The Pennsylvania State University

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FIBROUS FUTURE OF ARCHITECTURE: COMPUTER-AIDED FABRICATION OF HYBRID CARBON FIBER AND JUTE FIBER TEXTILE CHAIR MADE WITH WEAVING AND 3D PRINTING TECHNIQUES

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Berfin Evrim

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The thesis of Berfin Evrim was reviewed and approved by the following:

Felecia Davis
Associate Professor of Architecture
Thesis Advisor

Shadi Nazarian
Associate Professor of Architecture

Charles E. Bakis
Distinguished Professor of Engineering Science and Mechanics

Mehrdad Hadighi
Professor of Architecture
Head of the Department or Chair of the Graduate Program

ABSTRACT

This thesis presents research that combines weaving and 3D Printing to fabricate a textile that will be used for supporting the weight of a person sitting on a stool or chair. This textile uses carbon-reinforced polymers and jute fibers that are stiffened by thermoplastic elastomer (TPE) to achieve adequate resistance with lightweight material. The use of TPE offers a biodegradable option as a stiffener in the textile. 3D Printing different geometric toolpaths allow for variable rigidity in the fabric. The goal of this research is to design a chair of 20 by 20 inches that withstands loads of a 250 pounds person, using a physical and digital model of 5 by 5 inches.

Contributions of this research include several geometric tool paths affecting the stiffness of the textile in combination with the weaving pattern and weaving materials. These toolpaths also include geometry inspired by cow bone structure. Besides, a digital tool was developed coded in Grasshopper that allows for parametric modeling of textiles (stiffness, geometry, etc.). These textiles can then be loaded in this digital tool, and their behavior simulated to understand the maximum strengths of each textile design. This approach prevents material waste and allows designers to generate fabrics for possible architectural applications in different loading conditions.

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Chapter 1: Overview

Introduction

Textiles have been a critical element for people to protect themselves from severe weather conditions and to build shelters since prehistoric times. Therefore, people invented different methods of fabrication of textiles such as knitting, weaving, and felting, according to The Primary Structures of Fabrics by Irene Emery (1966). These fabrication methods are further developed in Fiber Reinforced Polymers. Notably, the weaving technique allows for fibers to interlace with different types of fibers and perform well in tension. This thesis investigates the hybridization of jute and carbon-reinforced polymers by utilizing weaving techniques focusing on crossed warp weaving and plain weaving to make a seating design.

Fibers present significant opportunities for the future practice of architecture because of their lightweight and high-strength properties. The ultra-lightweight characteristic of fibers lowers transportation and construction costs. Moreover, carbon-reinforced material can be shaped to a wide range of geometries and interlaced with natural fibers such as jute fibers. The use of jute fibers can lower the negative environmental impact and benefit for material and cost-efficiency. After the production of three-dimensional geometry, Computer-aided fabrication systems that print Thermoplastic Elastomer (TPE) or Polylactic Acid (PLA) can augment the use of material by stiffening the fibers to make them more adaptable to shear loading conditions. Continuous fiber printing and printing on the fabric present two different approaches to the relationship between 3D printing and fibers. To take another step forward in optimization of the textile design, digital tools as Grasshopper (Rutten, 2014) offers a platform for coding algorithms, allowing designers to test the structural resistance of the textile and to change the parameters easily to withstand allowable stress.

High-strength fibrous structures can be analyzed through biological systems such as bone growth for a better understanding of design optimization. The trabecular structure gives a lesson about how density and alignment of material can provide tensile and compressive strength in specific loading conditions. This knowledge can be imposed on a digital tool for stronger architectural elements such as barrier walls, columns, beams, structural ceiling, and certainly furniture construction, as is the intention in for this thesis project.

Thesis Structure

This thesis includes four super sections and seven chapters in total. In the first section, *Understanding*, the author summarizes the structure of the thesis and explains the topic that this thesis focuses on and approaches to exploring the research question and problem statement in Chapter 1. The first section, *Understanding*, covers the knowledge that is gained by other literature and experiments. In Chapter 2, the author provides background information about the properties of fibers, fabrication methods, architectural application, biomimicry, design optimization, simulation analysis, and seating unit analysis.

In the second section titled *Experiments*, the author explains the methods developed and experiments throughout this research. In Chapter 3, the author describes the analysis of cow femur bone structure to understand this biological structure for use in architecture and making designed objects such as a chair or stool. In Chapter 4, the author explains fabrication methods and a combination of traditional textile fabrication with 3D printing. In Chapter 5, the author explains the digital tool that allows parametric textile fabrication and tests the structural resistance of the textile under a uniform loading condition.

In the third section titled *Synthesis*, the author explains the synthesis and contributions resulting from the experiments. In Chapter 6, the author gives an overview of the stool design. In the last section is titled *Conclusion*, the author concludes the thesis by describing limitations, further research opportunities, and the summary of contributions in Chapter 7.

Research Question

The goal of this research is to investigate an integrative fabrication technique of weaving and 3D printing to stiffen the fabric, which is a part of a stool design that is inspired by biological principles. Furthermore, the author of this research explores a novel digital tool to optimize the design of a seating unit to achieve material efficiency with maximum structural resistance in tension and displacement. Seating units have horizontal load-bearing and vertical loading-bearing elements that transfer their load to the ground. This makes them a good object to understand when thinking about building for architecture.

The other goal of this research is to avoid any strength failure such as fracturing and breaking and increase the resistance of the pre-tensioned structure under an applied load. Therefore, the author's research question is; How can the integration of weaving and 3D printing techniques enhance future seating unit design with less material than conventional fabrication while adopting biological principles such as cow bone growth?

Problem Statement

Former manufacturing techniques of Fiber Reinforced Polymers are mostly concentrated on the molding method. This method requires an extra mold fabrication, which can be made of polystyrene foam or wood, and causes waste of material. The weaving method that is presented in this thesis emphasizes the lightweight property of the material and decreases the amount of material used during the fabrication with analyzing the loading conditions of the seating unit and avoids waste of any kind of material.

For the analysis of the effects of various loading conditions, there are limited platforms for designers to design parametric textiles and test the structural properties of the textile on the same platform. This author of this thesis presents a novel digital tool that is coded in Grasshopper allows designers to hybridize different fibers and plastics and test a variety of textile structures to optimize the final design of architectural elements. It makes it possible to add more material where loading passes; therefore, it prevents unnecessary material usage and creates stronger and less heavy structures than structures produced with conventional fabrications.

Additionally, the author explores a less toxic and more sustainable way of adding stiffness to the fabric. Instead of using any kind of synthetic resin for stiffening the fabric, 3D printing Thermoplastic Elastomer, which is non-toxic, biodegradable, plasticizer-free, can be a substitute to prevent significant deformation in a specific direction of the fabric.

The reason for choosing a stool as a design element is understanding the relationship between vertical and horizontal elements to carry the applied load to the ground. The study of this functional furniture creates the potential to apply the knowledge that is gained from this research to a larger scale architectural compositions such as a wall, floor, and ceiling construction. The fabrication technique for combining weaving and 3D printing can result in the development of the use of textiles in architecture.

In short, the goal of this research is to decrease the amount of material used for the fabrication of structural elements. The author presents a novel approach for the application of fibers in architectural systems. The author explains how weaving and 3D printing methods can be synthesized with the biological principles to create stronger and lightweight structural elements.

Hypothesis

The integrative fabrication method of 3D printing and weaving allows interlacing natural fibers with fiber-reinforced polymers and stiffen the woven fabrics by 3D printing thermoplastic elastomer. The digital tool makes parametric fabric modeling and structural testing possible and results in the grading of material where the is greater loading. Designers can reduce the overall amount of material used to support loads in design objects such as chairs, columns, beams, etc. made of fabric while simulating the structures under the load with the digital tool.

Research Methodology

The author tests the feasibility of the thesis with the following methods:

1) Analyzing cow bone structure with SEM imaging.
2) Exploring a traditional weaving pattern and relating to the cow bone structure.
3) Designing a weaving loom for fabrication.
4) Weaving prototypes of three different weaving patterns (two of crossed warp interlacing and one of plain weaving).
5) Testing tool paths of extrusion of different filaments on fibers to achieve maximum strength.
6) Coding an algorithm in Grasshopper to create a digital platform to make parametric fabric modeling possible.
7) Modeling the woven fabrics in the digital platform for structural analysis.
8) Fabrication of layers of woven fabric and 3D printing in between layers.
9) Designing a frame that holds the fabric that is the final chair design.

Contributions

The author of this thesis aims to make the following contributions:

1) Explore traditional weaving fabrication techniques and combined with 3D printing to add stiffness to the woven structure.
2) Design a digital tool allows modeling of parametric fabric with different weaving patterns and analyze the structural resistance of textile in various loading conditions.
3) Develop a construction technique that differs from continuous fiber and chopped fiber fabrication but integrates both approaches.
4) Interlace different fibers to achieve maximum strength with less material as possible, inspired by cow bone structure.
5) Present an experimental stage of continuous fiber 3D printing with a robotic arm for larger-scale structural and architectural element production.
6) Synthesize the result of experiments with a seating unit and explain the potential future architectural applications.

UNDERSTANDING

Chapter 2: Literature Review

This literature review consists of seven sections; understanding the mechanical properties of fibers, comparing different manufacturing and fabrication methods, learning the weaving techniques, analyzing the former architectural application of fibers, relating bio-mimicry and bone architecture into the design, and comprehending the use of topological optimization for form-finding, simulation analysis, and seating unit analysis.

The Mechanical Properties of Fibers

First of all, understanding the mechanical and physical properties of the material is the critical component of this research. Martin Alberto published “Fiber Reinforced Polymers” in 2013. He talks about the mechanical properties of the Fiber Reinforced Polymer, explaining the use of the material in different fields. He describes the various manufacturing processes and concepts. He explains the strength, toughness, elongation, and modulus of this material. John Fernandez has a more general approach in his book, which published in 2006. His book talks about the properties of architectural materials. The goal of this book is to create an opportunity for designers to analyze and compare different materials. This book has three sections. In the first section, he talks about the history of materials; how it used in the past and contemporary design. The second section explains metals, polymers, ceramics, composites, and natural materials. Finally, he talks about architectural assemblies that are innovative while presenting case studies. Yiqi Yang (2017) also focuses on lightweight composite made of different fibers by varied processing technologies. He talks about the areas that use FRP. The book covers the reinforcement properties of composite materials. He explains raw material, processing technologies, performance properties, and end uses of lightweight composites.

The properties of natural fibers such as jute play a significant role in the development of the project. The use of natural fibers has been increasing in civil engineering, automotive, and architecture field. Sanyal (2017) has published a book about geotextiles made of jute and proposed solutions for soil-related problems. He gives a brief history of Jute and explains characteristics, physical properties, and types of jute and their functions. After understanding the general properties of the jute fiber, Faruk (2015) has discussed jute reinforced polymer composites. He explains the mechanical properties of jute composites and their application in a different field. Additionally, he describes possible surface modifications such as grafting, mercerization, oxidation, ultra-violet, and gamma radiation to increase the adhesion between polymer matrices and jute fiber. Another researcher, Jabbar (2017), studies sustainable jute based composite materials. He explains the advantage of replacing synthetic fiber in specific applications with natural fibers. He presents novel environment-friendly treatment methods and mechanical, creep, and dynamic mechanical properties of composites. He suggests that he uses the jute because of good mechanical properties, low-cost, easy availability, and renewability.

