SILK SYNTHESIS: FIBROIN-BASED DIGITAL FABRICATION OF SCREEN WALL SYSTEMS

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Science in Matter Design Computation

by

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ABSTRACT

Silk is a natural fiber produced by the silkworm and other insect species. Humans have cultivated and used silk for thousands of years, primarily in the textile industry. However, over the last decade several novel applications of silk have been discovered, with the potential to revolutionize different technologies such as electronics, printing, optics, sensors, and biomedicine. Currently these applications operate only at the micro-scale with only a few examples exploring the possibilities of expanding the material in a larger context.

This thesis aims to build upon the latest innovative works that have been produced with silk as a biomaterial. The focus of this research is concentrated on the potential architectural applications that silk can offer as a biomaterial. Through a digital bio-fabrication process, a silk-chitosan solution is deposited over custom 3D printed frames to create hybridized bio-composite panels. The panels developed are used to inform the design and development of a parametric screen wall system.

BIOGRAPHICAL SKETCH

Asbiel Samaniego is currently a second-year graduate student in the Department of Architecture, Art, and Planning at Cornell University. In May 2022, he will graduate with a Master of Science in Matter Design Computation. He holds an accredited professional Bachelor of Architecture (B.Arch.) from Kennesaw State University. The same year he graduated he became an official Associate member of the American Institute of Architects (AIA). Since then, he has been involved in numerous networking and professional events.

Throughout his academic career, Asbiel has worked on a diverse range of projects in the field of architecture and design. As an undergraduate his final thesis titled "*The [Hydro-Gen] Cell: A Hydroponic, Regenerative, Modular System for Optimized Vertical Farming*" received multiple awards and recognition from the Department of Architecture. His work was selected by the faculty to represent the university at a domestic and international level. He would go on and present his work at the 2020 Critical MASS Graduate Research Symposium at Charlotte, North Carolina and was included in the 2021 Archiprix International competition.

While pursuing his master's degree at Cornell, Asbiel worked as a Research Assistant in the Rural-Urban Building Innovation Lab (RUBI) directed by Assistant Professor Leslie Lok. While working for RUBI in 2021, he managed to co-author and receive a publication for "*Timber De-Standardized: A Mixed Reality Framework for the Assembly of Irregular Tree Log Structures*". Along with the publication, Asbiel got to present at the 41st Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA). In his final semester he served as a Teaching Assistant for the College of Human Ecology, where he led class discussions on interdisciplinary design and sustainability.

I dedicate this thesis to my family for their constant love and support. This journey would not have been possible had it not been for your words of encouragement and desire to see me succeed in life.

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CHAPTER 1

Introduction

This thesis is structured and presented in the following order: Chapter 1 introduces the motivation behind this work by addressing the current problems that modern building materials have on the environment. It sets the groundwork by suggesting a material-based fabrication approach and the importance it has in resolving our ecological footprint. Chapter 2 discusses the contemporary use of regenerated silk proteins in digital fabrication. Chapter 3 proposes a hybridized bio-fabrication process that combines a biomaterial solution with standardized 3D printing filament to create hybridized bio-composite panels. Chapter 4 concludes by critically analyzing the work produced and suggests the speculative potential for future development.

1.1 Research Motivation

The motivation behind this research is driven by the responsibility we as humans have inherited as the dominant species on earth. If we are to ensure the survival of future generations and the prosperity for every life, we must do everything we can to preserve and restore the natural balance of earth's ecosystems. The passion for innovation and experimentation in design is what inspires the investigations made in this research. In this work a bio-fabrication process is designed, modified, and characterized to test its validity in developing a system for an interior parametric screen wall.

1.1.1 The Biomaterial Revolution

Throughout the course of history, natural materials have always been apart of our daily lives and have helped advance human civilization in many different ways. From sticks and stones to timber and bamboo, natural materials have played an integral role in the way we live today. They have had a positive impact on our health and comfort as many of these biomaterials have been used for our medical treatments, clothing, and for shelter. As human beings began to intellectually develop and become aware of their surroundings, the need to protect themselves against the environment became a priority. The Primitive Hut by Marc-Antoine Laugier (Laugier, 1755) is a conceptual hut that depicts and explores how architecture came to be. The Primitive Hut is described as not being a physical hut, but rather an abstract concept that was created as a result of human response to the natural environment.

The theory provides a moment in human history where at some point we became aware and used the natural materials around us to create shelter. Starting with timber, “pieces of wood raised perpendicularly, give us the idea of columns. The horizontal pieces that are laid upon them, afford us the idea of entablatures.” (Laugier, 1755). Humans began to develop an understanding for construction methods and eventually other material systems. Depending on the region, different civilizations would use the materials available in their immediate surroundings for their structures. African tribes used mud and rammed earth to create their homes, whereas in South Asia, bamboo an abundant natural resource was utilized as the main building material for construction.

In the 19th and 20th centuries the emergence of new materials in the form of steel and concrete became the standard for modern construction. It was during the industrial revolution that the mass production of these materials skyrocketed and began to lay the foundations for modern cities. In today’s practice the most commonly used building materials are concrete, steel, timber, stone, and masonry. Although natural materials are being used in the form of timber and stone, the manufacturing and processing models of their use in construction is highly unsustainable. For instance, with timber products which are considered to be the more sustainable of the building materials has several issues that cause the polluting of environments and ecosystems (Adhikari and Ozarska, 2018) with glue toxins, energy consumption, transportation and waste produced in the form of sawdust. According to the 2020 Global Status Report for Buildings and Construction, “the emissions released by the building construction industry accounts for 38% of the total global energy related CO^2 emissions. In terms of electricity consumption, building operations represent nearly 55% of all global electricity consumption” (United Nations Environment Programme, 2020). It has become evident that our current practices in the field of construction are having a negative impact on the planet. The more we build the more resources are being excavated and the more damage to ecosystems occur.

As the climate-crisis accelerates, architects and designers are facing even higher pressure for coming up with new and novel sustainable design solutions to reduce the carbon footprint. The need for change has led to new models of thinking in terms of how we view architecture and design. Pioneers in the field such as Achim Menges, Neri Oxman, Jenny Sabin, and Skylar Tibbits have already begun to investigate and test new methodologies by taking on an interdisciplinary approach to design. Oxman the founder and director of the Mediated Matter Group at MIT pioneered a relatively new field called Material Ecology, which takes on an interdisciplinary approach by combining several fields of expertise including: material science, computational design, digital fabrication, and biology. This new methodology centers around a philosophy of designing “by, for, and with nature” (Oxman, 2018). The work produced by her team is revolutionary in the sense that material properties can be fined-tune and designed for rigidity, elasticity, color, and transparency.

1.1.2 Towards a New Architecture

A material-based approach beginning at the micro scale, allows for the augmentation and dispersion of biological properties to be strategically placed. With the most recent technological tools at our disposal, these material systems and their properties can be engineered to fulfill specific purposes and functions. Materials of different molecular concentrations can be digitally deposited to fulfill color gradient dispersion, behavioral responses, and structural reinforcement. An example of this can be seen in the *Aguahoja* project by the Mediated Matter Group (Mogas-Soldevila and Oxman, 2015). In this study, chitosan, chemically modified chitin which is commonly found in the shells of crustaceans was combined with an acetic acid solution. The chitosan solutions ranged from 1% to 12% w/v affecting the coloration and stiffness of each mixture. These material properties (Figure 1-1) ultimately became design parameters that the Mediated Matter Group used for the strategic deposition of the overall structure and the color variation that the Aguahoja is commonly known for.

This one example highlights how biology can influence design through a Bottom-Up Approach. With this approach "biological knowledge influences human design. One advantage of this is that the knowledge of biology may influence the design in ways other than the predetermined design problem." (Nkandu and Alibaba, 2018). Through this process we can now imbed intelligence within material systems to achieve certain properties and behaviors. In order for us to create a synergetic bond between the natural and built environments, a biomimetic approach is needed and "requires the development of design methods that take into consideration the modeling of behavior, the constraints of materials and the influence of environmental factors." (Nkandu and Alibaba, 2018).

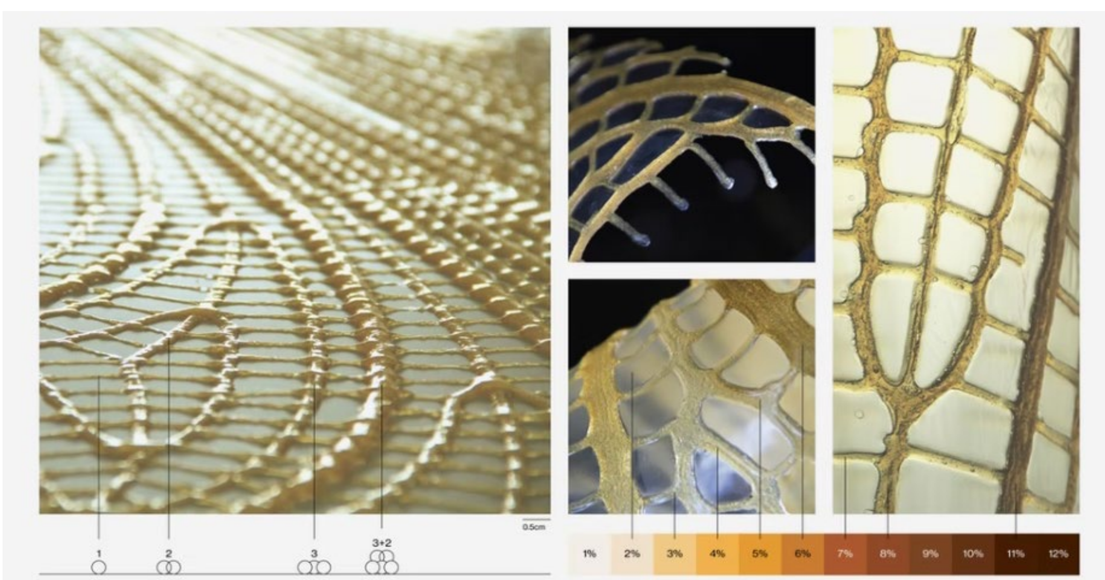

Figure 1-1: Varying degrees of color gradients and their placement along the Aguahoja structural composition. Figure from the Meditated Matter Group (Mogas-Soldevila and Oxman, 2015).

1.2 Intended Contributions

The following sub-chapters bring forth a set of ideas and practices that this research aspires to achieve.

1.2.1 Ethical Silk Cultivation

Since its initial discovery dating back to ancient China, the silk cocoons produced by silkworms have been boiled while the larvae are undergoing their metamorphosis. As a result, the insects die before transforming into moths. Regardless of the extreme cruelty towards the larvae, as of today, this practice continues to be the main form of obtaining silk fibers as the boiling process allows for the continuous silk strand to stay intact. When silkworms are allowed to complete their metamorphosis cycle, they damage the continuous filament of the cocoon as the moth emerges from the cocoon, breaking the filaments. This leads to shorter fibers and a less profitable business model for textile manufacturing companies. In this research, a fundamental component involves the ethical treatment when raising silkworms. The objective is to allow the silkworms to complete their lifecycle as intended and then maximize what's left of the cocoons to create a silk-based solution which is then utilized for digital bio-fabrication processes.

1.2.2 Synthesis: Merging of Biological and Artificial Systems

This thesis explores the design potential between a material system comprised of silk-fibroin and chitosan within a customized 3D printed framework. The core of my research builds upon the relationship between the biological and artificial. More specifically how one can inform the other and vice versa. This project as a collective presents a synthesis of multiple ideas, disciplines, collaborations, and methods of fabrication to create a design process that has potential in architectural applications. The research presents a framework along with its methodologies for the design and production of biomaterial and PLA hybridized bio-composites. The proposed hybridized system can be customized and scaled to aggregate via a modular approach. Thus, expanding the scalability and function of this system.

CHAPTER 2

Background

2.1 Silk: An Ancient Material

Since the age of the dinosaurs, silk has been a part of earths ecology. The ancestral species of today's silk producing insects have been making and refining this material for millions of years. Throughout its evolutionary development it's been primarily used by insects as a means of protection against the elements and as a way to capture prey. As a result, the material has been modified to achieve a wide range of functions that have allowed numerous species to survive.

2.1.1 Biological Origin and Mechanical Properties

Silk, is a natural fiber produced by the silkworm and other insect species. In the case of the silkworm, silk is utilized in the making of its cocoon enclosure, which serves as a protective barrier against predators and the environment. The cocoon is an evolutionary construct that allows the silkworm larvae to undergo its metamorphosis, acting as a defensive shield against temperature, rain, and predators while simultaneously keeping the pupa comfortable in the interior. As a natural polymer composite, the cocoon is made from a continuous silk strand consisting of two parallel fibroin protein strands (fibers) that are bonded by a thin layer of sericin, a glue-like protein. "Fibroin is a natural fibrous protein with a semicrystalline structure, which provides stiffness and strength. Sericin is an amorphous protein polymer, which acts as an adhesive binder to maintain the structural integrity of the fibers and cocoon." (Chen et al., 2012).

