynamic models as a testbed.

Similar to the ribosome, 4D printing encodes instructions, actuation, sensing, and assembly capabilities directly into the material itself for future smart and adaptive designs (Tibbits et al., 2014). Therefore, it is possible to be seen 4D printed self-transforming structures across various industries such as; aerospace, automotive, medical devices, wearable products, and construction materials. This technology can also be utilized as a manufacturing technique for non-human constructed space architecture like space antennae or solar arrays, where Printed raw materials transform into extremely large functional structures from small-volume machines. In addition, building materials with varying thicknesses and active surface treatments may soon be able to adapt to fluctuating environments and dynamically mediate moisture control, sound, and temperature.

Products started to become much more resilient and highly adapted to changes in the environment, humidity, temperature, pressure, altitude, or sound included. Unique and highly responsive products will be generated in completely new approaches that materials are enabled to come together, reconfigure, mutate, and reproduce themselves by their ambient energies. Therefore, shipping volume constraints will dramatically be reduced with flat-pack materials activated to full volume and functionality upon delivery. When they fail, not all these programmable products of the future will be thrown away, but in order to meet new demands, they will error-correct and self-repair. Even when they become obsolete, for pure recyclability, they can self-disassemble, breaking down to their essential components to be reconstituted in the future as new products with lifelike capabilities.

4D Printing and programmable active composite structures, therefore, promising exciting opportunities in terms of manufacturing the future of the products. And, additive manufacturing is likely to expand into a range of materials with almost limitless responses to external stimuli.

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