Hybridization of Materials

Hybridization of polymers results in increasing the strength of the structure and decreasing the cost of construction. Jagannatha and Harrish (2015) explain the mechanical properties of carbon and glass fibers reinforced epoxy hybrid composite. They suggest that hybrid composite materials have great potential for future design and engineering fields. They study hardness, tensile strength, tensile modulus, ductility, and a peak load of the hybrid composites. They use different kinds of fiber with the same resin matrix to investigate mechanical properties. Furthermore, Swolfs, Gorbatikh, and Verpoest (2014) focus on hybridization and talk about the market of FRP for the construction of the structural system. However, they support that further growth of the market is constrained by a lack of toughness. Hybridization is a solution that they suggest for toughening composite materials. A combination of multiple fibers can result in better mechanical properties. Their research expresses the basic mechanisms of these hybrid effects. They investigate the tensile, flexural, impact, and fatigue properties of hybrid composites, and it can be optimized in design.

For reducing the environmental effect, the hybridization of natural fibers with synthetic fiber plays a significant role. Sezgin and Berkalp (2016) study the impact of hybrid composites such as jute/carbon reinforced composites, and jute/ glass-reinforced composites. They determine fiber weight and ratios in the laminate system. They explore the effect of stacking layers of fabric on mechanical properties such as tensile and impact strength. Their study shows that high impact resistance material should be located in outer layers, and high tensile strength fiber should be located in inner layers to achieve maximum strength at hybrid composite laminates. Aakash et al. (2019) explored more about the hybridization of carbon/jute fabric reinforced epoxy hybrid composites. They also suggest that carbon fibers have a lower strain to failure, and jute fibers have a higher strain to failure property, and hybridization of these fibers results in between strength and strain to failure. They study the flexural behavior of hybrid composite experimentally and numerically. They test different ratios of jute, and carbon-reinforced polymer and epoxy to achieve maximum flexural strength.

Additionally, hybridization of materials such as thermoplastics and fibers creates an excellent opportunity for additive manufacturing while increasing the strength of the 3D printing parts. Thomas (2018) investigates carbon nanotube-based filaments made with carbon nanotubes in an acrylonitrile butadiene styrene (ABS) polymer matrix with a different polymer to matrix ratio. His research shows that integration of ABS and enhanced filaments can be used for the fabrication of multi-functional structures. He talks about the advantages and disadvantages of the use of a nanostructured 3D printed filament. He tests the electrical conductivity and strength of printed parts. He suggests that 3D printing polymer filaments promise for the development of integrated devices with a little increase in the cost of fabrication. Zhou and Chen (2018) also study 3D Printing of Carbon Reinforced Plastics and their applications. They suggest that the use of carbon fiber filament can allow the production of complex and lightweight structures. They discuss short carbon fiber reinforced plastics and continuous carbon-fiber plastics. They compare the tensile strength of various commercial short carbon fiber reinforced plastics that are used for 3D printing.

Manufacturing and Fabrication Methods

After studying the properties of fiber-reinforced polymers and hybridization of materials, manufacturing and fabrication methods of fibers are studied. Park published a book in 2018, focusing on carbon fiber. The author talks about manufacturing methods, surface treatment, composite interfaces, and microstructure-property relationships. He explains the mechanical and physical properties of carbon fiber and composites. This book suggests that carbon fiber is strong, stiff, and lightweight, and it is used in as aerospace, sports, automotive, wind energy, oil and gas, infrastructure, defense, and semiconductors. The author talks about the advantages and disadvantages of the material, which has significant potential in the future. He also investigates the manufacturing process of carbon fiber and carbon fiber structures. The other source that investigates the fabrication process is “The Mechanical Properties of 3D Woven Composites,” written by Umer, Zhou, and Cantwell in 2017. These authors focus on three types of 3D woven fabric: orthogonal, angle interlock, and layer-to-layer. The authors investigate the mechanical properties of each type of woven production. They measure compaction and permeability characteristics of reinforcements. They talk about the results that they have derived from the experiments they did. They explain the mechanical properties of the final product that they generated from different fabrication methods.

There are other researchers who demonstrate studies showing various fabrication methods. Menges et al. published a book in 2017. They gathered conference publications in a book that takes place at the University of Stuttgart. Their main theme is "Negotiating Design and Making" They focus on larger scale projects that demonstrate high tech strategies in construction. They emphasize the concept of materialization, additive strategies, and construction. They question the cyber-physical production system and new forms of man-machine interaction.

The researchers that show the production of hybrid polymer systems present different ways of fabrication. Irina et al. (2015) investigate different arrangements of hybrid composites, which are made of glass fiber and carbon fiber polymer and their mechanical properties. They used the vacuum technique for resin transfer molding and produced hybrid composite panels. They explain the tensile strength, flexural strength, and volume fraction of the hybrid composites. Zhang et al. (2012) focus more on the environmental and economic aspects of the use of a lightweight structure that can form with a fiber-reinforced polymer. To reduce construction costs, the use of hybrid composite material is significant. Researchers talk about the strength and stiffness of hybrid composites. Hybrid composites are a combination of different ratio of glass fiber and carbon fiber in an epoxy matrix. Reseacrhers investigate how the ratio of carbon fiber and glass fiber can affect the tensile and compressive strength of the structure.

Some researchers are more specific about their fabrication method, and they analyze their final product’s mechanical properties. Corazza et al., who are researchers from the Architecture Association School of Architecture (2016), focus on the geometrical framework with sandwich materials to develop fiber composite fabrication methods in architectural applications. Bending behavior of thermoplastic foam functions as an extensive formwork for geometrical articulations. This research explains varied material manipulation techniques to control bending curvatures that can be found in natural systems. Sharmin and Sean (2016) demonstrate a material system with hybrid material properties, which is differentiated tensile, and bending-active forces in a single, seamless knitted composite material. They talk about how they achieved these behaviors during materialization and composite formation process. They used knitted textiles with tensile reinforcement and vacuuming techniques in the resin matrix. They use a flatbed industrial knitting machine for the fabrication of knitted textiles. They explain how they control the material types, densities, and cross-sections.

Additionally, Blonder and Yasha (2016) explain how Fiber Reinforced Polymer has embedded fabric materiality. It has a form of fabric, but the fabrication process is different than that of textiles. The advantage of having this property is the adaptability of it in the fabrication of architectural FRP. The complexity of architecture can be generated through understanding the nature of the biological materials. Authors suggest fabric materiality can be a framework for architectural design, and they prove their argument through presenting a case study, which has a complex bio-inspired structure. Corbin et al. (2018) explain the mechanical properties of the 3D Warp interlock fabrics, where these fabrics are used for fibrous reinforcement. They explain how binding warp yarns can show varied mechanical behavior. They support that there is a lack of experience on the optimized fabric parameters. To experiment with different fabric parameters, they used different types of 3D warp interlock architectures and different raw materials. However, they did not change the weaving pattern, and they explained the results of their research. Dias et al. (2015) explore the ways of adding a new function into a conventional textile where it integrates electronics and textiles. They can be used in communication, healthcare, protection, and wearable technology. First, she explains conductive fibers, carbon nanotubes, and polymer yarns and then fabrication of smart fabrics and the design of sensors and actuators and energy harvesting methods. She also covers the application of smart fabrics in wearable electronics and communication sensors.

Researchers also try to investigate different weaving techniques for FRP textiles. Liu and Kiju (2018) develop a novel technique of weaving 3D Textiles, which is called wire-woven bulk Kagome with polymer wires or threads. Their invented weaving machine is based on a manual loom. The research explains the advantages, limitations, and plans of this machine with detailed mechanisms. Tong et al. (2002) interpret 3D composites made using the textile technologies of weaving, braiding, knitting, stitching, and z-pining. The author explains the areas that FRP is used. They mention new high-performance resin systems and carbon nanotubes and nanoparticles. Karkkainen et al. (2009) also talk about the fabrication methods to increase delamination resistance and through-thickness properties with 3D reinforced composites. These methods are weaving, stitching, and z-pinning. The authors talk about the limitations of the fabrication process. They explain the properties of the specimen that are produced with these fabrication methods. Their goal is to optimize the design with stiff and strong properties.

The other fabrication method is the additive manufacturing of Fiber Reinforced Polymers. Ning et al. (2017) suggest that additive manufacturing of carbon-reinforced plastic composites (CRFP) can allow short manufacturing cycle time and low production cost compare to the molding process. Researchers analyze CFRP composite parts that are produced by Fused Deposition Modeling. They test raster angle, infill speed, nozzle temperature, and layer thickness on the tensile strength of the part with using a scanning electron microscope. Naranjo-Lozada et al. (2019) evaluate the effects of different geometric parameters and tensile properties of 3D printed composites manufactured by continuous fiber printing and chopped fiber printing. Researchers believe that fused filament fabrication has advantages as low input energy and material cost, minimum waste, no need for chemical post-processing, and consistent prototype accuracy. They test the printed composite parts, which have varied infill density, infill pattern, and materials to analyze the impact of these variables on tensile strength. Lasova and Sedlacek (2018) contribute to the study of additive manufacturing of short carbon-fiber reinforcement using Fused Deposition Modeling. They study the filaments of short carbon fibers in nylon polymer. They print the parts with different temperatures to evaluate the strength and heat deflection of each printed parts.

After analyzing different fabrication methods, the weaving techniques are studied to produce structural elements that allow the interlacing of different fibers to perform their maximum strength and achieve material efficiency. Irene Emery(1966) published a book titled *The Primary Structures of Fabrics*. Emery explains different types of textiles produced with different methods. The book is structured under three categories; interlocked, interlaced, and felted fabric structures. Emery demonstrates each structure with images and defines the terminologies. Felecia Davis (2012) explains three traditional fabric structures that are mentioned by Emery and translates them into digital code to fabricate 3D printed textiles in the paper titled 3D Printed Textiles from Textile Code: Structural Form and Material Operations. Davis investigates printed textile geometries and material of the textile unit. Davis presents a novel perspective on how textile behavior relates to its structure and how to design kinetic structures with the digitally constructed textile structures.

Additionally, Felecia Davis (2012) publishes another paper from a workshop, Form Active Translations: Knitted Textiles to 3D Printed Textiles. Davis translates the machine knitted textiles to 3D prototyped textiles. Davis presents a platform where designers can understand geometric textile structures and their behaviors to build a kinetic building system using textiles. Davis develops an idea for students, who have less knowledge in Rhinoceros, which is a 3D visualization software to model a pegboard for a better understanding of fabric structures.

Previous Architectural Application

After understanding the properties of Fiber Reinforced Polymer and different fabrication methods, the former applications of this material in the architectural field is explored to understand what this material promises for future architecture. Jiping Bai (2013) describes FRP applications in Advanced Fiber-Reinforced Polymer (FRP) Composites for Structural Applications. Bai talks about how Fiber Reinforced Polymer has the potential of strengthening infrastructure. The researcher explains how FRP composite materials can develop novel hybrid material and structural systems. Bai suggests that engineers need to know the constraints of the material and design composite structures. Smits (2016) talks about the use of Fiber Reinforced Polymer in bridge design specifically. Smits focuses on the bridge designs in the Netherlands. This paper explains the limitations and benefits of the use of FRP. Smits supports that engineers have been the pioneers of the use of FRP in construction, and architects should start to explore this material to improve bridge design that is made of FRP with an architectural perspective.

Other sources have focused on the use of carbon fiber in infrastructural and structural systems. Volmer (2015) proves that Carbon Fiber Reinforced polymer can use for large-span structure in the architectural field. The material is lightweight and has a significant strength to weight ratio. This property of CFRP can help the infrastructure system in dense cities. This material can also become a significant structural material for high-rise buildings. The authors explain possible CRFC implementation and the future of the material. Wit et al. (2016) also suggest that Carbon Fiber Reinforced Polymer provides opportunities for innovative form and fabrication methods into the architectural discipline. Wit supports that the geometries and construction techniques will no longer be limited by conventional materials. The use of CFRP can result in less construction waste and structural objectives. They talk about the design, fabrication, and structural potentials of the wound, pre-impregnated CFRP composites in architectural-scale applications. They present two-research projects that are based on composite winding implementation.