The in vivo processing of silk begins with an aqueous solution made in the posterior section of the silkworm's gland. "This solution is extruded through two spinnerets and coated and fastened together with sericin into twin filaments during coagulation." (Zang et al., 2013). Due to the complex physiological processes that take place within the silkworm's glands, silk as a material has developed a wide range of mechanical properties. Along with its good strength "the fibroin fibers are endowed with a combination of toughness, biocompatibility/biodegradability and thermal stability, representing one of the most impressive natural protein fibers, with properties that surpass those of many synthetic and natural fibers." (Koh et al., 2015).

2.1.2 Sericulture: Ethics and Practice

According to legend, silk was first discovered by Chinese Empress His Ling Shi around 27th century BC (The Corticelli Silk Mills, 1930). The dynasties that followed soon developed the art of sericulture, which involved the raising of silkworms and degumming of their cocoons. Today, silk is best known for its beauty and shine making it one of the most sought-after materials in the textile industry. According to a report from the ISC (International Sericultural Commission, 2021), an estimated 91,765 metric tons were produced in 2020. The number suggests that the industry is performing at a high level and generating profit. The truth is that the current production of silk is highly unsustainable and faces several problems "including environmental pollution, low production efficiency, increased labor intensity, significant material waste, and excessive energy consumption." (Yin et al., 2021).

Each year the textile and clothing industry accounts for 10% of the total carbon emissions emitted. A major contributing factor to this is that the production models for the vast majority of textiles are outdated. With silk production, the factories in use are old, overcrowded, have sanitary issues, and require high amounts of energy for basic operating systems. Additionally, there is a high necessity for water as it is needed for the efficient degumming of the cocoons. The current methods used in sericulture are responsible for lots of environmental pollution with "silk yarn production producing a carbon footprint of 6964 kg of CO_2 equivalent (CO_2e) per metric ton, which is 2.58 times that of polyester yarns." (Yin et al., 2021).

Apart from the ecological and environmental damage, another issue that is present in sericulture practice is the treatment of the silkworms. When a silkworm is ready to transform into a moth it spins a continuous silk fiber to create a cocoon. In order to maximize profits, cocoons are boiled while the silkworm pupa undergoes its metamorphosis, killing the insect before it reaches the final stage of its lifecycle. This is done so that during the degumming process the 1 km strand remains intact. Under normal circumstances when the pupa successfully transforms into a moth it secretes a brownish fluid that allows it to break free from the cocoon, damaging and staining the continuous filament.

The cruel treatment of these creatures has brought the attention of animal rights activists to lead movements against the silk industry. This includes the elimination or refusal of purchasing or using silk-based products. Luckily an alternative method known as Ahimsa silk has been slowly working its way to the market. Ahimsa silk practices a non-violent method of silk breeding and harvesting. In this method the larvae are allowed to complete their metamorphosis and live as moths. The only downside to Ahimsa silk is that in allowing the moth to emerge from the cocoon they end up damaging the continuous silk strand. Resulting in only a sixth of the filaments length which increases the price for Ahimsa silk products. Ahimsa, in Sanskrit (an ancient Indian language), means 'noninjury' or 'nonkilling'.

2.2 Silk: The Biomaterial of the Future

For centuries silk has been primarily used in the making of textiles due to its elegance and durability. However, within the last decade the material has been repurposed and has led to remarkable innovations across multiple fields. "The new generation of silks with controllable degradation rates based on processing, biomaterial scaffolds, and related systems for a range of medical needs is anticipated. In the next few years, silk sutures, drug delivery systems, and fiber-based tissue products that exploit the mechanical properties of silks can be envisioned for ligament, bone, and other tissue repairs." (Omenetto and Kaplan, 2010).

2.2.1 Applications of Regenerated Silk Proteins

The advancements and progress made with silk-based products has primarily originated from the Silklab at Tufts University (Bradley, 2017). The Silklab directed by Fiorenzo Omenetto is an interdisciplinary research team that looks to expand the use and potential of silk as a biomaterial. Some of the innovative applications that have emerged from the lab include edible and implantable electronics, energy harvesting tools, wearable sensors, and medical devices. Such technological advancements would not be possible without the extraction of the pure fibroin proteins in silk. The Silklab has developed a protocol (Figure 2-1) that takes raw cocoons to create an aqueous solution that serves as the basis for a wide range of applications (Rockwood et al., 2011). The extracted silk solution can be used to fabricate various types of hydrogels, sponges, composites, and films. All of which have a direct impact on the medical industry as the biomaterial is highly compatible with the human body. "These materials can be used directly as biomaterials for implants, as scaffolding in tissue engineering and *in vitro* disease models, as well as for drug delivery." (Rockwood et al., 2011).

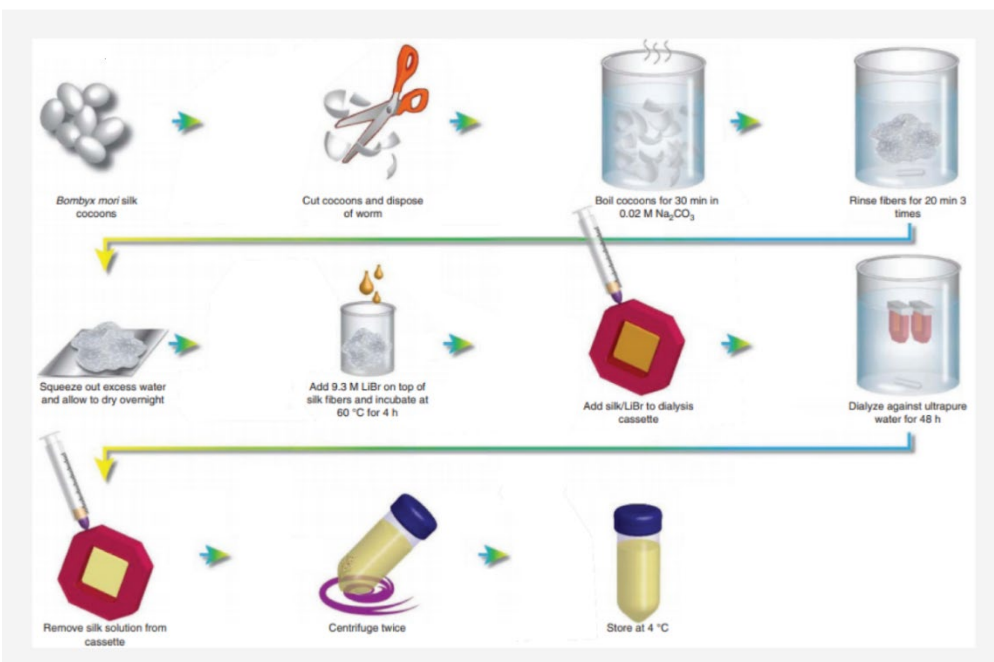

Figure 2-1: Schematic showing the step-by-step process for creating a silk-based aqueous solution that can be used for different fabrication mediums. Figure from the Department of Biomedical Engineering, Tufts University (Rockwood et al., 2011).

2.2.2 Fibroin-Based Digital Fabrication

The vast majority of the work produced with silk-based materials have primarily been used at the microscopic level. Whether its for surgical operations, optics, or biomedicine the material has mainly been applied in fields that work at a fine scale. However, within the last two years the material has been researched and proven to be applicable at a larger context. With the technological advancements made with digital fabrication, the processing and manufacturing of regenerated silk is able to take on new forms that tie directly with the latest fabrication techniques.

The Silklab research team at Tufts University has been successful in creating hydrogel formulations for additively-manufacturable silk-based biomaterials. The framework they developed consists of attaching a pneumatic extrusion system to a 3-axis CNC machine. They were able to program the toolpaths for the CNC that would follow and dispense the predetermined amount of material at a time. In one particular study they created a hybridized material composite by printing a “thin chitosan base layer to confer flexibility and a thick fibroin structure layer to confer tunable stiffness and tensile strength to constructs.” (Mogas-Soldevila et al., 2021). The research team investigated multiple parameters within the composites to test varying levels of material thickness, flexibility, opacity, and responsiveness (Figure 2-2).

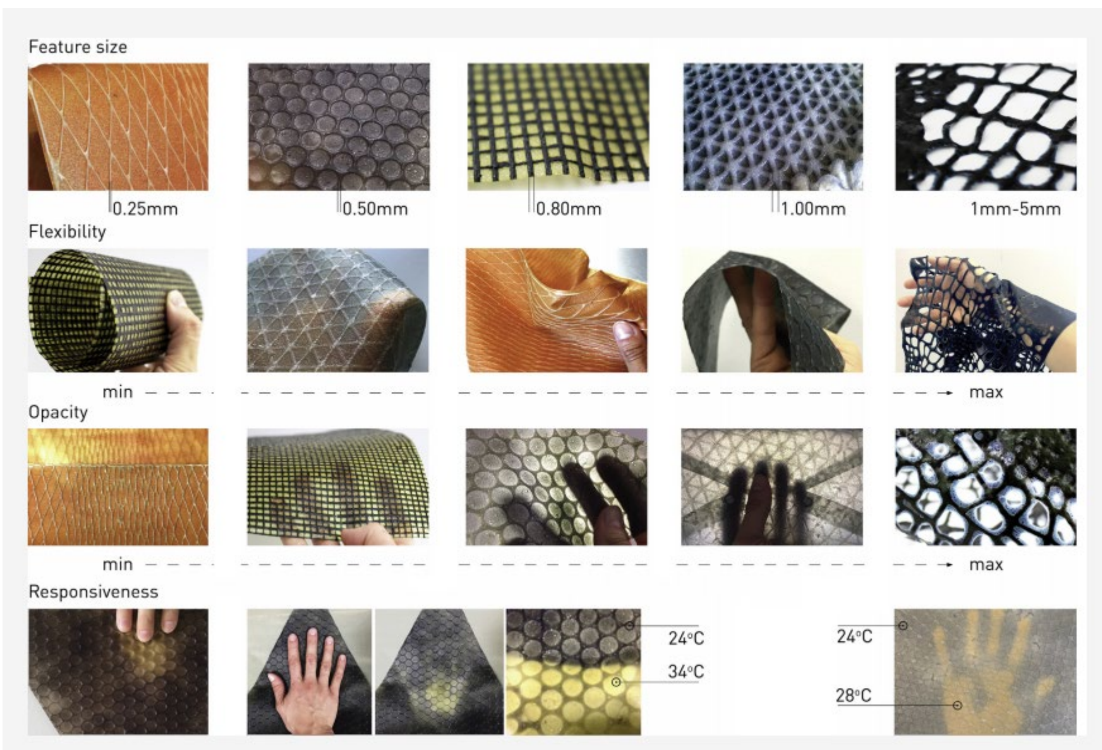

Figure 2-2: Images highlighting the multi-properties of the biomaterial composites. Figure from the Department of Biomedical Engineering, Tufts University (Mogas-Soldevila et al., 2021).

CHAPTER 3

Methods

3.1 Silkworms and Silk Production

Driven by the cruel and unethical practices in the silk industry, this portion is dedicated to the *Bombyx mori*. Rather than harming and killing the lifeform a more reasonable and sensitive approach is taken in the raising and care of the silkworms. The following is a demonstration of how silk can be cultivated without mistreating or killing the creatures that produce the material.

3.1.1 Raising and Care of Silkworms

The ethical approach that this research aims to uphold, first began with the raising and care of real silkworms. 250 silkworm eggs were purchased online from Coastal Silkworms, a company that specializes in the raising and distributing of silkworms. Along with the eggs, several silkworm food packets were also purchased as part of their nutrition and diet. Documentation played an important role as it showcased the entire lifecycle of the silkworms used in this research. For the documentation process a Victure 4k 60FPS Touch Screen Action Camera was used to record the growth and development of the silkworms. Video footage was recorded daily and broken down into frames, as shown in Figure 3-1, highlighting the silkworm's different growth stages starting as an egg and ending as a moth.

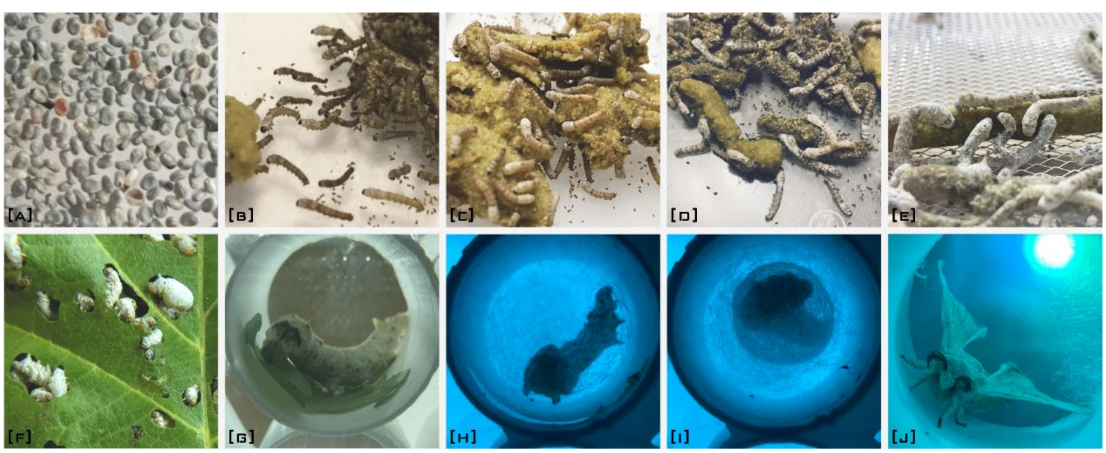

Figure 3-1: Photographs capturing the lifecycle of the Bombyx mori in the author's home studio. Photos: Asbiel Samaniego.

The silkworms were fed daily with a powdered mulberry paste and as they reached the final larvae stage, fresh mulberry leaves were introduced to their diet. The silkworms raised in this experiment took a total of 10 weeks to complete their lifecycle with most of them reaching a length of 2 inches on average. By allowing the silkworms to fully mature and reach the moth stage, they were able to reproduce. Resulting in a new generation of silkworms from which more cocoons could be collected and used for the material experiments later discussed in this thesis.

3.1.2 Cocoon Cells: Design for Enhanced Material Strength

As the silkworms grew larger in size they were transported multiple times going from the petri dish they arrived, to plastic containers and eventually into a 20-gallon tank. Once the silkworms reached maturity and were ready to form cocoons, the layout of the container was designed to house individual cocooning cells. The purpose in creating the cells was so that each silkworm could inhabit one and form the cocoon inside. The 3D printed cells were specifically designed to limit the amount of space that the silkworms had while making their cocoons. The cells are comprised of four geometric groups in the form of rectangular prisms [a], triangular prisms [b], hexagonal prisms [c], and cylinders [d]. In each group the individual cells varied in terms of their width and depth as represented in Figure 3-2. By having the silkworms form the cocoons in confined spaces, the strength and quality of their silk is significantly increased (Cheng et al., 2018). This experiment builds upon an earlier study researchers performed at Southwest University in which round paper tubes were used as constraints to limit the size of cocooning space for silkworms. The findings from that study resulted in "the densification of silkworm cocoons by a natural pressing process, which leads to a robust fiber network and improves the load capacity of these cocoons." (Cheng et al., 2018).

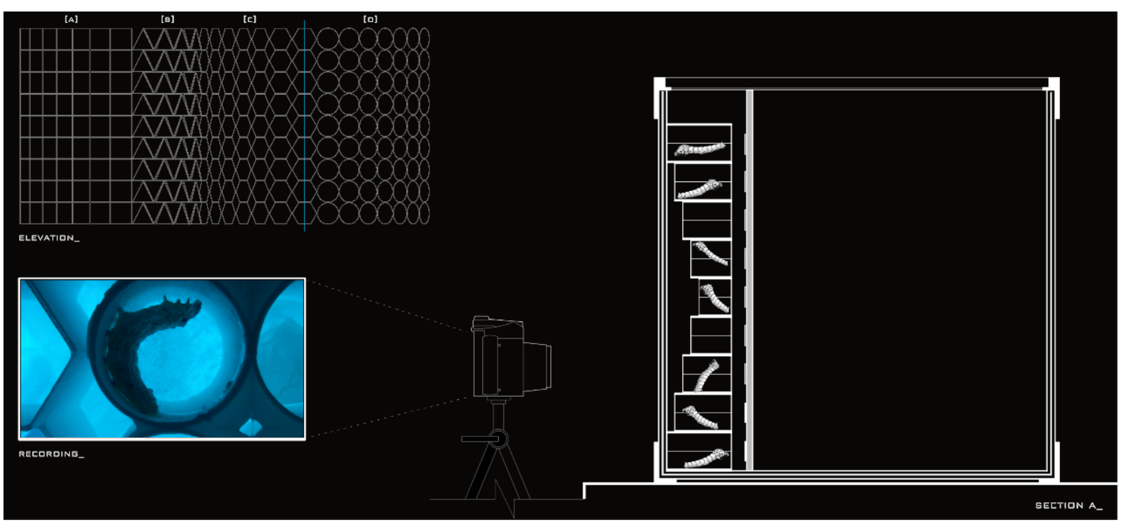

Figure 3-2: Section and elevation drawings of the Cocooning Cells layout.

Through the design of the cells the objective was to biologically enhance the mechanical properties of the final cocoons. As it's been stated the cocoons conceived in confined spaces tend to have better mechanical properties, thus improving the performance of silk-based composites and biomimetic materials (Cheng et al., 2018).

3.1.3 Documentation and Ethical Material Sourcing

The silkworms used in this project were constantly recorded as it helped keep track of their growth and development. It also provided the opportunity to record the cocooning process as shown in Figure 3-3. The documentation also served as the evidence regarding the practice of "peace silk" (or Ahimsa silk) followed in this research which allowed the silkworms to live and complete their life cycle. This portion of the research was a success as a large number of cocoons were collected without having to harm the silkworms. The hope from this is that it sets an example within the sericulture industry to reconsider how they go about obtaining silk. That they appreciate and give the silkworm its due respect for everything it has to offer. That they get treated fairly and allowed to complete their lifecycle just as mother nature intended.

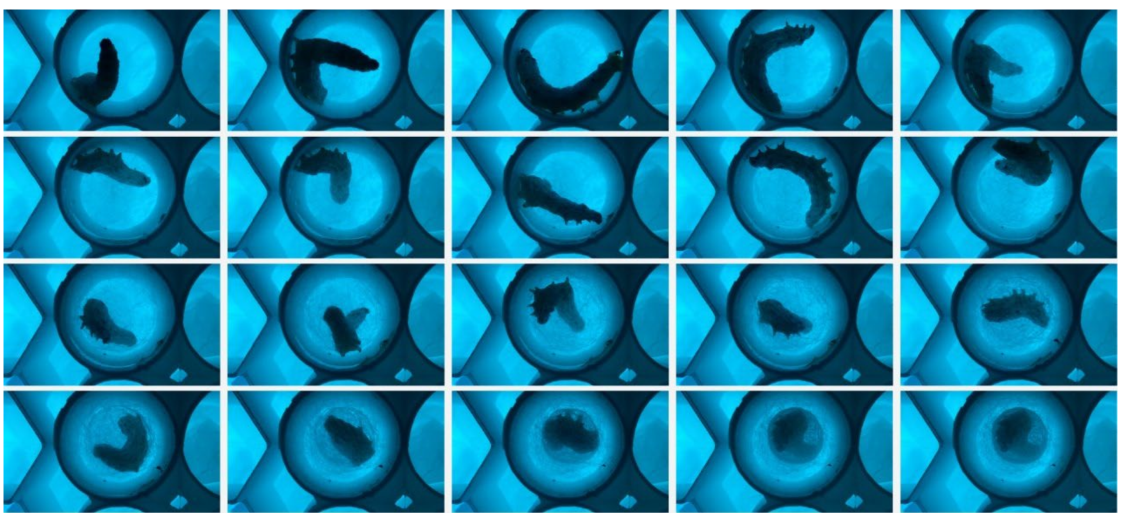

Figure 3-3: Frames extracted from a timelapse video capturing the cocooning process of the Bombyx mori within a 3d printed Cocoon Cell. Total time duration: 32 hours.

3.2 Biomaterial Experimentation

With the silkworm cocoons collected from the previous phase, the next phase of this research consisted of recreating a silk-based solution by following a protocol obtained from Tufts University. The solution was mixed and combined with another biomaterial in the form of chitosan to create hydrogels for fabrication. The following is a demonstration of the fibroin extraction process along with the different material studies that emerged from the combination of the two biomaterial mixtures.

3.2.1 Regenerated Silk: From Cocoon to Aqueous Solution

After completing their metamorphosis and successfully transforming into moths the silkworm cocoons were collected and stored for the recreation of a silk-based solution. However, before the fibroin could be extracted, the cocoons had to be free from any debris left over by the pupa. Additionally, areas covered by the brown fluid secreted by the moths also had to be discarded to reduce the contamination. The fibroin extraction process for this research took place in the Netravali Lab located in the College of Human Ecology at Cornell University.

The fibroin extraction process followed a step-by-step protocol developed by Tufts University (Rockwood et al., 2011). The protocol presented in Figure 3-4, began by taking the cocoons [a] collected from the silkworms discussed in Section 3.1 and cutting them into dime sized pieces [b] with a pair of scissors. Next, 4.24 grams of sodium carbonate were added to a 2-liter beaker containing boiling water. Then 5 grams of the cocoon pieces were added to the boiling water for a total of 30 minutes. After 30 minutes the silk fibroin was rinsed in ultrapure cold water, squeezing any excess water from the silk. The silk was then placed in a 1-liter beaker [c] filled with ultrapure water and a large stir bar. The beaker was placed over a stir plate for 20 minutes with the rotation speed set at a low setting. This step was repeated twice for a total of three rinses and three 20-minute cycles on the stir plate. After the third rinse the silk was squeezed tightly to remove as much water as possible and then spread out on a piece of aluminum foil to dry overnight [d].

The following day a lithium bromide solution was made and calculated based on the weight of the dried silk. The solution was poured over tightly packed silk in a 50 ml beaker [e]. The beaker was then placed into an oven for 4 hours at a constant temperature of 60°C, resulting in a highly viscous solution with an amber coloration [f]. While still warm the solution was transferred into a 12 ml dialysis cassette with a syringe and 18-gauge needle [g]. Once all the material was inserted into the cassette a float buoy [h] was added to help the cassette float during the dialysis phase. This phase involved placing the cassette with the silk solution in a 1-liter beaker filled with ultrapure water and a large stir bar. The beaker was placed onto the stir plate with the rotation speed set to a medium setting. The water was changed after 1 hour, 4 hours, in the evening, the next morning and night, as well as the following morning resulting in a total of 6 changes within 48 hrs. After the sixth change the solution was notably different in coloration going from an amber-like color to a transparent white [i]. The solution was finally removed from the dialysis cassette and poured into a 15 ml conical tube [j]. Based on the total volume of the solution, it was divided into two conical tubes each one containing about 7-8 ml. The tubes were then placed into a centrifuge [k] that was set to 9,000 r.p.m at 4°C for 20 minutes. Once finished the solution in the tubes was transferred to a new pair of conical tubes that are then placed into the centrifuge for another cycle. After the centrifuge had completed its final cycle the silk solution was complete and ready to use [l]. The average duration of the fibroin extraction process took approximately five days.

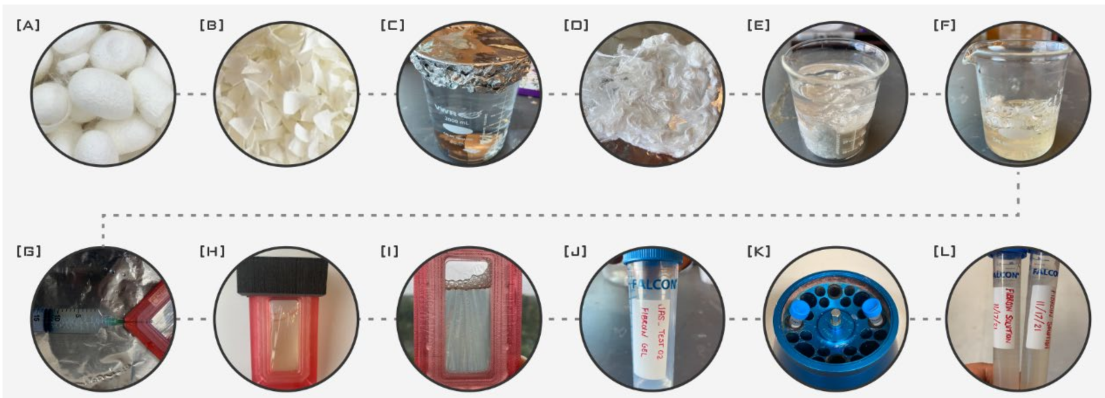

Figure 3-4: Fibroin extraction process. [a] cocoons, [b] cocoons cut into pieces, [c] pieces boiled with sodium carbonate for 30 minutes, [d] silk left to dry, [e] lithium bromide solution added to silk, [f] solution after 4 hours in oven at 60°C, [g] solution inserted into dialysis cassette, [h] cassette with solution, [i] cassette with solution after 48 hours of dialysis, [j] solution transferred to test tubes, [k] tubes are centrifuged twice, [l] regenerated silk solution.