For further understanding of the use of Fiber Reinforced Polymer in structural systems, the application of Fiber Reinforced Polymer in column and beam design are studied. Wang (2019) has utilized Glass Fiber Reinforced Polymer (GFRP) for wrapping the syntactic foams that are hollow glass macrospheres bonded with a polymer matrix. The goal of their research is to improve structural performance and energy absorption. In their experimental research, they manufactured load-carrying structural columns with a GFRP composite shell. They measured the strength of the columns with load, strain, and deflection responses. They analyzed the factors of shell thickness, fiber volume percent, syntactic foam density, and cross-shaped fiber orientation.

Another research that is conducted by Mike Silver has received a patent for the invention of composite beam structure in a matrix of thermoplastic resin. The structure is 1.5 times stronger and seven times lighter than a steel beam. They aimed to produce trusses with various open and closed surfaces for modulation of natural light. They optimized the structure by placing the fibers according to the direction of the loads. Their goal was enabling maximum load with an ultra-lightweight beam structure.

Chairs made of Fibers

After studying the use of FRP in column and beam design, the seating unit and chair design that are fabricated with carbon fiber reinforced polymer are investigated. Iida et al. (2014) have designed a zig-zag chair made of carbon-fiber-reinforced polymer. Their concept depends on Sullivan's “Form follows function” idea. They calculate the loading conditions and fold the carbon fiber reinforced polymer fabric for optimized chair design. Iida et al. (2015) conduct new research focusing on the displacement of the structure of the zig-zag chair. They compared three different structural models; rib structure, hollow structure, and fold structure. They used a molding technique to build a different zig-zag chair. After analyzing the models, they suggest that fold structure is the most well-balanced compare to others.

Eames et al. (1989) have designed a prototype armchair made of fiberglass. They used hydraulic press molds to shape polyester reinforced with fiberglass. The deep seat is crafted to distribute the user’s weight and pressure ergonomically. Shigeru Ban (2009), a Japanese architect, has designed a lightweight chair made of carbon fiber. He creates his own sandwich structure of layers of carbon fiber and aluminum. Matthew Strong (2014) uses 12K carbon fiber tows to fabricate an intertwined sofa. The sofa is inspired by Eames fiberglass armchair, and the seating surface has an openwork woven structure that provides transparency and reflects the lightweight property of the chair.

Estrada et al. (2019) design a lightweight and hanging chair made of carbon fiber reinforced polymer and steel bars. They are inspired by Gaudi’s models; therefore, they use Karamba 3D for form-finding reasons to apply gravity. They impregnated carbon fiber with epoxy resin. They optimize their design with an integrative approach to design and fabrication by focusing on material research and computational design.

Biomimicry in Design

More methods have been used by designers to produce optimized structures. For instance, architects have been inspired by nature for a stronger and more efficient architectural design. Claus Mattheck has written *Design in Nature* (1998) to explain the biomechanical optimization of shape. He believes that mechanical structural members can be improved with the knowledge of the process in nature. He demonstrates how nature can inspire architects for eco-design with following nature's laws. In chapter 11, "Bone Design," he gives an example of trabecular bone and its capability of carrying heavy loads. He describes trabecular bone as "micro-frameworks as pressure distributor, dashpot, and lightweight." He also demonstrates a different process in nature, such as trees, for a better understanding of how nature can be the inspiration source.

Some researchers have started engaging with computation and biology for architectural applications. Reichert et al. (2014) talk about integrative computational design methodology while using a robotic implementation of fiber-composite systems. They integrate biological principles such as lobster's pincher claw with material and structural analysis while robotic filament winding within a coherent computational design process. They focus on fiber layout based on the global morphology of the system. They also talk about plans to create a full-scale architectural prototype.

To apply biological principles to develop novel fabrication methods, the bio-mimicry is studied. In 2015, Pohl and Werner, who are biologist and architects respectively, discuss the application of biological principles in architectural design. They compare nature and technology while analyzing the architectural translation of inspiring biology. They explain sustainable and advanced design derived from mimicking nature. They present a nature-inspired architecture that is designed by bionic design methods. The University of Stuttgart has a research institute that focuses explicitly on Fiber Reinforced polymers. In 2014, Dörstelmann et al. at University of Stuttgart explain the integration process of computation, material, structure, and biomimicry. They explained the process through a case study ICD/ ITKE Research Pavilion 2013-14. The integrated design process involved different disciplines while generating form and materialization. Material and form are interrelated, and fiber composite material is the form generator. They focused on fibrous structures in nature such as elytron to create principles for the development of integrative computational design methodologies.

Bone Growth

Many studies show that a computational framework for FRP can be designed through the analysis of the bone structure. Libonati et al. (2019) are inspired by bone structure for the design of novel composite. Their goal is to optimize strength-toughness and stiffness-density combinations. They analyze 2D lattice spring models with different reinforcement geometries that are derived from bone structure to achieve improved fracture resistance and balance with stiffness and strength. Audibert et al. (2018) are other researchers that study bone architecture to produce structurally optimized workpieces to reduce the weight of structure while maintaining the resistance. They consider the shape, size, and orientation of porosities to 3D print metal beams. In addition to these studies, designers have used the bone structure for the form-finding process. Halem (2013) published a book called Acquisitions: Twentieth-century Fine and Applied Art. He talks about the bone chair, which is designed by Joris Laarman. A designer meets Claus Mattheck, and he gets inspired by bone growth while designing the chair. He uses topological optimization software and carves out the material where it is stronger.

Topological Optimization

As Joris Laarman, many designers and architects have used topological optimization methods. Flavio Craveiro (2016) designs a wall made of concrete and cork using additive manufacturing. He gets the data of structural loading conditions with finite element analysis, and he uses the data for optimized wall construction by adding more concrete where it is needed.

Neri Oxman (2016) is another designer who analyzes the loading conditions for design optimization. She designed the Beast Project that presents a single continuous surface modulated with Voronoi tessellation according to structural load to function to create a skin and structure. She integrates structural and material performance by analyzing the effect of the loads, curvature, pressure on the thickness, stiffness, density, and pattern of the material. She fabricates the seating unit with multi-material 3D printing using acrylic composites. She designs rigid vertical walls for structural stability and soft horizontal planes for a comfortable seating surface.

Martinez (2017) has published an article about additive manufacturing and mentions the work of Lillian Van Daal. She had used a similar approach as Oxman when she was designing Biomimicry Chair. Van Daal is inspired by the plant cell, and she 3D printed prototypes for flexible and rigid surfaces. She uses less material in horizontal alignment where the seating surface is and more material in vertical alignment for structural purposes. She produces her chair with 3D printing biodegradable materials.

Simulation Analysis

Topological optimization can be achieved by the utilization of simulation tools that allows finite element analysis. Karamba 3D is a plug-in to Grasshopper that allows testing 3D modeled geometries under a given loading condition. Dzwierzynska et al. (2019) use Karamba 3D to test the curvilinear steel bar roofs' structures shaped based on Catalan surfaces to choose the most efficient structure. They test three various shaped roof structure that are cylindroid shape, conoid shape, and hyperbolic paraboloid shape. They determine the optimal positions of columns and the base surface. They aim to reduce the weight of the structure as much as possible.

The other study that uses Karamba 3D is titled as "Design and Analysis of Bending Active Formwork for Shell Structures Based on 3D-Printing Technology". Zhang et al. (2019) design a 3D printed thin bending active formwork for shell structure. They use Kangaroo, which is a plug-in of Grasshopper for form-finding purposes. Then, they 3D print principle stress lines on the shell and use Karamba 3D to simulate shell deformation under gravity load (Figure 2- 1).

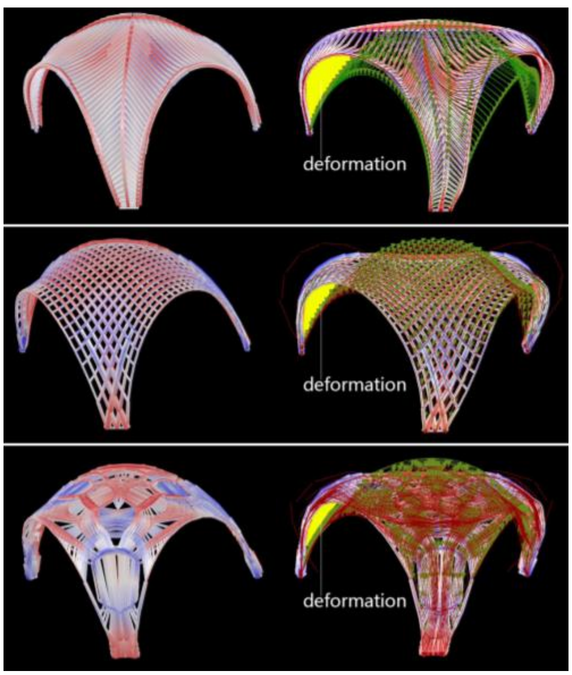


Figure 2- 1 Various Grid Shell Geometries Tested by Zhang et al. 2019. "Design and Analysis of Bending Active Formwork for Shell Structures Based on 3D-Printing Technology"

Seat Unit Analysis

After understanding how simulation tools help designers to design strong and materially efficient structures, the loading conditions of the chair are studied. Herman Miller, a known furniture company, studies pressure mapping strategies to increase comfort in the chair. Behar et al. (2013) published a research essay named “The Art and Science of Pressure Distribution Ergonomic Criteria for the Design of Work Chairs” in 2013. The researchers study pressure mapping on office chairs to design more comfortable chairs for the denser user population. They develop experiments with various people sitting on the chair and calculate how much pressure is applied to cushion and back seat.

Eckelman, who is a faculty member at Purdue University, published a book titled *Textbook of Product Engineering and Strength Design of Furniture* in 2003. In Chapter 3, he supports that the furniture design should consider loading conditions and deflection. They explain the loads, forces, and support reactions that occur in chair design. He explains the equations of loading conditions by giving examples of various conditions.

Another research about loading conditions is conducted for car seats. Shen et al. (1999) investigate weight distribution on various seat components at different seated positions. They pursue three experiments. The first experiment included thirty-six adult subjects at thirteen selected normal positions, the second has eleven adults at seventeen non-normal positions, and the third has nineteen children at seven positions. They investigate the weight distribution on the cushion, back, armrest, and the floor.

In short, this literature review presents the properties of fiber-reinforced polymers, different fabrication methods, architectural applications of the material, and understanding the relationship between design and nature, the importance of topological optimization in the design process, the role of simulation analysis in optimization and seating unit loading analysis. After understanding all the information above, this research aims to integrate the properties of hybrid carbon fiber and jute fiber with biological principles and explore weaving and 3D printing methods to design a stool with the structural capacity of holding a human body weight 250 pounds. This research utilizes a novel digital of finite element analysis to optimize the design of fabric and test the stool, which is inspired by cow bone growth.

EXPERIMENTS

Chapter 3: Analytic Methods

Overall Methodology

To develop this research, a mixed research methodology combining analytic, fabrication, simulation, and design research methods are proposed. As a design element, this research focuses on the manufacture of a stool because of carrying a variety of loading conditions such as horizontal loads (beam-like) and vertical loads (column-like) that must be transferred to the ground. This research consists of three parts. The first part is understanding the literature and previous studies that have been done by various scholars and researchers. The second part is an analysis of biological principles and an exploration of traditional weaving and digital fabrication method and translating the biological rules into a toolpath pattern to stiffen hybrid carbon/ jute fiber-reinforced polymer. Additionally, this part includes coding a digital tool in Grasshopper for modeling parametric fabric and analyzing loading conditions through finite element analysis. The third part is a synthesis of designing the chair with the knowledge that is gained from different types of analyses and testing the structural strength of 5-inch by 5-inch stool.

Bone Analysis

Nature presents different examples of functionally graded material systems to provide compressive and tensile strength for a specific situation. Designers can learn from nature to come up with a solution for a complex problem that has already been solved by natural systems. They can stop constructing against nature and start applying the systematic processes of nature into the design process.

This research begins with the study of Scanning Electron Microscope (SEM) images of a cow femur bone to understand the trabecular bone structure and trabeculae alignments to provide compressive and tensile strength to the femur bone. After photographing the SEM images, three different structural elements are detected. In the section of analysis of SEM images, the structural elements are discussed with more details.

SEM Sample Preparation and Imaging

SEM imaging helps to see the trabecular structure of bone in micro and Nanoscale. First, the bone is boiled in 50% vinegar and 50% water mixture to clean up residues of blood to SEM image a cow femur bone. After that procedure, the bone is cut in 1in x 1in x 1in to be able to fit in the SEM imaging machine. The moisture and water inside the bone structure create a danger for the device. Therefore, the procedure of SEM sample preparation is pursued for bacterial growth to fix, dehydrate, and dry the sample. The process of preparation starts with fixation to avoid any structural damage. The solid sample is fixed in buffer fixative, 2.5% Glutaraldehyde in 0.1 M Phosphate Buffer pH 7.2. The sample stored in the fixative for more than 24 hours. Then, the fixative is removed and stored in a hazardous waste container. The sample is washed in the buffer for five minutes, and three times.

Later, the dehydration process is started with the application of dehydrants, which are graded series of ethanol. The sample is adequately covered for 10 minutes in the same order of 25%, 50%, 70%, 85%, 95%, and 100%. The sample is washed in 100% ethanol for three times. Then, the sample is ready for critical point drying to prevent structural damages due to surface tension caused by the change of liquid state into a gaseous state. After the sample stays in a critical point dryer for three hours, the sample is ready for SEM imaging.

Trabecular Alignment

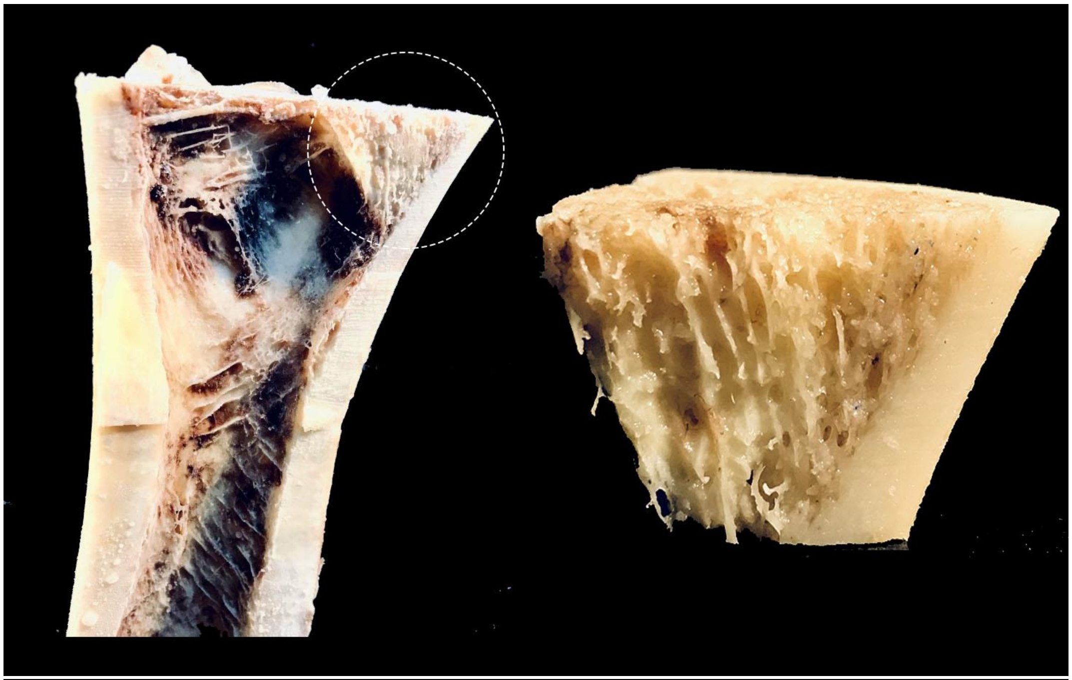


Figure 3- 1 Cow Femur Bone and Trabecular Structure

First, the bone analysis started with understanding the relationship of trabecular alignment with loading conditions. From the literature that is studied previously, it is derived that the trabecular bone (spongy bone) structure enables blood vessels to travel from compact bone to supply materials for blood cell production. Blood vessels carry nutrients and expel waste through channels on the trabecular surface. Additionally, the bone structure consists of compact bone and spongy bone. The spongy bone is the porous structure that allows the bone to withstand various loads. The specific positioning of trabecular adds compressive or tensile strength to the bone.

It is visible from Figure 3- 1 that there are more trabeculae where loading passes. This knowledge teaches designers and architects about how lightweight and strong structural elements can be designed by analyzing nature. Figure 3- 2 illustrates a study for the understanding reaction of bone structure towards loads and simple geometry of trabeculae.

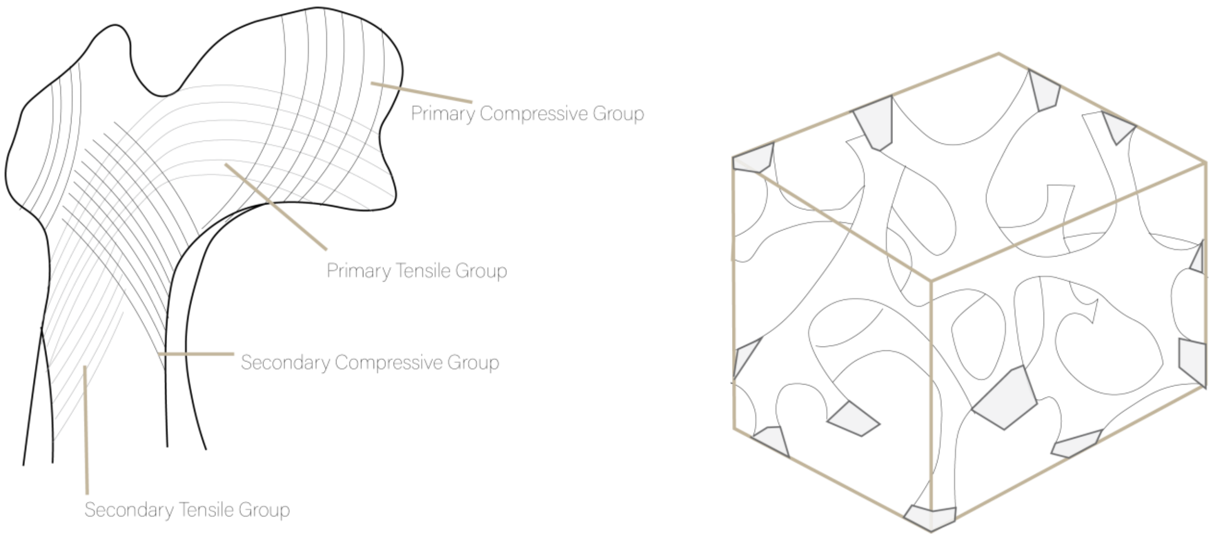


Figure 3- 2 Left: Trabecular Alignment Right: Trabecular Geometry

Analysis of SEM Images

After understanding the bigger image of bone structure, SEM images help to start micro-scale and Nanoscale analysis of the cut trabecular bone sample. As Figure 3- 3 shows, bone has a porous structure. It is visible that there is a denser part that provides resistance to the bone.

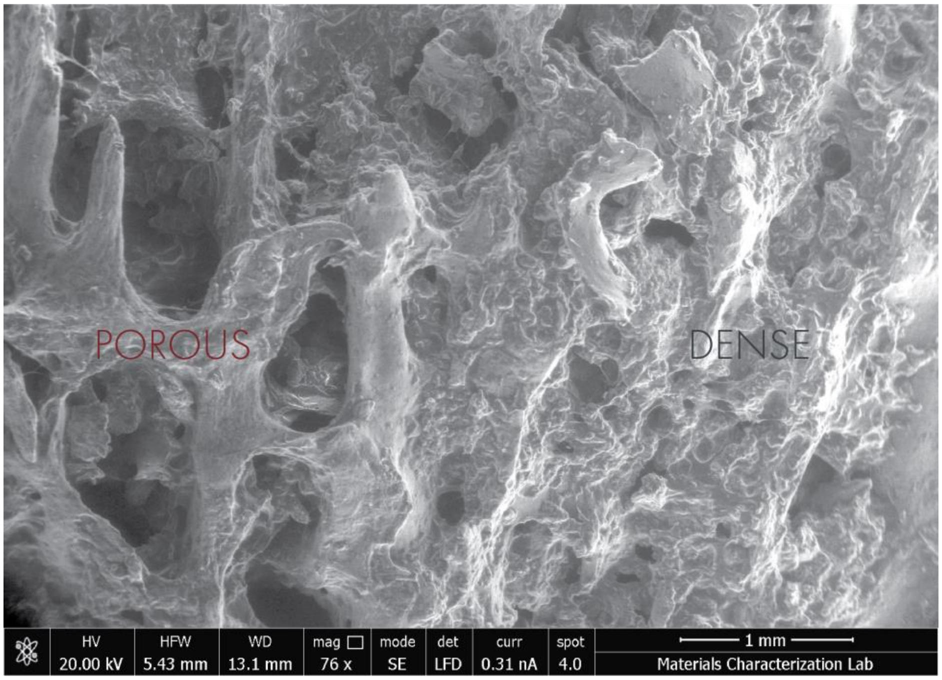


Figure 3- 3 Porous and Dense Structure

Figure 3- 4 is taken to show the top surface area and side of the sample. Some holes extrude through *y* and *z*-directions. In the Nanoscale, there are Voronoi cells that are filled with a fibrous structure, as shown in Figure 3- 5. From this image, it is derived that Voronoi tessellation is a geometrical translation that can be used in chair design.