3.2.2 Fibroin and Chitosan Mixtures

After the completion of the fibroin extraction protocol the next phase involved combining of the silk solution with another biomaterial in the form of chitosan. The two biomaterials would be mixed to create multiple combinations with the aim of making a material matrix that possessed the unique characteristics of both materials. Chitosan was the ideal choice to pair with the fibroin solution given its cost, accessibility, and responsive characteristics. Along with the two biomaterials the use of plasticizers and thickeners were introduced in the form of glycerol, sodium alginate, acetic acid, hydrochloric acid, and calcium carbonate. These would be mixed with the fibroin solution and chitosan resulting in a total of four distinct blends (Figure 3-5). Blend [1] consisted of a mixture containing chitosan at 8% w/v mixed with acetic acid at 5% w/v (60%), glycerol (30%), fibroin solution (10%). Blend [2]: chitosan at 8% w/v (55%), glycerol (15%), sodium alginate (15%), fibroin solution (15%). Blend [3]: chitosan at 8% w/v (85%), hydrochloric acid at 25% w/v (5%), fibroin solution (10%). Blend [4]: chitosan at 8% w/v (75%), hydrochloric acid at 25% w/v (5%), calcium carbonate (20%), fibroin solution (10%).

From the material experiments the following observations were noted. Blend [1] resulted in a highly flexible material with a constant thickness of 1/8". The coloration of the blend was a light greige with a frosted transparency. One side contained a rougher texture whereas the other had a smooth complexion. Blend [2] was the first of the material studies to show signs of curling during the curing process. The outcome resulted in an orange-brown material with a hard and stiff structure. There were no visible signs of transparency throughout the material as it was mostly opaque. Blend [3] like the previous blend showed signs of curling and deformation. Except in this material matrix there was more transparency in the final product. Another noticeable feature was the golden coloration and its shiny quality. The structure was stiff, but it had areas that could slightly flex and bend. Blend [4] produced a more brittle structure with little to no transparency. Like the two previous blends it deformed as it cured, however due to its delicate structure it resulted with several cracks.

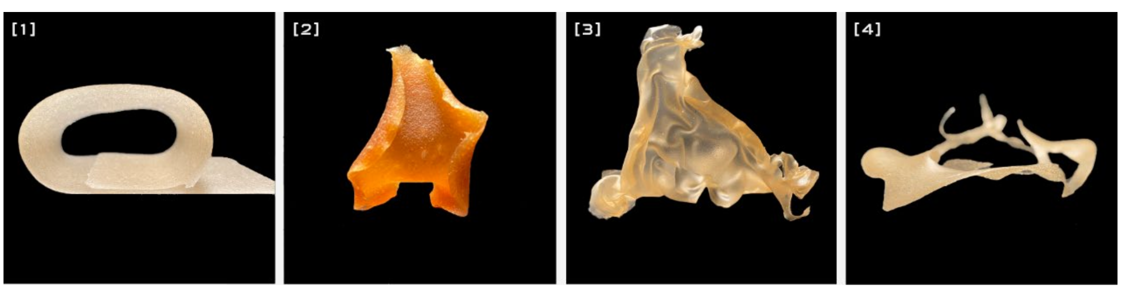

Figure 3-5: Fibroin and chitosan material studies. [1] chitosan, glycerol, and fibroin solution, [2] chitosan, glycerol, sodium alginate, and fibroin solution, [3] chitosan, hydrochloric acid, and fibroin solution, [4] chitosan, hydrochloric acid, calcium carbonate, and fibroin solution.

3.3 Extrusion Device Setup

When dealing with the fabrication of biomaterials in a hydrogel format the need for an extrusion system is required. Such systems can be coded and programmed to control several parameters that directly affect the fabrication of the materials. This includes the amount of material deposited over a period of time to the generation of custom toolpaths. The following is an overview of the system developed and used for the bio-fabrication of the material studies conducted in this research.

3.3.1 Syringe Extruder Design

A syringe extrusion device was chosen for the purpose of this study as it proved to be the most viable approach regarding the scale of the material studies. The syringe extruder developed for this research consists of multiple pieces that include the following: two 3D printed parts that act as the main frame and plunger for the syringe, a Nema17 stepper motor, one 5 mm to 8 mm shaft coupler, one T8 lead screw with a length of 130mm and an 8mm diameter, one brass nut, a 60ml syringe, and a customized 3D printed nozzle head to control the material thickness. The electrical components required to program the extrusion device includes: the Nema17 stepper motor, an Arduino Uno Rev3, power supply of 8-35 volts, breadboard, A4988 stepper motor driver, 100µF capacitor, breadboard jumper wires, breadboard DC barrel jack, and a A-B USB cable. Figure 3-6 presents a schematic of all the electrical pieces and their wiring to program and power the syringe extruder.

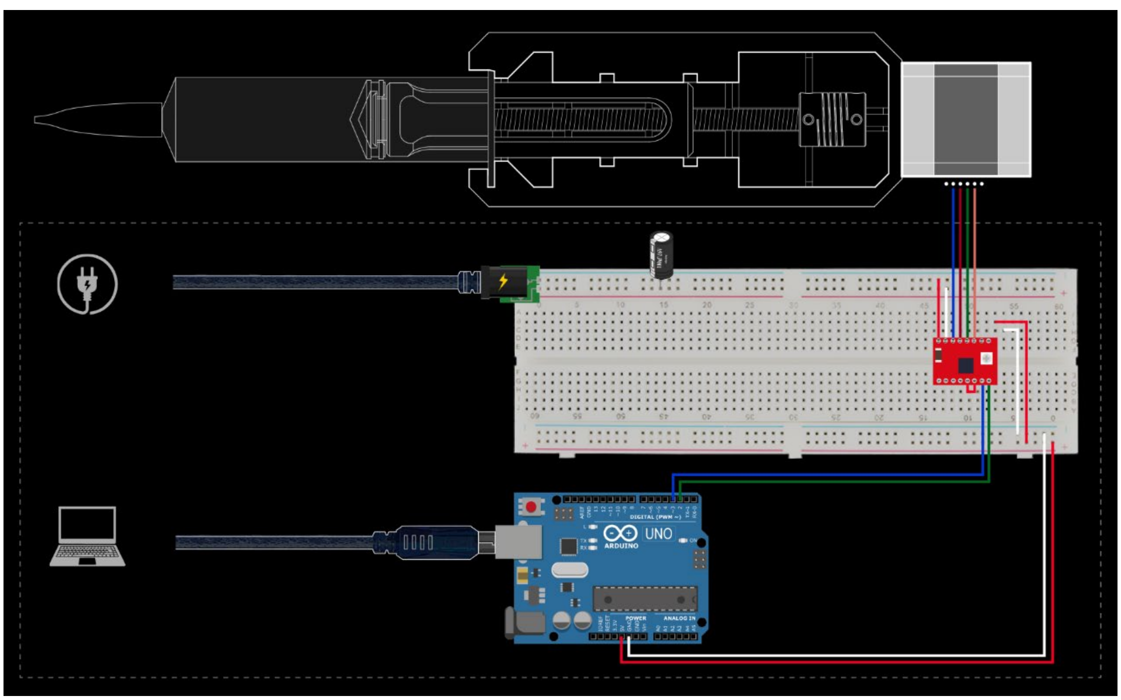

Figure 3-6: Schematic diagram highlighting the wiring between individual components.

3.3.2 CNC Positioning and Calibration

There were certain constraints in which the syringe extruder had to comply with. These were mainly due to the CNC machine as it was going to house the extrusion device. The 3D printed frame had to be designed with an exterior diameter of 65mm to fit within the collet holder as shown in Figure 3-7. The extrusion device is placed inside and adjusted to where the height of the nozzle is at 1/8” (3.175 mm) above the CNC bed. Once positioned the collet holder is tightened to prevent the extruder from sliding and touching the bed. The CNC machine is then programmed to run a quick toolpath simulation to test the spacing between the nozzle and the print bed. The test was critical as it helped ensure the extrusion process worked properly and that there wouldn’t be any technical difficulties moving forward.

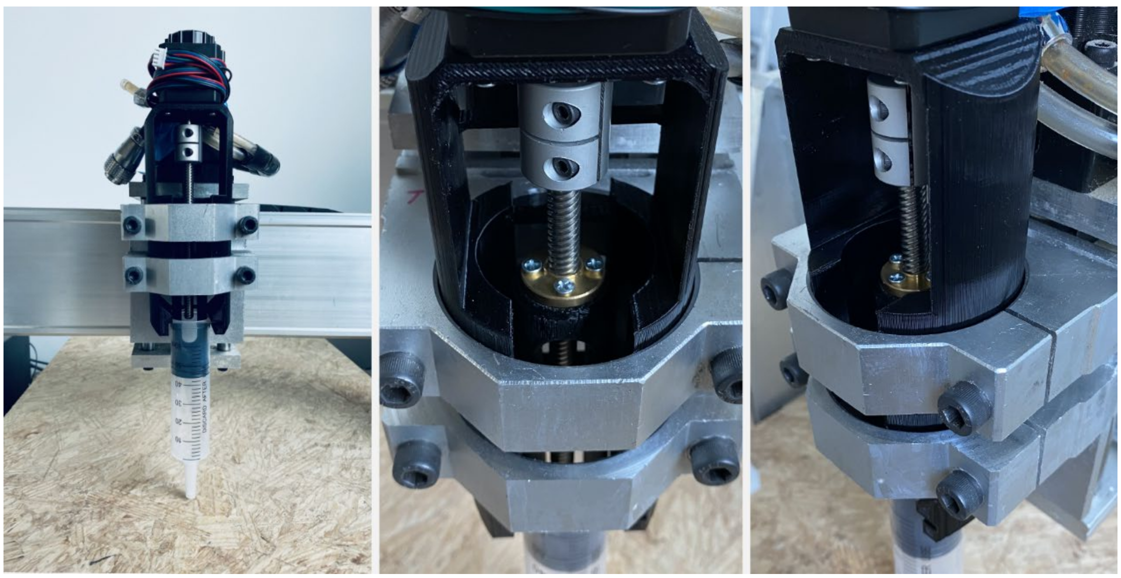

Figure 3-7: Syringe extruder designed to fit within the collet holder of the CNC machine.

3.3.3 Programming and Coding

The syringe extruder was programmed using an Arduino Uno microcontroller to control the rate at which the biomaterial was deposited. (Figure 3-8) highlights the code used for the Nema17 stepper motor. Lines 22-27 controls the number of steps per second that the motor makes, which directly affects the amount of material pushed through the 3D printed nozzle head. The speed was set to a setting of 2 steps/second as it was enough to push the material out of the extruder without any excess material overflowing. With 2 steps/second more material can be preserved, making the fabrication process much more efficient with its resources. Lines 31-39 focus on getting the 3D printed plunger back to the starting position once all 60ml of the material is extruded. The speed was significantly increased to -300 steps/second as there was no material left in the syringe making the high setting safe. Once the plunger returned to its original position the syringe could be removed from the 3D printed frame. Once removed a new batch of material is poured into the syringe and is carefully inserted back into the frame ready to use again.

```
1  // Include the AccelStepper library:
2  #include <AccelStepper.h>
3
4  // Define stepper motor connections and motor interface type. Motor interface type must be set to 1
5  when using a driver:
6  #define dirPin 2
7  #define stepPin 3
8  #define motorInterfaceType 1
9
10 // Create a new instance of the AccelStepper class:
11 AccelStepper stepper = AccelStepper(motorInterfaceType, stepPin, dirPin);
12
13 void setup() {
14   // Set the maximum speed in steps per second:
15   stepper.setMaxSpeed(300);
16 }
17
18 void loop() {
19   // Set the current position to 0:
20   stepper.setCurrentPosition(0);
21
22   // Runs the motor forward at 2 steps/second until the black rubber reaches the end of syringe:
23   while(stepper.currentPosition() != 2280)
24   {
25     stepper.setSpeed(2);
26     stepper.runSpeed();
27   }
28
29   delay(1000);
30
31   // Reset the position to 0:
32   stepper.setCurrentPosition(0);
33   // Runs the motor backwards at 300 steps/second until the black rubber returns back to its
34 original starting postion:
35   while(stepper.currentPosition() != -2280)
36   {
37     stepper.setSpeed(-300);
38     stepper.runSpeed();
39   }
40
41 }
```

Figure 3-8: Code used in the programming of the Nema17 stepper motor. Controls the speed of the plunger as it pushes material out of the nozzle.

Along with the coding for the syringe extruder came the programming of the toolpaths required in generating the material studies. Through the use of RhinoCAM a computer-aided manufacturing plug-in for Rhinoceros 6.0, a 3D modeling program. The generation of code was obtained by setting a continuous curve as the path of travel from which the extruder would follow. Figure 3-9 highlights an example of a continuous curve that was used in the programming of the extruder with both the starting and ending points. Between these points are the x and y coordinates that determine the traveling path for the syringe extruder as its attached to the CNC collet holder. The curves are generated by taking a base surface and through a computational process a continuous curve is produced with the ability to control the spacing between the lines running parallel to each other. The spacing was determined by the thickness of the material solution as it was deposited onto the bed. Several trials were tested prior to the fabrication of the final artifacts, ensuring that the workflow functioned properly across different toolpaths.

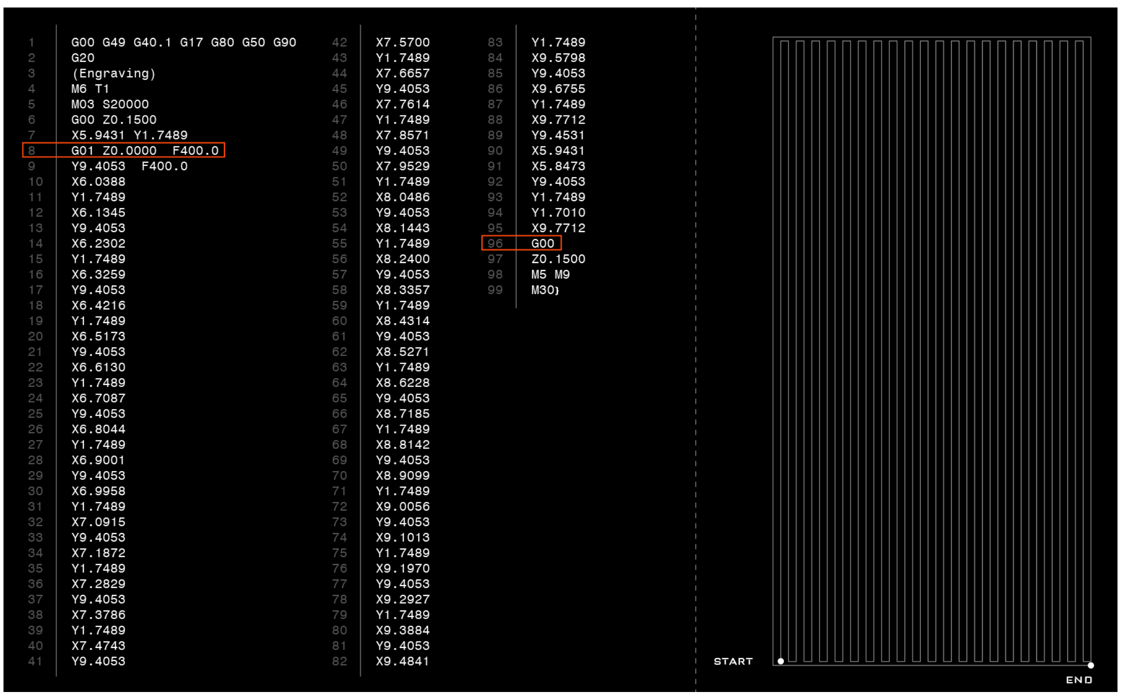

Figure 3-9: Code generated from RhinoCAM provides the CNC router instructions for the path of travel.

3.4 Bio-Fabrication Process

With the groundwork established the following presents a series of studies that explore material driven design. The general focus of this work is centered on the hybridization between fibroin-chitosan blends and standardized 3D printing filament to create a new material composite. The following presents the design and fabrication methodologies used in exploring the relationship between the biomaterials and the 3D printed geometries. The material studies were developed at the Netravali Lab in the College of Human Ecology and fabricated in Rand Hall of the College of Architecture, Art, and Planning.

3.4.1 Biomaterial Matrix

Based on the results from the fibroin and chitosan mixtures, Blend [3] proved to have the best qualities amongst the four blends prepared and became the base material moving forward. The composition of Blend [3] the final mixture used in the fabrication process consisted of the following materials: chitosan powder from BulkSupplements.com, distilled water, hydrochloric acid, 16 oz food scale, 8 oz plastic cups, spatula spoon, stir plate, small stir bar, 50 ml beaker and a 15ml tube with the regenerated silk solution. Figure 3-10 highlights the steps required along with the ratios needed to complete the final biomaterial matrix.

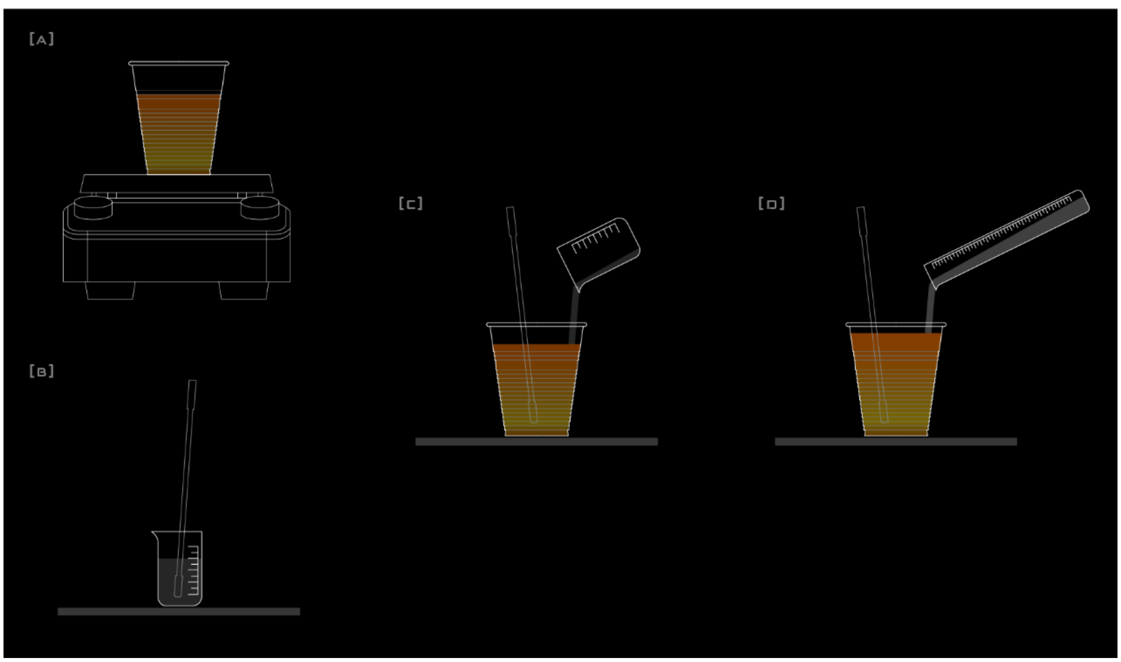

Figure 3-10: Final biomaterial composition used in the fabrication of the material studies. [a] powdered chitosan mixed with water, [b] hydrochloric acid mix, [c] acid added to dissolved chitosan solution, [d] regenerated silk solution added.

8 grams of chitosan powder are dissolved into 95 grams of distilled water inside an 8 oz plastic cup. Within the cup the small stir bar is placed, and the cup is placed onto a stir plate to mix [a]. The plate speed was adjusted to where a small vortex was visible and the dissolvement was noticeable. While the chitosan powder gets mixed, a solution of hydrochloric acid is prepared. 5 grams of hydrochloric acid are mixed with 20 grams of distilled water [b] in a 50 ml beaker. While manually stirring the chitosan solution, the acid is slowly added to the mix [c] until it reaches a viscosity level of 2000-3000 CPS. Achieving this level of viscosity was important as it relates to the extrusion of the material through the syringe extruder. Lastly, 8-10 ml of the regenerated silk solution are poured into the newly formed chitosan gel [d]. After stirring the solution for 5 minutes it can then be loaded into the syringe extruder and used for fabrication.

3.4.2 Bio-Fabrication Setup

With the newly made fibroin-chitosan solution the bio-fabrication process can begin. The setup (Figure 3-11) starts with the solution being poured into the 60 ml syringe [1]. The syringe is then inserted back into the 3D printed frame and plunger. The extrusion device is then positioned and calibrated onto the collet holder of the CNC machine. Once positioned, the CNC router is programmed with a toolpath [b] for the extruder to follow. The extruder follows the toolpath to the end and deposits the biomaterial solution, thus creating a surface based on the geometry modeled in Rhino. After the print is complete the extruder is removed from the CNC and the material test is left to cure for a minimum of 24 hours.

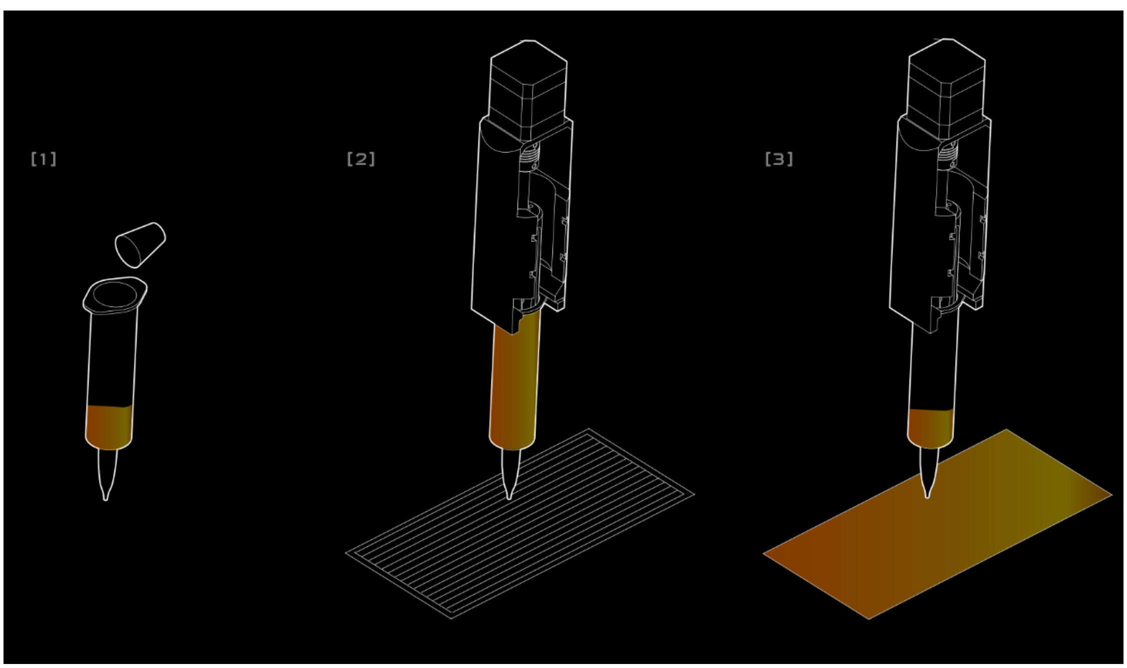

Figure 3-11: Bio-fabrication setup with the syringe extruder.

3.4.3 Structural Reinforcement: Introduction of PLA

During the earliest stages in the development of the fibroin-chitosan solution several material studies were conducted. Using Blend [3] and the syringe extruder, a wide range of geometric studies were 3D printed. The objective was to test the role of geometry and how it influenced the natural curling process of the biomaterial. The earliest study models focused on simple geometric shapes such as squares, triangles, and circles. In all three studies the material drastically shriveled producing crumpled frames. Openings in the form of a circle were introduced amongst the squared study models. Figure 3-12 highlights the results of three different 8x8 inch (203x203 mm) squares with a circular opening. Material study [a] is of a square with a 1 ½ inch (38.1 mm) circular opening. As shown in the image the outcome resulted in a highly shriveled material composite with the geometry of the hole somewhat intact. The same geometric study would be repeated again. However, this time a 3D printed polylactic acid (PLA) ring with the same diameter as the opening would be placed in the middle of the print. This resulted in a completely different outcome with the final form [b] as the square managed to keep its overall shape. With the introduction of the ring there was now a tension force in which the biomaterial could be controlled and steered to take on a specific form. To validate this hypothesis another 8x8 inch (203x203 mm) square was printed, this time with an opening towards the upper right corner [c]. Another 3D printed ring would be placed in this opening and once again the square managed to keep its form intact. With this study the placement of the ring resulted in a higher lift in that corner of the square as it cured. This first round of studies confirmed two things: 1) With the right settings PLA can be 3D printed to fully integrate with the biomaterial matrix and 2) The placement and geometry of the PLA structure has a direct influence on the curling behavior of the biomaterial.