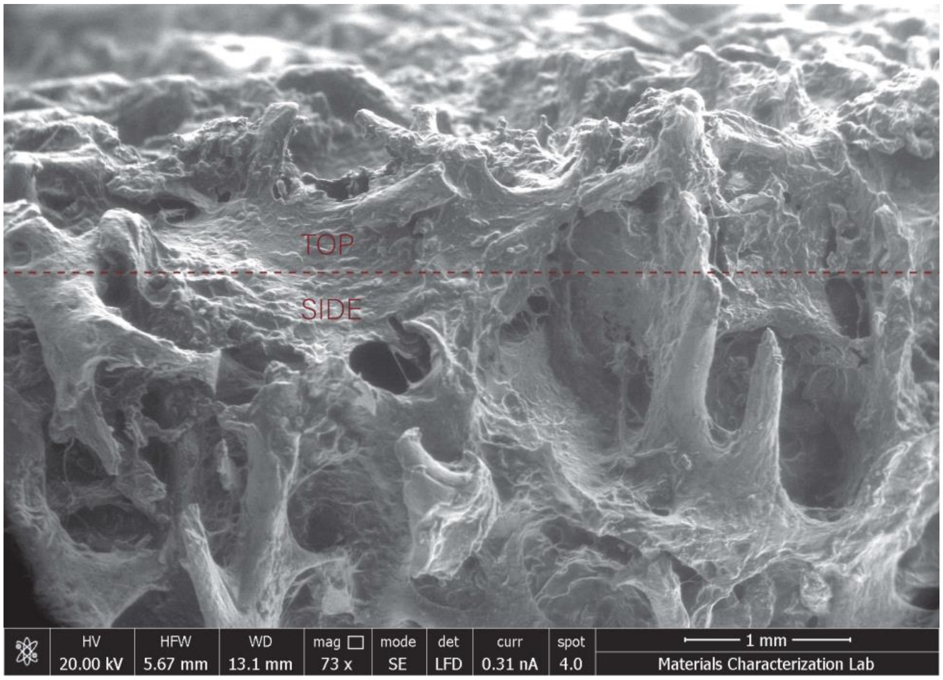


Figure 3- 4 Compact Bone and Spongy

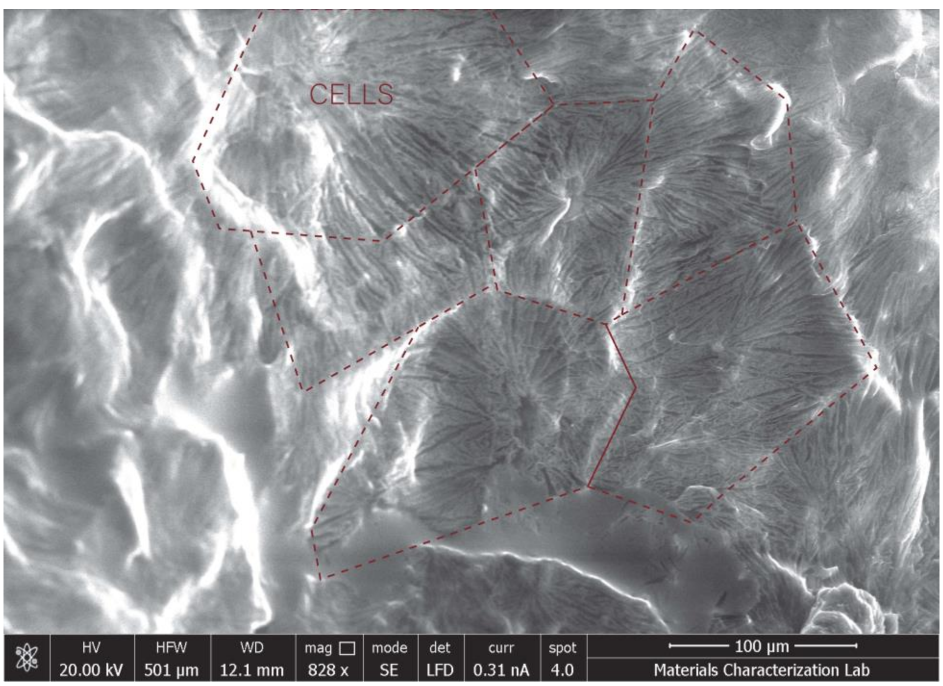


Figure 3- 5 Voronoi Cell Structure

Moreover, Figure 3- 6 demonstrates three structural elements that are visible in trabecular bone. In this micro-scale image, it is shown that there are channel-like structures that are supported by beam-like rods. Figure 3- 7 is the Nanoscale image of trabecular rods and plates, and it illustrates how the surface is composed of Voronoi cells. This study shows us that the chair frame can have beam-like structures in between structural elements to support an applied force. The channels can be translated into layered woven fabrics and extruded plastic in one direction. This thesis focuses on the formal shape and structural system of the bone structure to apply to a stool design.

Furthermore, the knowledge that is gained from the bone structure can be used as a reference for the design of larger-scale architectural elements such as beams, columns, and roofs. Bone structure can be mimicked in a formal shape and structural system. For instance, a roof can be self-standing with a porous and functionally graded material structure. This approach can result in more lightweight construction.

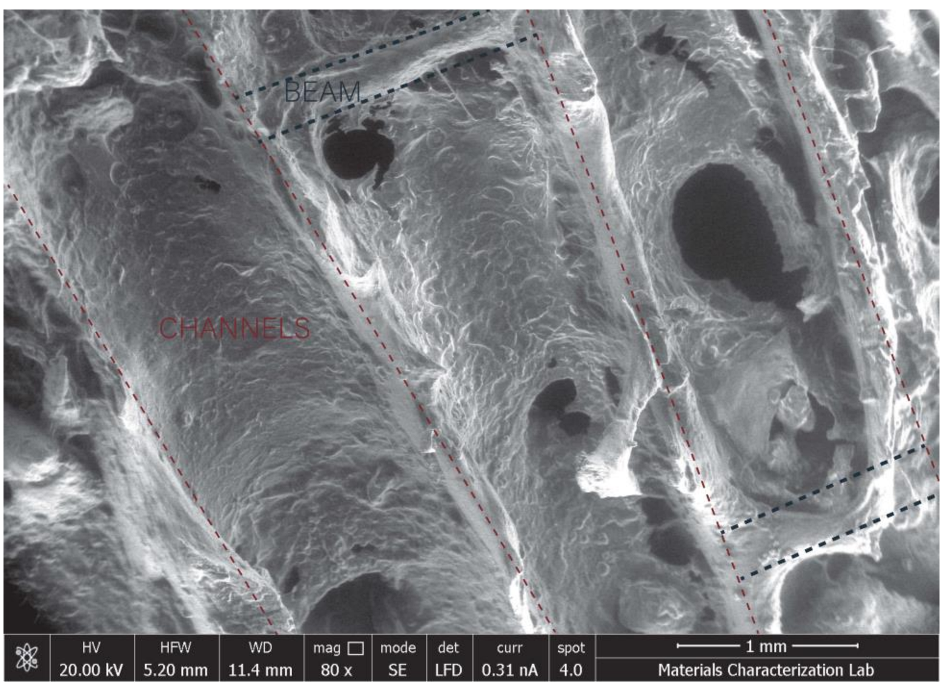


Figure 3- 6 Channel Forms in the Trabecular Bone Sample

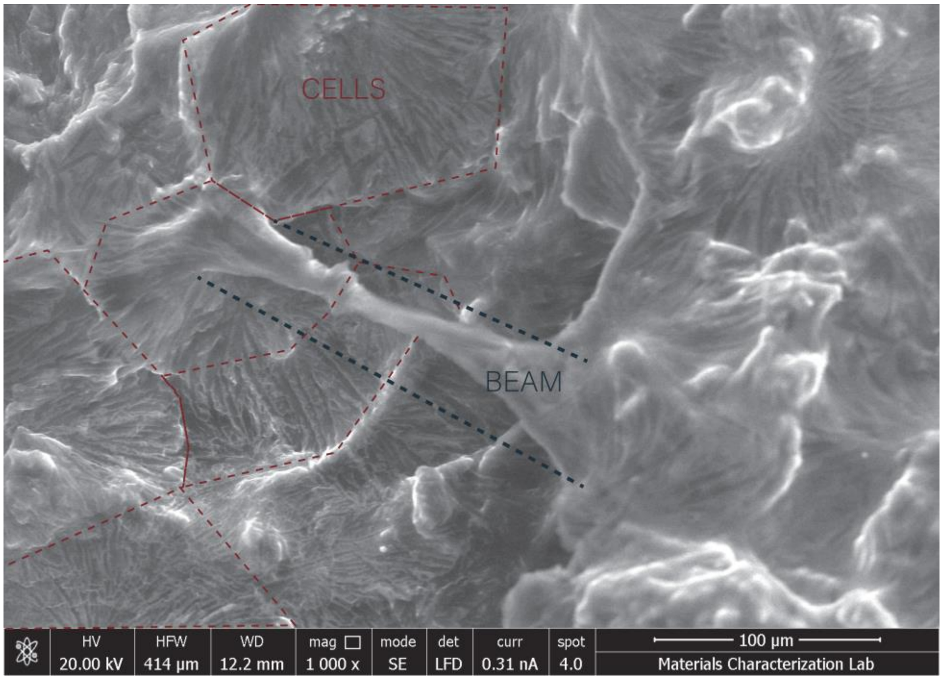


Figure 3- 7 Voronoi Cells and Beam-Like Structure

Chapter 4: Fabrication Methods: Weaving And 3D Printing

Material

For this research, the hybridization of natural and synthetic fibers plays a significant role in achieving the desired strength. Jute fibers have a lightweight, non-toxicity property, high specific modulus, and pollution-free fabrication. The other advantage of the use of jute fiber in the construction industry is easy accessibility with low cost. As well as these benefits, there are some disadvantages of jute fibers that create significant problems such as high moisture absorption, which causes weaker interfacial bond and mechanical properties. A combination of two or more fiber types allows taking advantage of the stronger feature of each material. Synthetic fibers such as carbon fiber have better mechanical properties such as higher tensile strength, stiffness, electrical conductivity, and low thermal expansion; however, they cost higher than natural fiber composites. Therefore, the combination of carbon and jute fibers results in a high-performance structural design at a lower cost.

In this thesis, 2-ply jute fiber, which is two-strand twisted with 1.3mm (0.05 in) thickness, is interlaced with continuous 3K carbon fiber tow. The hybrid woven fabric is stiffened by 3D printing thermoplastic elastomer (TPE). The TPE filament is a thermoplastic rubber that contains thermoplastic and elastomeric properties. In other words, it is a combination of rubber and plastic. Later on, this paper, it is explained how TPE is chosen as 3D printing filament within an experimental process.

Traditional Fabrication: Weaving

The relationship between textiles and architecture commences during Neolithic age to provide woven fibers to the primitive dwelling of man. The textile has been used as a surface over a compressive structural system for Millennium. Different textile fabrication methods have been explored for ornamental, functional, and structural purposes. Irene Emery categorizes fabrication methods in *The Primary Structures of Fabrics* (1966). Felecia Davis(2012) illustrates the classification of the fabrication methods that are mentioned by Emery that is shown in Figure 4- 1. This research explores interlaced elements and focuses on the plain weave and crossed warp weaves.

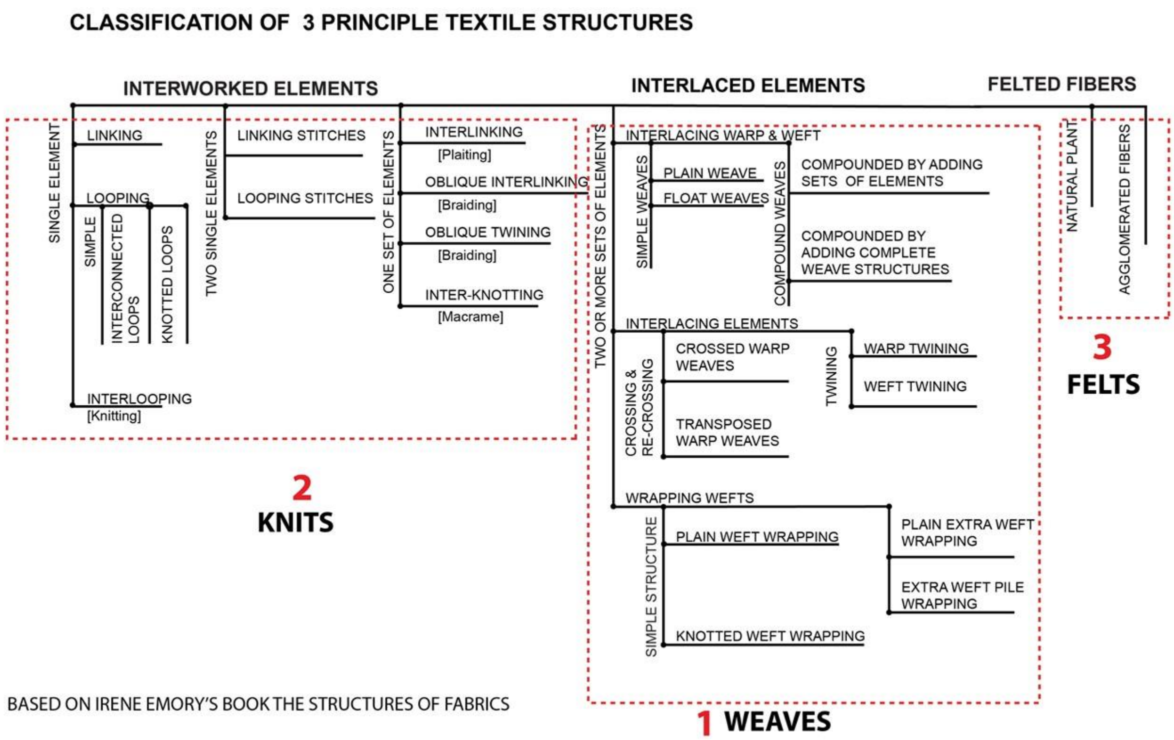


Figure 4- 1 Classification of Textile Structures Adapted from "3D Printed Textiles from Textile Code: Structural Form and Material Operations." by Davis. Felecia, 2012, In [Formation], Proceedings of the Iberoamerican Society of Digital Graphics [SIGRADI] Fortaleza, p.327-331 Copyright 2012 by Felecia Davis