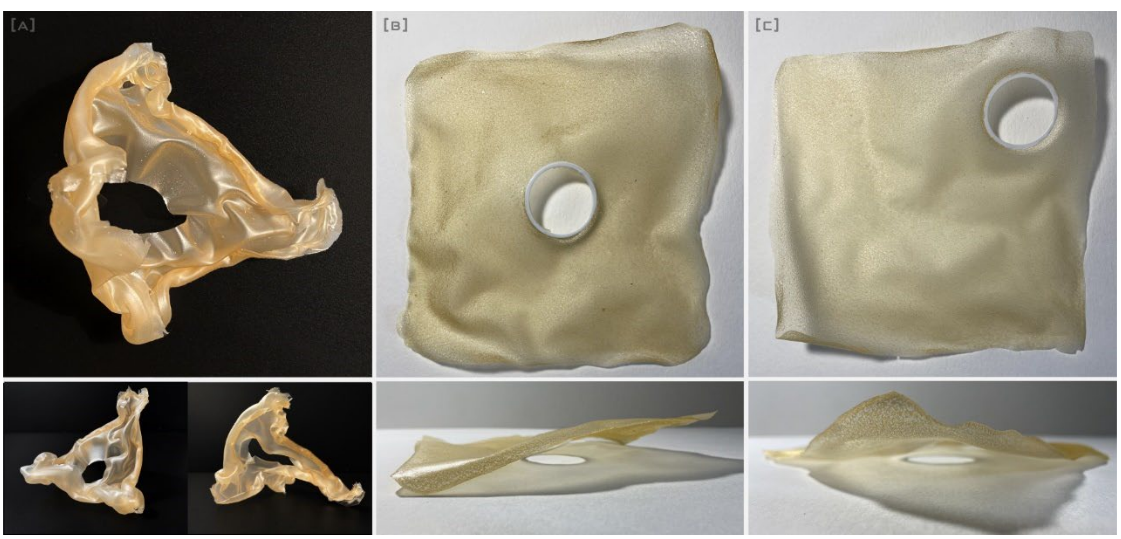

Figure 3-12: Material studies exploring the integration of PLA [a] material study with no PLA, [b] material study with a PLA ring placed in the middle, [c] material study with a PLA ring placed in the upper right corner.

3.4.4 Hybrid Bio-Composites

Based on the findings from the previous studies the next tests focused on different patterning systems. Due to the size constraints of the printer bed the modules were designed and printed with the following dimensions: length 8” (203 mm), width 2” (50.8 mm), outer frame thickness 1/16” (1.59 mm), and the patterns at 0.28 mm. Finding the right PLA thickness was important in getting it to bond with the biomaterial. The matrix diagram as shown in Figure 3-13 highlights the varying types of patterns that were 3D printed. The studies in this iteration focused on three main categories with parallel lines, Voronoi cells, and overlapping/random curves. As demonstrated by the images, some patterns showed better results than the others, with random curve [c] proving to have the best outcome. Good cohesion between the PLA and the biomaterial solution resulted in a clean and seamless bond between the two materials. The main findings from this first round of iterations was that symmetry and the density of the pattern had a direct effect on the final form of the biomaterial once it cured or dried. For the first time the natural curling of the material could be controlled and purposely shaped into a specific form.

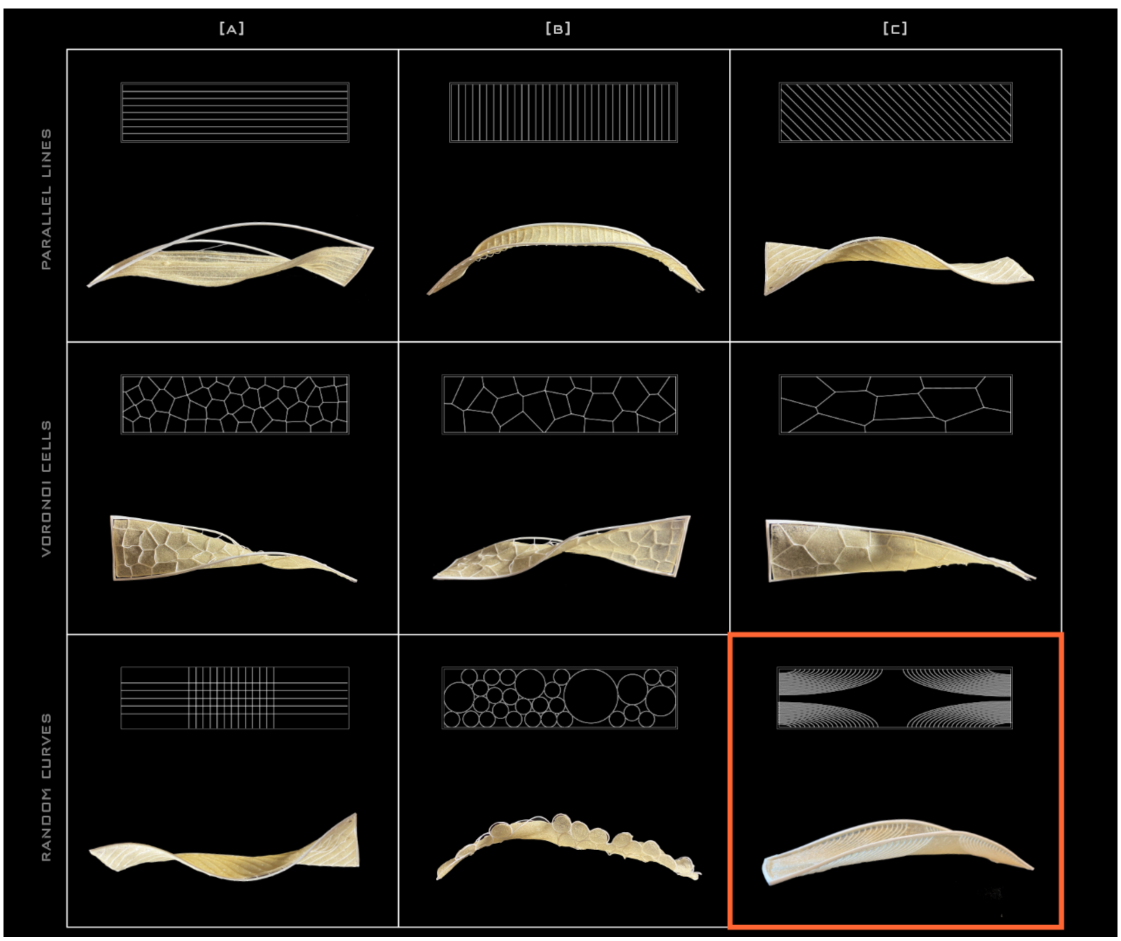

Figure 3-13: Matrix of the first iteration of patterns tested and their outcomes.

Building upon the success of module [c] random curves, the next round of studies focused on two specific design parameters which were: the length and density of the fins within the outer frame. By taking the original module and modifying its parameters the second round of experiments served as verification regarding the importance of symmetry and density. As shown in Figure 3-14 the original module consisting of long symmetrical curves with a high density proved to have the best results amongst the other studies. The reduction in density created a lack of surface area for the biomaterial to bind with towards the middle. This produced a lot of stringing with several striations not being able to fully bond with the biomaterial as it cured and shrank somewhat.

The reduced length of the fins had the biggest impact on the overall binding process. The further away the curves were from the midpoint the less surface area there was for the material to bind with apart from the rectangular frame. The lack of fins towards the middle resulted in no cohesion, creating large gaps between the outer frame and the biomaterial as shown in the studies below.

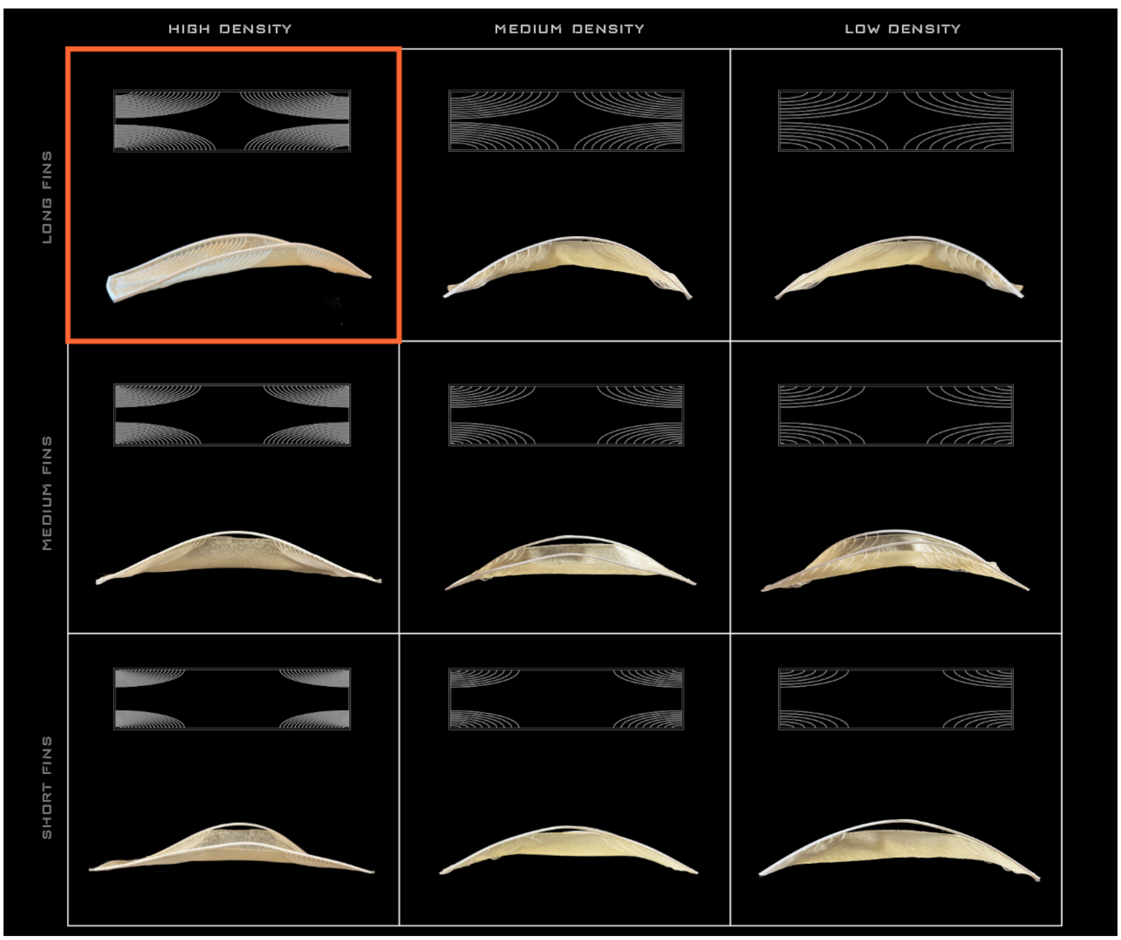

Figure 3-14: Matrix exploring the second iteration of patterns and their outcomes. Parameters tested: length and density of the fins within the rectangular outer frame.

After confirming the importance in having a high density with long curves, the third round of experiments looked at creating a double module. The original module is mirrored and printed as one seamless piece with the new base dimensions of: length 8” (203.2 mm), width 4” (101.6 mm), and the fins at 0.28 mm. The dual module was categorized into three main categories that involved the aera in which the module was mirrored. The categories consisted of modules that had no spine, a single spine, or a double spine running down the middle. Along with the three categories the PLA thickness of the modules spine and outer frame was doubled from 1/16” (1.59 mm) to 1/8” (3.18 mm). Figure 3-15 shows the variety of results between the thickness of the spines and frames along with the number of spines in the middle. The main takeaways from the dual module were that in the absence of a central spine the final outcome resulted in a non-symmetrical form. The other main finding involved the double thickness of the spine running down the middle. A thicker spine(s) creates a flat reference point amongst the hybridized system and preserves its straightness. The spine can then become either a vertical or horizontal member within the module/frame and be used as an advantage for design.

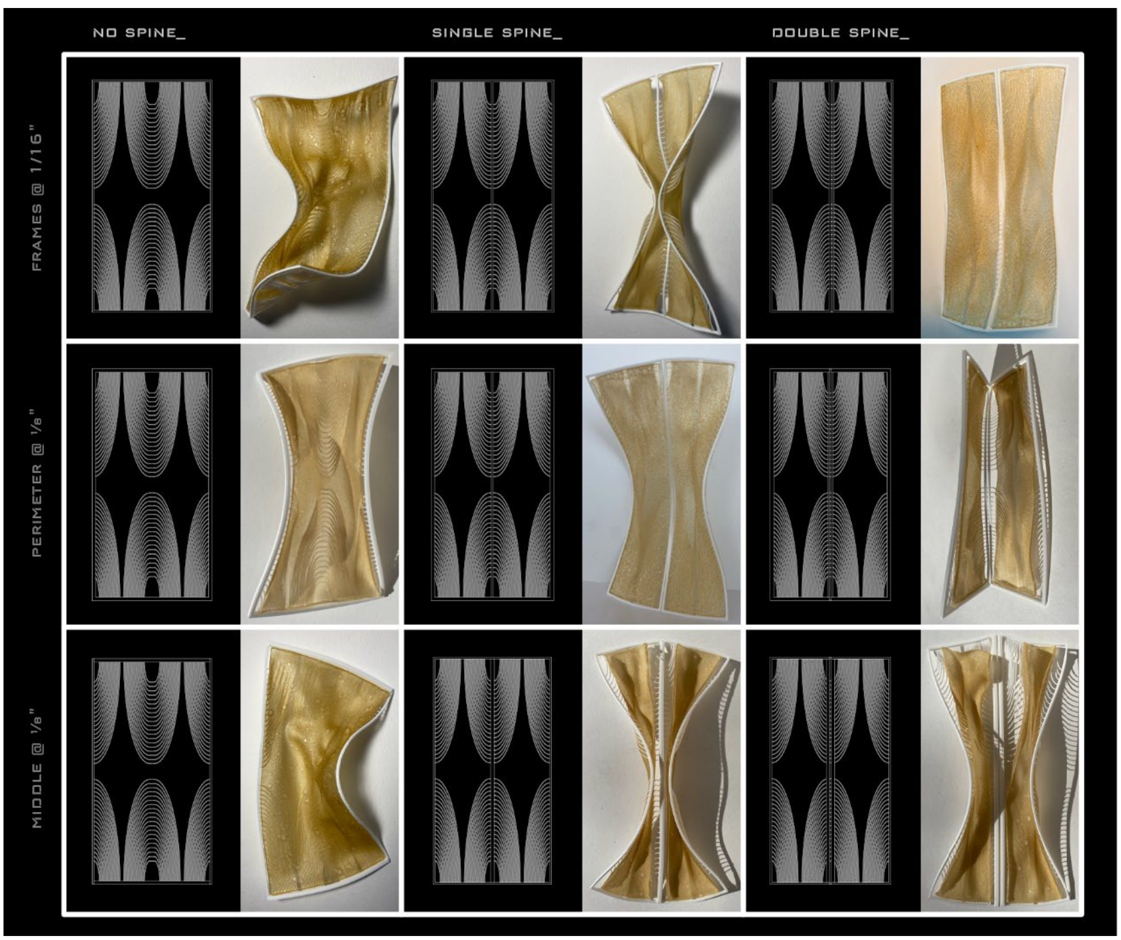

Figure 3-15: Matrix of a dual module exploring different thicknesses along the spine and perimeter of the module.