Traditional Patterns

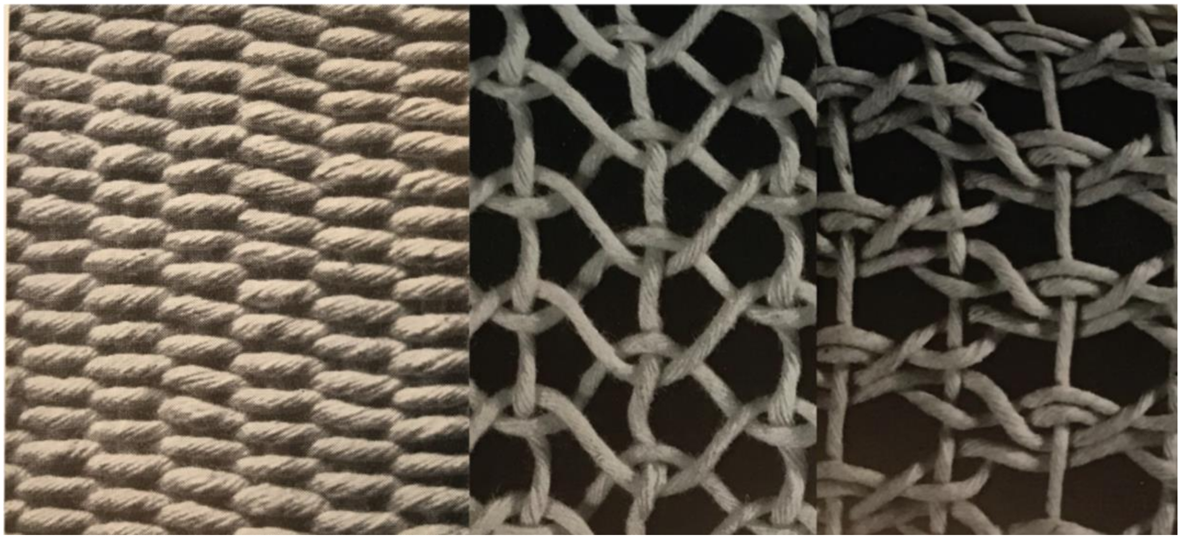


Figure 4- 2 Left: Weft-Faced Plain Weave pg.86 Center: Plain Alternating Gauze Weave. pg183 Left: A Complex Alternating Gauze Weave pg.185 , Adapted from “The Primary Structures of Fabrics” by Emery, Irène, 1966, Washington: Textile Museum. Copyright 1966 by the Textile Museum

The basic interlacing technique is using plain weave patterns. *Each weft unit passes alternately over and under successive warp units, and each reverses the procedure of the one before it.* (Emery 1966,76) Plain weave structures have been used in different periods and areas of textile manufacturing. For instance, Weft-faced plain weave is a type of plain weave that weft threads dominate the warp threads by covering them, and it has been used in tapestry weaving. For instance, kilim rugs originated in Anatolia; Turkey has been produced by this technique since ancient times.

Figure 4- 3Anatolian Double Niche Rug, Konya, Anatolia, Turkey 1650-1750 LACMA Gift of the 2004 Collectors Committee (M.2004.32)

The other fabric structure is crossed warp weaves, as it is shown in Figure 4- 2 Left. It is also known as gauze weaving. Irine Emery describes crossed warp weave structure by saying: *It is an interworking sequence of warp over warp and under weft or vice versa, and any enumeration of the interworking order of the warps must take both into account.* (Emery 1966, 180) The weft elements are parallel to each other. This structure is characterized by its openwork and lightness. Gauze weaving has sub-categories for alternative structures. Plain alternating gauze weave (Figure 4- 2 Center) consists of warp shifted in one direction and interweaving others in the opposite direction. In the end, all warps return to the starting point. This weave structure adds stability to fabric even though it is an open weave. The other type of gauze weaving is complex alternating gauze weaving, shown in Figure 4- 2 Right. It is a structure made of two-weft interlacing and two different orders of warp interworking.

This thesis focuses on the plain weave and gauze weave that have a weft-shifting structure instead of warp shifting. Gauze weaving is considered as a surface element where a person interacts directly while sitting on the stool. Plain weave is used as a lower structural element that allows the combining jute and carbon fiber.

The Tool of Fabrication and Woven Fabrics

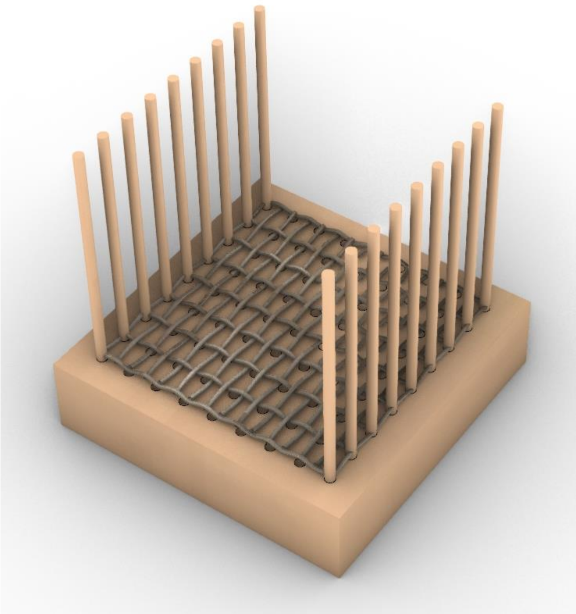


Figure 4- 4 Weaving Loom

The weaving loom is designed, as shown in Figure 4- 4 for fabricating woven textiles. The tool design combines the functionality of pegboard and rug loom. It is made of 1/8 inch birch plywood and 1/4 inch diameter of dowels. The base of the loom is cut by laser cutters, and it contains equally-spaced holes for dowels. Each dowel can be replaced according to the shape and size of the fabric. It can be woven in *z*-direction to achieve 3D woven fabric structures. However, this research focuses on a 5x5 inch single layer weaving and binding two layers after 3D printing on the woven fabrics. Figure 4- 5 shows the woven fabric structures made of jute fiber by using the loom.

Figure 4- 5 Woven Fabrics Made of Jute Fibers: Plain Weave, Single Gauze Weave and Double Gauze Weave (Horizontal Warp Direction)

The plain weave structure is used for combining different ratios of carbon fiber and jute fiber. The main reason for testing different ratios is to understand the amount of carbon fiber that needs to be interlaced with jute to withstand the sitting force of a 250-pound person. This hybrid fabric is designated as a structural layer of the chair. All of the woven fabric has a structure of 9 carbon fiber warps and 48 weft elements. The material ratios of carbon fiber to jute fiber are 16/32, 10/38, and 0/48, as is shown in Figure 4- 6

Figure 4- 6 Left: Warps: 9 x CFRP Wefts: 16 x CFRP, 32 x Jute, Center: Warps: 9 x CFRP Wefts: 10 x CFRP, 38 x Jute, Right: Warps: 9 x CFRP, Wefts: 0 x CFRP, 48 x Jute (Vertical Warp Direction)

Digital Fabrication: 3D Printing

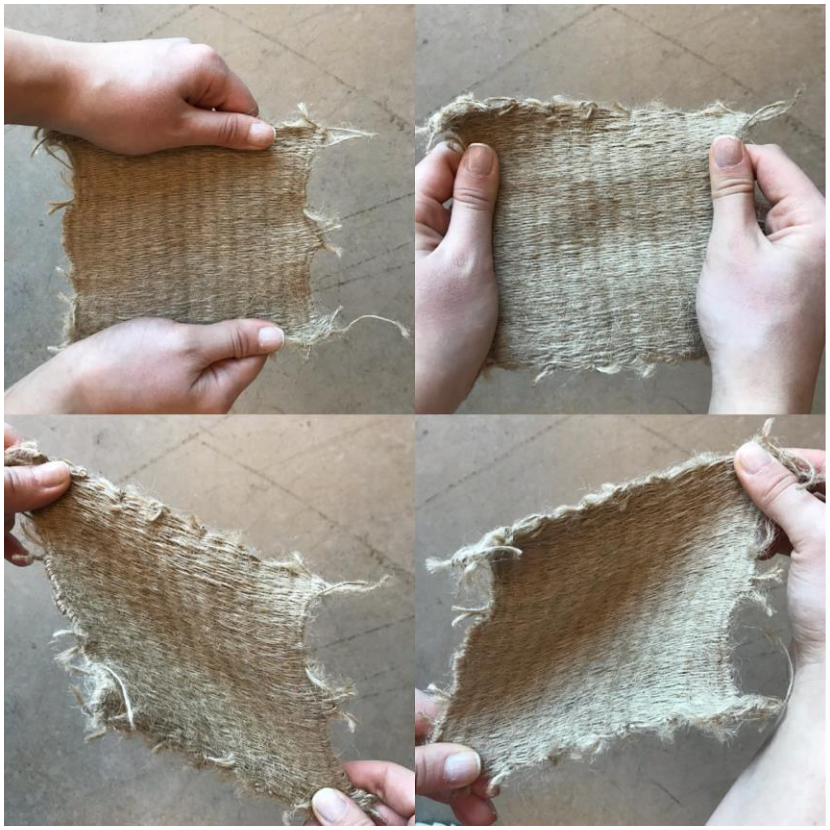


Figure 4- 7 Fabric Deformation in Diagonal Direction

The fabric in Figure 4- 7 is easily deformed in the diagonal direction; 3D printing is a solution to add stiffness and stability to this woven fabric. 3D printing on clothing has been developed by threeASFOUR in the fashion sector. They aimed to design clothes that are bulletproof, fireproof, pressure-resistant, or able to trap heat or cold. In this thesis project, the goal of 3D printing on woven fabric is to create a layered fabric system that has sub-layers of printed TPE to decrease deformation and add stiffness to the textile. Consequently, it is essential to test various toolpath on the fabric to decide which toolpath adds more strength most efficiently to achieve this goal. Before choosing 3D printing filament to print on textile, multiple 3D printing filaments such as PLA, PETG, and TPE are tested. The first consideration is to discover the right settings to allow PLA to stick on fabric with 90% shape accuracy.

Before printing on the actual woven prototype, different settings on medical gauze fabric are studied. The reason for having medical gauze fabric as a testing material is because of its porous structure and elasticity. The 3D printer that is used for these experiments is Prusa MK3S, and the software is PrusaSlicer. First, the bed level is adjusted higher to keep heat-bed closer to the nozzle with first layer calibration and resetting. The fabric needs to be in full tension; therefore, the double-sided tape was used for setting experiments. The speed of printing is adjusted to 40%, and the infill density is set as 30%. The machine and fabric, which is taped to the heat-bed, are preheated before starting printing.

Setting Experiments

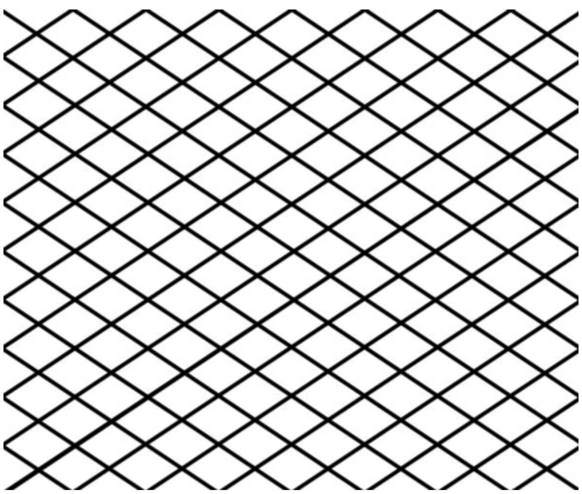


Figure 4- 8 Showing the Toolpath That is Used for Setting Experiments (5 inch by 6 inch)

For the setting experiments, the toolpath that is shown in Figure 4- 8 is used and printed on four by six inches of medical gauze fabric. The plastic is 3D printed with zig-zag motion on the fabrics. The first trial shows that the fabric is required to be more in tension because the corners of fabric created an obstacle to the movement of the nozzle. Temperature settings are applied as 215°C (419°F) for the extruder and 60°C (140°F) for heat bed. PLA does not stick well on the fabric; therefore, the temperature of the extruder and heat bed is another variable that needed to be adjusted. The first trial is printed with 40% speed, which is 8 mm/s to increase shape accuracy (Figure 4- 9). Trial 1 has two layers of printing because the dimension of the first layer height is 0.2 mm (0.008 inch), and the first layer width is 0.42 mm (0.0165 inch). In total, printing takes 22 minutes. For the second trial, the temperature settings are 230℃ (446℉) for the extruder and 85℃ (185℉) for the heat bed. The other settings remain similar to Trial 1. However, the shape inaccuracy and the sticking issue of PLA is not solved in Trial 2 (Figure 4-10).

Figure 4- 9 Showing the Result of Trial 1: First Layer Infill Width: 0.42 mm (0.0165 inch), First Layer Infill Height: 0.2 mm (0.008 inch), Extruder Temperature: 215℃ (419℉), Heat Bead Temperature: 60℃ (140℉)

Figure 4- 10 Showing the Result of Trial 2: First Layer Infill Width: 0.42 mm (0.0165 inch), First Layer Infill Height: 0.2 mm (0.008 inch), Extruder Temperature: 230℃ (446℉), Heat Bead Temperature: 85℃ (185℉)

The problems of the first two trials are addressed by changing the first layer infill width and height parameters on the software to solve adhesion problems. The first layer height is set at

0.4 mm (0.016 inch). The only setting that is changed from Trial 3 to Trial 4 is the first layer width. During trial 3 (Figure 4- 11), a 3D printer extrudes a 0.8 mm (0.032 inch) wide first layer. The printing time decreases to 10 minutes. It results in one-layer printing. In trial 4 (Figure 4- 12), the first layer width increases to 1 mm (0.04 inch). Finally, more extrusion of PLA on fabric results in higher shape accuracy and adhesion.

Figure 4- 11 Showing the Result of Trial 3: First Layer Infill Width: 0.8 mm (0.032 inch) ,First Layer Infill Height: 0.4 mm (0.016 inch). Extruder Temperature: 215℃ (419°F), Heat Bead Temperature: 60℃ (140°F)

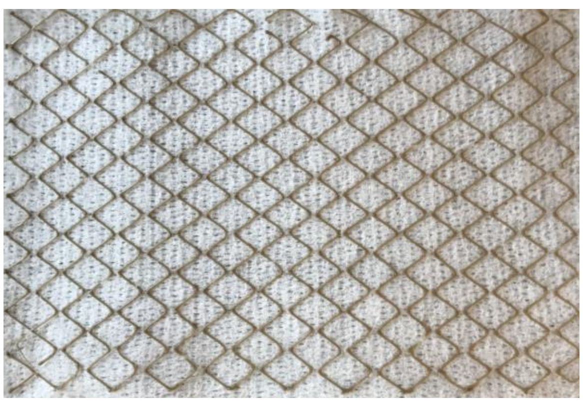


Figure 4- 12 Showing the Result of Trial 4: First Layer Infill Width: 1 mm (0.04 inch), First Layer Infill Height: 0.4 mm (0.016 inch). Extruder Temperature: 215℃ (419°F), Heat Bead Temperature: 60℃ (140°F)

Tool Path

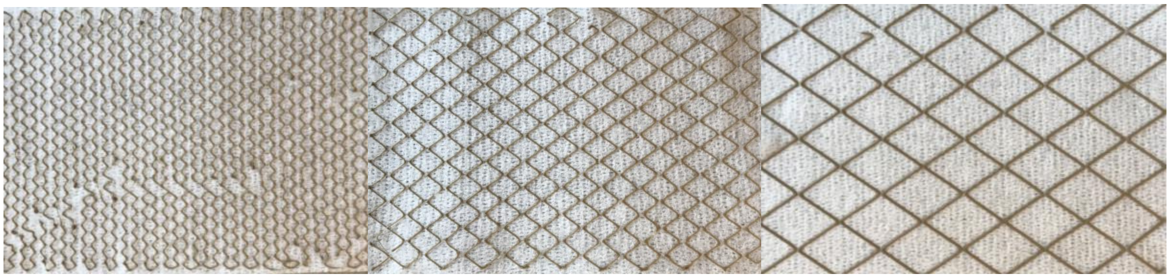


Figure 4- 13 Showing the Result of Diamond-Shaped Tool Path (Density: 80,40, and 20 Borderlines)

After adjusting the settings on the software and the 3D printer, different patterns are tested (Figure 4- 13). Since most deformation occurred in the diagonal direction, diamond shape patterns are checked to minimize displacement when tensile forces applied on *x* and *y*-direction with 45-degree. Even though printing the 20 and 40 borderlines of diamonds takes more time to print, they added more strength to fabric than the least dense diamond shape. The best shape accuracy occurs on the medium and least dense pattern.

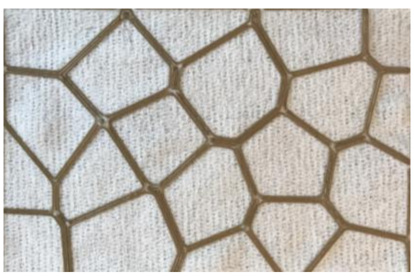


Figure 4- 14 Showing the Result of Voronoi Tool Path

For the translation of geometry in bone structure into a 3D printing pattern, Voronoi tessellation is printed on medical gauze fabric(Figure 4- 14). The shape accuracy is higher than the diamond shape pattern. The printing time is significantly less than previous toolpath patterns. The number of Voronoi cells can increase where loading passes to decrease the deformation.

Material Selection for 3D printing

3D printing of specific patterns on the fabric adds stability and strength to fibers. The material that is printed on the weave structure is significant. After applying a force into PLA printed fabrics, the pattern starts cracking. Therefore, different 3D printing filaments are tested. The same settings from Trial 4 are used for the infill and first layer width and height during material testing.

First, PETG is printed on fabric. The first layer does not stick well on the fabric, as shown in Figure 4- 15. Hence, the temperature settings are re-adjusted to 255℃ (491°F) for extruder and 95℃ (203°F) for heat bed. Typically, PETG requires temperature settings of 250℃ (482°F) for the extruder and 90℃ (194°F) for the heat bed. Even though PETG is less brittle than PLA, the result of printing PETG does not solve the cracking issue. However, it is realized that PETG gives a fabric great shape in the second trial.

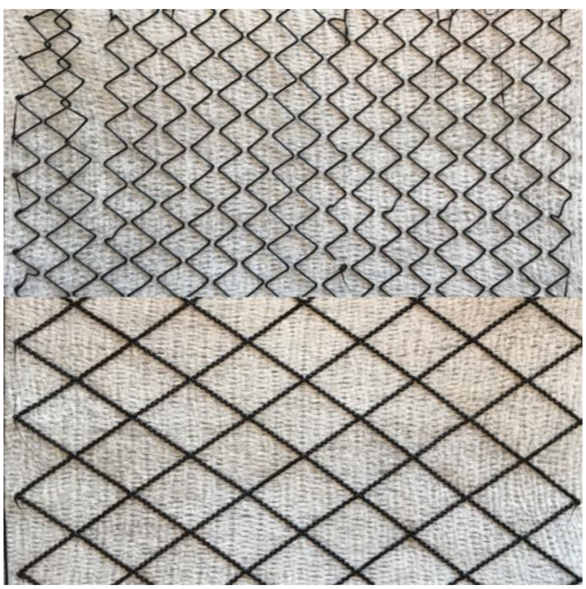


Figure 4- 15 PETG Printed on Medical Gauze

Lastly, thermoplastic elastomer flexible filament is printed on fabric (Figure 4- 16). Since TPE is a mix of hard plastic and rubber, the cracking problem is solved. The printing time is doubled with a change of filament. All toolpaths are printed to understand the relationship between the material and shape accuracy. The default temperature settings of TPE are 240 ℃ (464°F) for the extruder and 50℃ (122°F) for heat bed. The first layer temperature is increased to 250℃ (482°F) and 60℃ (140°F). The height and infill dimensions are changed on PrusaSlicer software before receiving a g-code, which contains commands to move parts within the 3D printer. This setting adjustment helps filament to stick well to fabric.

Figure 4- 16 TPE Printed on Medical Gauze

After selecting TPE, which is the sustainable material for being biodegradable and cost-efficient 3D printing material, the jute fabric that is woven as a plain weave is used for further experiments. The jute textile that is used for transition from medical gauze to jute fabric is manufactured with 1 mm (0.04 inch) jute fibers. The material is cut to five-inch by five-inch samples. Jute fiber's high absorption property allowed TPE to stick well on the fabric and the patterns that are printed results with a similar shape as computed in Grasshopper (Figure 4- 17).

Figure 4- 17 3D Printing on Plain Weave Jute Fabric

The next step for 3D Printing exploration is printing on handwoven gauze weave fabric. The same settings are used to print on double gauze woven fabric. As shown in Figure 4- 18 Left, the pattern is not printed consistently on the material. While printing, the thermistor sensor tangles fibers and drags the fabric according to hot end motion. Therefore, the heat bed is lowered by a command on the 3D printer titled a live Z-direction adjustment. The second trial that is shown in Figure 4- 18 Right does not have any problems occurring while printing. Single gauze woven fabric is stuck to bed with double-sided tape, and the filament is extruded accurately based on g-code.

Figure 4- 18 Left: Failed Trial of 3D Printing, Right: Successful Result of 3D Printing

As a result of 3D printing on fabric, the elements of warp and weft are stabilized, and threads stop moving when force is applied. Large deformation in a diagonal direction is avoided, and the fabric has higher strength in the warp, weft, and diagonal direction, as shown in Figure 4- 19.

Even though this thesis focuses on a stool design with combining weaving and 3D printing techniques, this integrative fabrication method appears promising for larger architectural projects. This method allows for fabricating lighter structures with an additive approach. 3D printing on fabric provides opportunities for stiffening the fabric and form-finding. Consequently, this fabrication technique can result in the construction of lighter façade and roof systems that can be an earthquake-resistant structure.