The dual module was just the first step in the scalability of the hybrid bio-composite. Any issues that presented themselves during the increase in size allowed for the appropriate adjustments to take place. By slowly increasing the scale of these study models, new findings would emerge and contribute to the design process moving forward. The dual module would ultimately serve as the main system in the development of a hybridized bio-composite panel (Figure 3-16) for interior screen wall systems. Figure 3-16

Figure 3-16: Photographs of a Hybrid Bio-Composite panel.

3.5 Screen Wall System

Based on the results of the form-finding series, the speculative use and application for the panels was determined by the biodegradability of the composites main material. To preserve the lifespan of the bio-composite panels the decision to select an interior function was essential. Thus, an interior screening wall system was designed based on the forms generated in earlier studies. The proposed screen wall takes advantage of the material's physical attributes such as its structure, transparency, color, and responsive behavior. Outlined below is a series of advanced studies exploring the scalability and potential interactions the system could have with users and the environment.

3.5.1 Scalability and Responsiveness

The next logistical step in the research involved testing the scalability of the framework. The PLA structure in previous studies was confined to the standard printer bed size of 8x8 (203.2x203.2 mm) inches. Moving forward a 14x14 inch (355.6x355.6 mm) printer was acquired and used to create larger frames. With the increase in size the new dimensions of the dual modules were: length 13.5 " (342.9 mm), width 7" (177.8 mm), with the fins remaining at 0.28 mm. The thickness of the spines and outer frame varied and were either 1/16" (1.59 mm) or 1/8" (3.18 mm). Figure 3-17 shows the size difference between a panel printed on an 8x8" (203.2x203.2 mm) printer and one printed on a 14x14" (355.6x355.6 mm) printer. The scaled versions led to the deformation of the PLA, however the cohesion with the biomaterial wasn't as uniform as with the smaller study models due to the increase in spacing between each individual striation. Regardless, the scaled versions proved that the framework continued to work at a larger scale as the material systems bonded and managed to shape and deform the PLA structure.

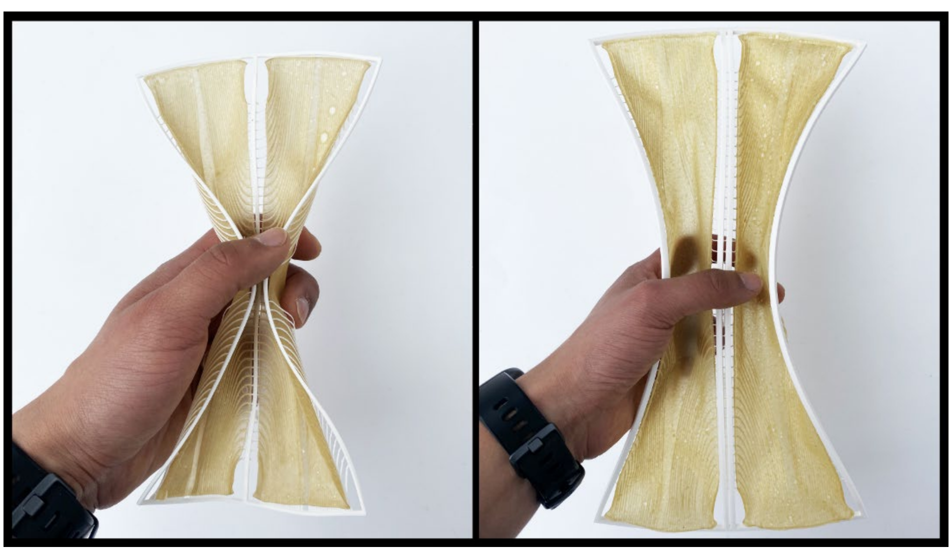

Figure 3-17: Difference in scale. Left: module printed on an 8x8" printer. Right: module printed on an 14x14" printer.

Another aesthetic feature explored was the introduction of thermochromic pigment within the biomaterial matrix. Thermochromic pigments were purchased online from Atlanta Chemical Engineering and were mixed with the final fibroin-chitosan solution. In this case study (Figure 3-18) the bio-composite panels would change color whenever the ambient temperature changed. Whenever the temperature was below 59° F the panels would appear yellow and when the temperature was higher than 59° F the panels would appear red. By embedding thermo-sensitive pigments, the panels as a system could serve as visual indicators that highlight changes in the environment or the program of a space.

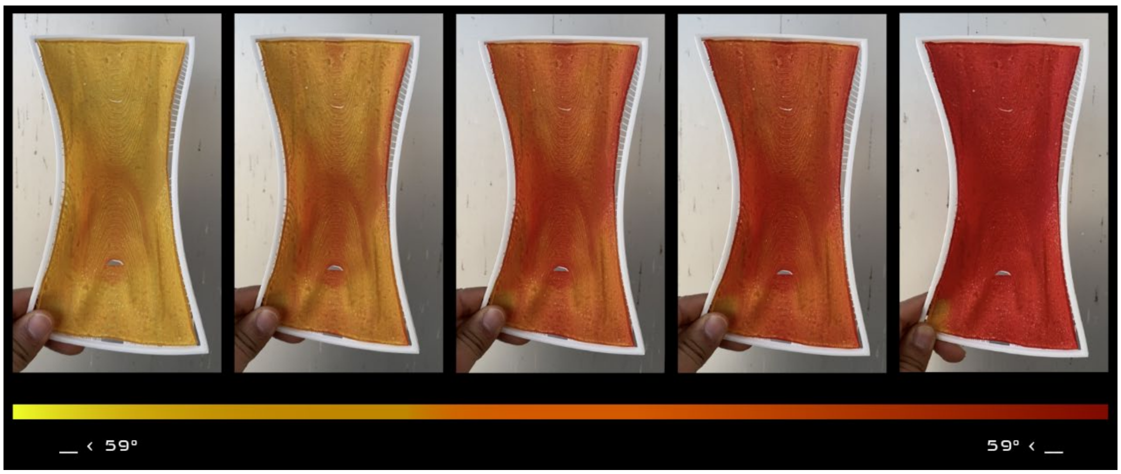

Figure 3-18: Color change as a response to fluctuations in temperature.

3.5.2 Speculative Design Application

For the purpose of this research a hypothetical scenario was developed in which a parametric screen wall system was designed. The selected scene takes place on the wooden floor next to the fire escape on the plate of Milstein Hall. The space was chosen as its commonly used for studio pinups and informal class sessions by the design studios. It also presented a great opportunity to work with the natural light that enters the space in the afternoons. The area (Figure 3-19) is exposed to a high amount of solar radiation due to the low sun angles coming from the west.

To control the lighting, the proposed screen wall system was designed to where it takes advantage of the panels verticality. It uses the spine as a point of reference (Figure 3-20) which allows the panels to pivot, rotate, and/or slide along a track system. The design of the screen wall serves as a response to the amount of light that enters the space. Through its design the individual panels can be adjusted by the users to create several spatial configurations. By introducing the screening system, the amount of radiation that enters the space is significantly reduced (Figure 3-21). Depending on the time of year the panels can be reconfigured to accommodate for different functions. The panels are part of an aesthetically pleasing interactive system that allows the users to engage and move them around. They also possess responsive behavior as they can change color in real time. This level of interaction serves as a visual indicator of the change in temperature of the space. A less occupiable space results in the panels appearing yellow, whereas a more crowed space sees the panels respond to the increase in temperature and turn red (Figure 3-22).

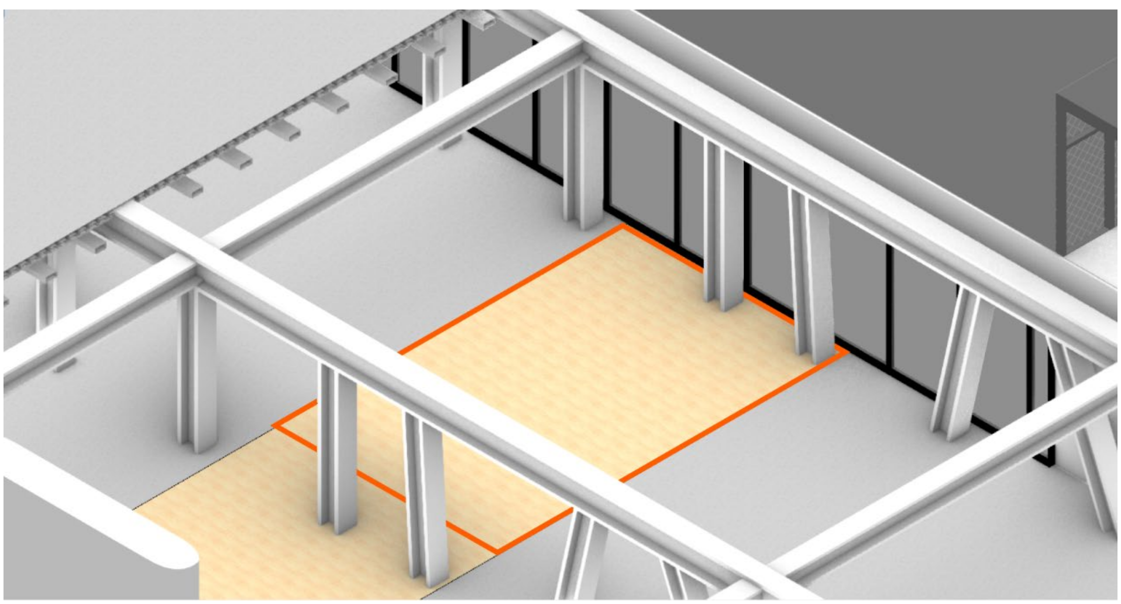

Figure 3-19: Site selection, critique space on the plate of Milstein Hall.

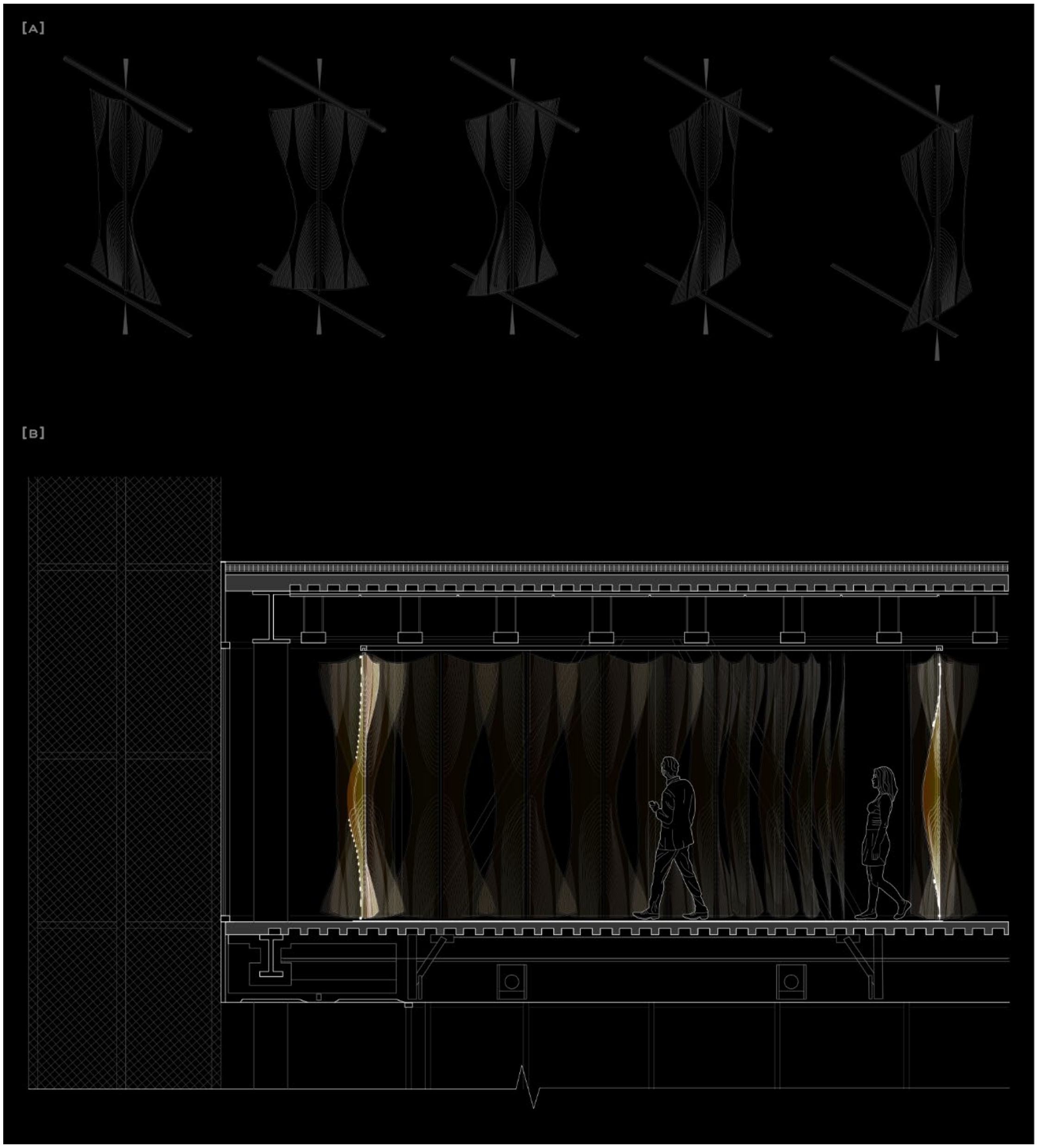

Figure 3-20: Architectural intervention: [a] Panels form part of a track system where they can pivot, rotate, and slide. [b] Section of a spatial configuration.

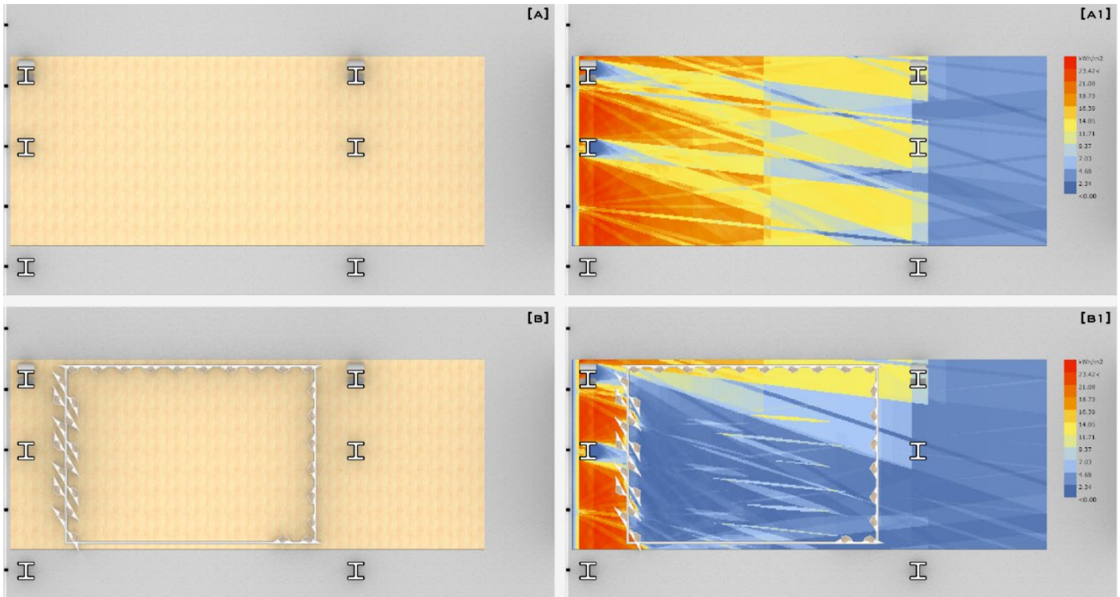

Figure 3-21: Floor plans highlighting the radiation exposure throughout the year. [a1] No intervention, [b1] with intervention.

Figure 3-22: Rendering of a screen wall system comprised of the hybrid bio-composite panels.

CHAPTER 4

Conclusions

4.1 Results

The work presented in this thesis serves as a continuation on some of the latest innovative uses of silk fibroin as a biomaterial. In previous works the material was only being investigated in the fields of biomedicine, optics, and electronics. Whereas in this body of work the scalability and application of silk was explored in a larger context. The framework established is a synthesis of multiple ideas and materials coming together to create a hybridized workflow that can be used in the field of design and architecture.

The hybrid bio-composite panels produced in this body of work serve as a proof of concept regarding the advancement of biomaterials in the role of architecture and design. More specifically how silk could be integrated and applied at a larger context through the design of a screen wall system. Moving forward the screen wall could take advantage of the conductive properties found in silk to harvest and store solar energy. As mentioned prior, silk is being used to create optics and electronics. With these technologies and the power of 3D printing the possibility of harvesting solar energy is a topic worth exploring in the future.

The framework presented takes advantage of the properties found in the fibroin-chitosan solution and through a bio-fabrication process the material was programmed to take on desired specific forms. Its natural ability to deform while curing/drying provided unique opportunities for design, regarding form generation. Along with the transformation process, the aesthetic properties such as the coloration and transparency are parameters that can be modified to achieve different functions. The addition of the silk solution to the chitosan gel contributed to more durable and stiffer bio-composites. With the main feature of the silk being its shiny and reflective coating that was present in all of the bio-composite panels. This along with the final geometry led to interesting results regarding the interactions the material had with natural and artificial light. The 13.5 x 7” (342.9x177.8 mm) panels proved that the scalability of the framework functioned and that it could continue to increase in size.

4.2 Contributions

The following highlights the two core concepts in which this research hopes to contribute to.

4.2.1 Design for Ethics and Optimization

Instead of boiling and killing silkworms just to obtain their cocoons, a more holistic and ethical approach was taken to allow the silkworms to complete their lifecycles. By designing specialized cocooning cells, the silkworms were able to cocoon and complete their metamorphosis. As a result, the continuous filament of silk was broken, however it did not have an effect as the cocoons are ultimately cut into small pieces. Designing confined spaces for the silkworms also proved to affect the density and quality of the silk. By limiting the space in which they had to form the cocoon the silk was naturally modified at a microscopic level, which enhanced the quality of the regenerated silk solution used in the bio-fabrication process.

In the near future the sericulture industry could benefit from the design of specialized cocooning cells. Based on the research that has proven that confined spaces lead to an increase in the quality and mechanical strength of silk. The hope is that through this case study, new design opportunities emerge and allow the silkworm to peacefully complete its lifecycle.

4.2.2 Framework for Hybrid Bio-Composites

The research in this thesis provides a methodology for the hybridization between biomaterials and regular PLA filament. It shows the potential between the two material systems and how the crossbreed can be applied at a larger context. More specifically for interior functions as the hybrid bio-composites are susceptible to biodegrading much quicker outdoors. The framework outlined provides a new form of fabrication in which an artificial material can be designed, and 3D printed in such a way that it naturally adheres to an organic biomaterial solution. Thus, resulting in a hybridized system or in this case hybridized bio-composite panels.

As the field of architecture continues to pursue the use of green materials for the built environment. This form of fabrication could be adopted and modified so that it can be applied to a wider range of building systems beyond interior screen walls.

4.3 Future Directions

Moving forward there are several methods in which the current framework could be modified to achieve better if not new results. This includes the following: 1) Substituting the materiality of the PLA with a more organic and eco-friendly material or biomaterial. 2) Explore how new geometries and patterns interact with the fibroin-chitosan solution. 3) Take advantage of the conductive properties found in silk to 3D print and imbed a photovoltaic interface within the bio-composite. Such system will require for another hybridized method of fabrication, one that merges the photovoltaic interface with the framing structure. 4) The development of a cocooning cell that allows the moth to emerge from the cocoon without compromising the continuity of the silk filament. The thesis in its current format is only at the early stages of its development. The next phase could be centered on achieving a perfect bond between the biomaterial solution and the 3D printed structure at a larger scale. As the scalability of this framework increases the possibility of integrating it into the built environment becomes much more probable.

REFERENCES

Bradley, David. "3D Biofunctional Silk Materials." *Materials Today*, 30 Jan. 2017, https://www.materialstoday.com/biomaterials/news/3d-biofunctional-silk-materials/.

Chen, Fujia, et al. "Morphology and Structure of Silkworm Cocoons." *Materials Science and Engineering: C*, vol. 32, no. 4, 31 Jan. 2012, pp. 772–778., https://doi.org/10.1016/j.msec.2012.01.023.

Cheng, Lan, et al. "Natural Silkworm Cocoon Composites with High Strength and Stiffness Constructed in Confined Cocooning Space." *Polymers*, vol. 10, no. 11, 2018, p. 1214., https://doi.org/10.3390/polym10111214.

Koh, Leng-Duei, et al. "Structures, Mechanical Properties and Applications of Silk Fibroin Materials." *Progress in Polymer Science*, vol. 46, 2015, pp. 86–110., https://doi.org/10.1016/j.progpolymsci.2015.02.001.

Laugier, Marc Antoine, and Samuel Wale. *An Essay on Architecture ; in Which Its True Principles Are Explained ... Adorned with a Frontispiece, Designed by Mr. Wale, Etc.. by Marc Antoine Laugier.* T. Osborne & Shipton, 1755.

Matzeu, Giusy, et al. "Large-Scale Patterning of Reactive Surfaces for Wearable and Environmentally Deployable Sensors." Advanced Materials, vol. 32, no. 28, 2020, p. 2001258., doi:10.1002/adma.202001258.

Mogas-Soldevila, L., et al. "Additively Manufactured Leather-like Silk Protein Materials." Materials & Design, vol. 203, 2021, p. 109631., doi:10.1016/j.matdes.2021.109631.

Mogas-Soldevila, Laia. "Water-Based Digital Design and Fabrication: Material, Product, and Architectural Explorations in Printing Chitosan and Its Composites." *Massachusetts Institute of Technology* , 2015.

Mogas-Soldevila, L., & Oxman, N. (2015). Water-based Engineering & Fabrication: Large-Scale Additive Manufacturing of Biomaterials. MRS Proceedings, 1800, Mrss15-2135989. doi:10.1557/opl.2015.659

Mwila Isabel Nkandu, Halil Zafer Alibaba, Biomimicry as an Alternative Approach to Sustainability, Architecture Research, Vol. 8 No. 1, 2018, pp. 1-11. doi: 10.5923/j.arch.20180801.01.

Omenetto, Fiorenzo G., and David L. Kaplan. "New Opportunities for an Ancient Material." *Science*, vol. 329, no. 5991, 2010, pp. 528–531., https://doi.org/10.1126/science.1188936.

Oxman, Neri. "Neri Oxman." *Neri Oxman | Neri Oxman*, 2018, https://neri.media.mit.edu/neri-oxman.html.

Rockwood, Danielle N, et al. "Materials Fabrication from Bombyx Mori Silk Fibroin." *Nature Protocols*, vol. 6, no. 10, 2011, pp. 1612–1631., https://doi.org/10.1038/nprot.2011.379.

The Corticelli Silk Mills. *Silk, Its Origin, Culture and Manufacture*. The Corticelli Silk Company, 1930.

United Nations Environment Programme (2020). 2020 Global Status Report for Buildings and Construction: Towards a Zero-emissions, Efficient and Resilient Buildings and Construction Sector - Executive Summary. https://wedocs.unep.org/20.500.11822/34572.

Yin, R., et al. "Cleaner Production of Mulberry Spun Silk Yarns via a Shortened and Gassing-Free Production Route." *Journal of Cleaner Production*, vol. 278, 2021, p. 123690., https://doi.org/10.1016/j.jclepro.2020.123690.

Zhang, J., et al. "Mechanical Properties and Structure of Silkworm Cocoons: A Comparative Study of Bombyx Mori, ANTHERAEA Assamensis, Antheraea Pernyi and Antheraea Mylitta Silkworm Cocoons." *Materials Science and Engineering: C*, vol. 33, no. 6, 2013, pp. 3206–3213., https://doi.org/10.1016/j.msec.2013.03.051.