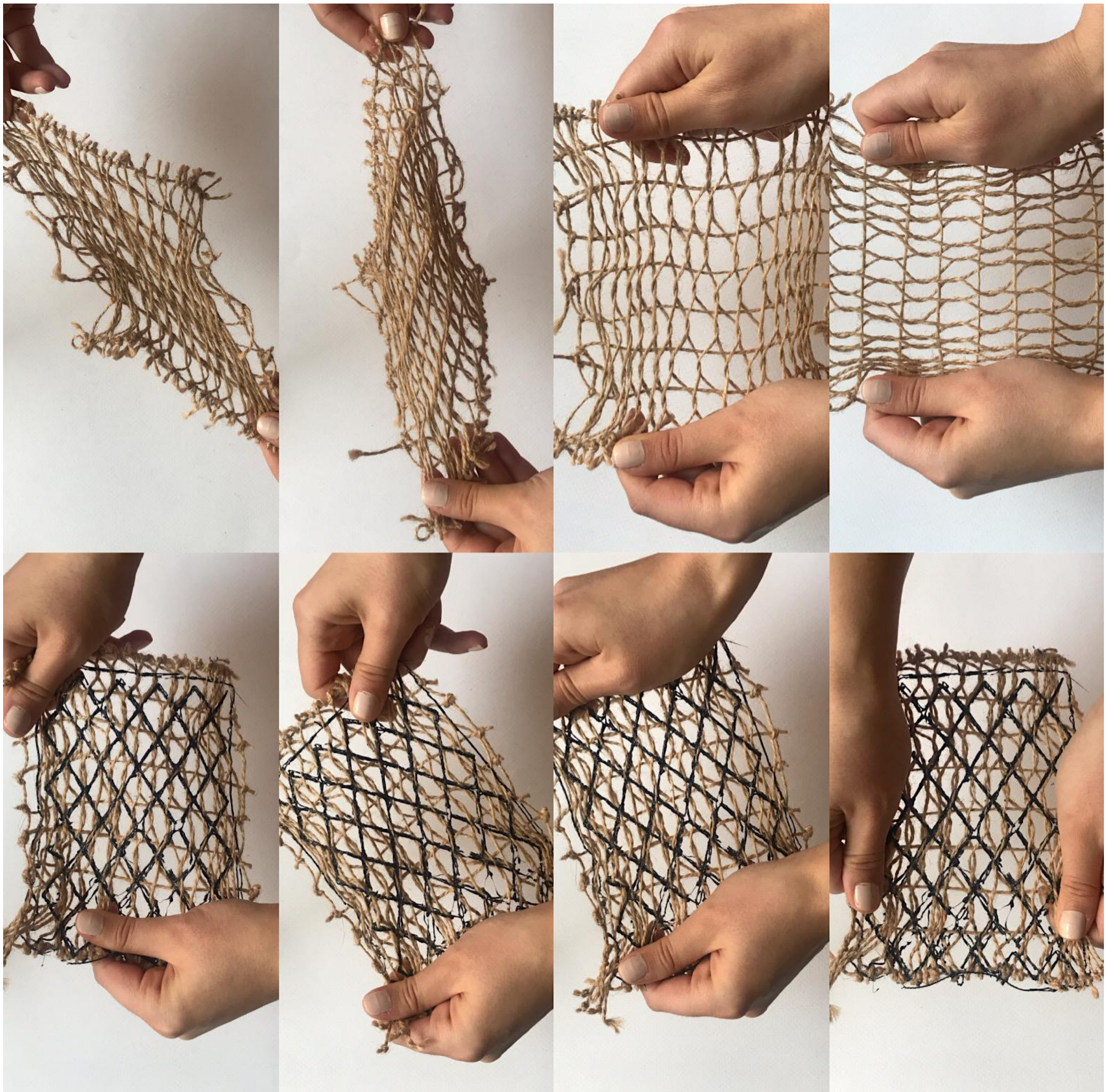


Figure 4- 19 Result of 3D Printing on Fabric

Lamination of Fabrics

After doing experiments with extrusion on fabric, The next step was exploring the lamination of composite materials. The lamination angle of the fabric layers is significant to achieve maximum resistance to an applied force. Lamination angles impact the amount of deflection that occurs as a result of load. Noh et al. (2016) studied Failure Analysis of

Glass/Epoxy and Graphite/Epoxy Laminates due to the Effect of Variation in Lamination Scheme and Angle of Fiber Orientation. They tested the fabric at 0, 45, and 90-degree angle of lamination. Their results show that the 0-degree angle has the most displacement, and a 90-degree angle has the least deformation.

In this research, two layers of fabric are oriented with their warp directions perpendicular to each other, according to the picture in Figure 4- 20. Each layer is 3D printed with the same pattern on the top and bottom of the material, and then the layers are overlayed. The fabric structure is discussed more in Chapter 6.

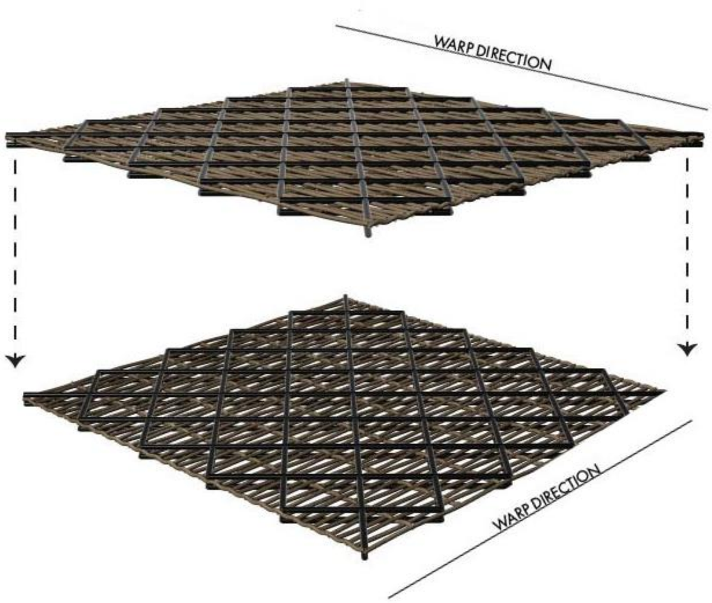


Figure 4- 20 Lamination Diagram

Chapter 5: Simulation Methods: Digital Tool of Textile Simulation

Digital Tool

After analyzing fabrication techniques, the next step is to test handwoven fabrics. Due to conditions of COVID-19, access to the laboratories is restricted. Therefore, the fabrics could not be tested in the laboratory. Instead a parametric workflow was created within Grasshopper, which is a visual programming environment that runs within Rhinoceros 3D (Robert McNeel & Associates, 2018). This platform allows for modeling various weave structures and structural analysis of the design elements. The analysis is performed by a plug-in called Karamba 3D (Preisinger, 2019) , which provides finite element analysis. In this research, the woven fabrics and final chair design are structurally tested with Karamba 3D.

Reference Geometry

The first part of the simulation is modeling weaving patterns in Grasshopper. The plain weave, single and double gauze weave structure is coded with parameters to allows users to decrease or increase the number of warps and weft. Figure 5- 1 shows the top view and section view of different woven fabric models. Additionally, the material thickness can be changed according to the fiber type. The ratio of carbon fiber and jute fiber can be determined by the designer in the reference geometry section of the algorithm. The code presents options of various material ratios of carbon fiber to jute fiber, which are 16/32, 10/38, and 0/48, respectively, in Figure 4- 6.

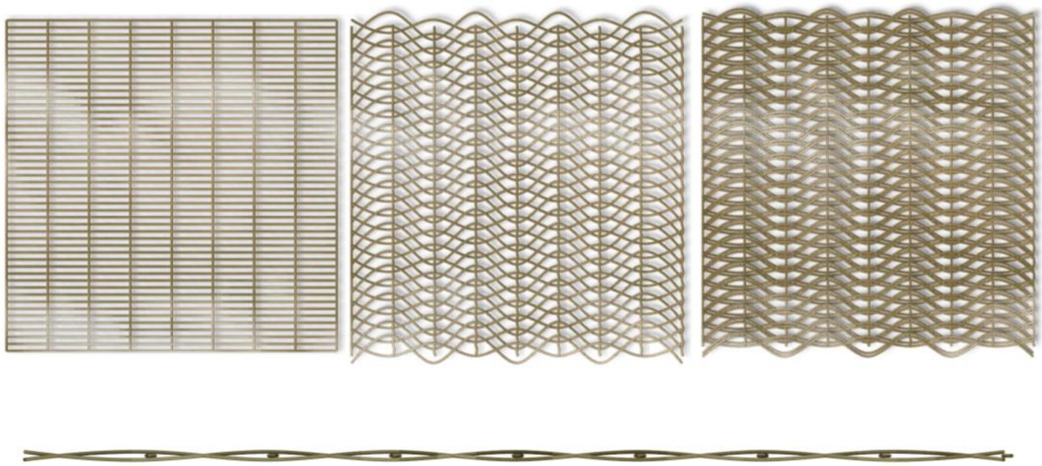


Figure 5- 1 Modeled Fabric Patterns

After modeling the fabric in Grasshopper, 3D printed patterns are also modeled in Grasshopper, as Figure 5- 2 shows. The patterns are diamond and bone-inspired Voronoi cells. The parameters of patterns allow increasing the density of the cells and the thickness of the walls. Point attractor, which is a component in Grasshopper, adds more cells or diamonds according to the location of load concentration by evaluating the surface and increasing the number of points. After analysis, they can be baked, which allows exporting the modeled meshes from Grasshopper to the Rhinoceros file and then saved as STL to be ready for 3D printing. Later, the modeled fabric and 3D printed patterns created a reference for producing lines to convert into a structural element within Karamba 3D.

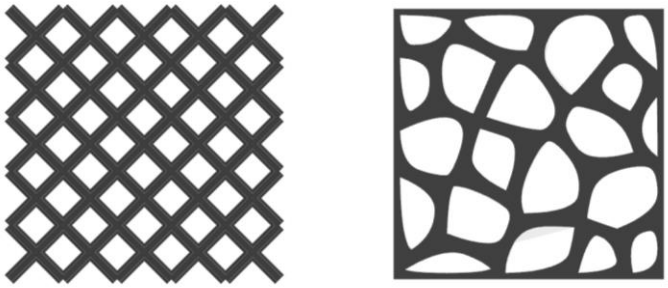


Figure 5- 2 3D Printing Pattern

Grasshopper provides a platform for various plug-ins for parametric design. Karamba 3D is a plug-in that offers finite element analysis of modeled geometries. After modeling fabrics, each weft and warp in converted into lines, which Karamba 3D defines the lines of the elements as beam structures. The beam structure has a cross-section that is determined by the user. The cross-section definition requires information about the thickness and the shape of the section, and the material properties.

Material

For accurate results, the material properties need to be entered in the cross-section component. However, the material properties in the Karamba 3D library are limited. Thus, material properties are edited manually for jute, carbon fiber, thermoplastic elastomer (TPE), and polyethylene terephthalate (PETG). The materials are categorized under two different material types that are orthotropic for jute and carbon fiber and isotropic if any TPE is printed alone. In Karamba, the information required for each material category are Young's modulus (modulus of elasticity), the shear modulus, specific weight, the coefficient thermal expansion, and yield strength. Table5- 1 shows the values that are added to the material properties component. The values are derived from MatWeb (MatWeb - The Online Materials Information Resource, 2020). After modifying the properties (Figure 5- 3), the material selection is connected to a cross-section definition that includes dimensional information of beams.

Table5- 1 Material Properties

	Young's Modulus/ E1: (kN/cm^2)	Young's Modulus/ E2: (kN/cm^2)	Shear Modulus: (kN/cm^2)	Specific Weight: (kN/m^3)	Coefficient Thermal Expansion: (1/°C)	Yield Strength: (kN/cm^2)
Carbon Fiber	23500 kN/cm^2	1500 kN/cm^2	2700 kN/cm^2	17.65 kN/m^3	Alpha1= -0.5e-06 /deg. C Alpha2 = 15e-06 / deg.C	370 kN/cm^2
Jute Fiber	2000 kN/cm^2	98 kN/cm^2	1760 kN/cm^2	12.75 kN/m^3	0.000012 1/°C	33.75 kN/cm^2
Thermoplastic Elastomer	75 kN/cm^2	-	25 kN/cm^2	9.73 kN/m^3	0.000171 1/°C	4.5 kN/cm^2
Polyethylene Terephthalate	265 kN/cm^2	-	89 kN/cm^2	12.52 kN/m^3	0.000077 1/°C	6.9 kN/cm^2

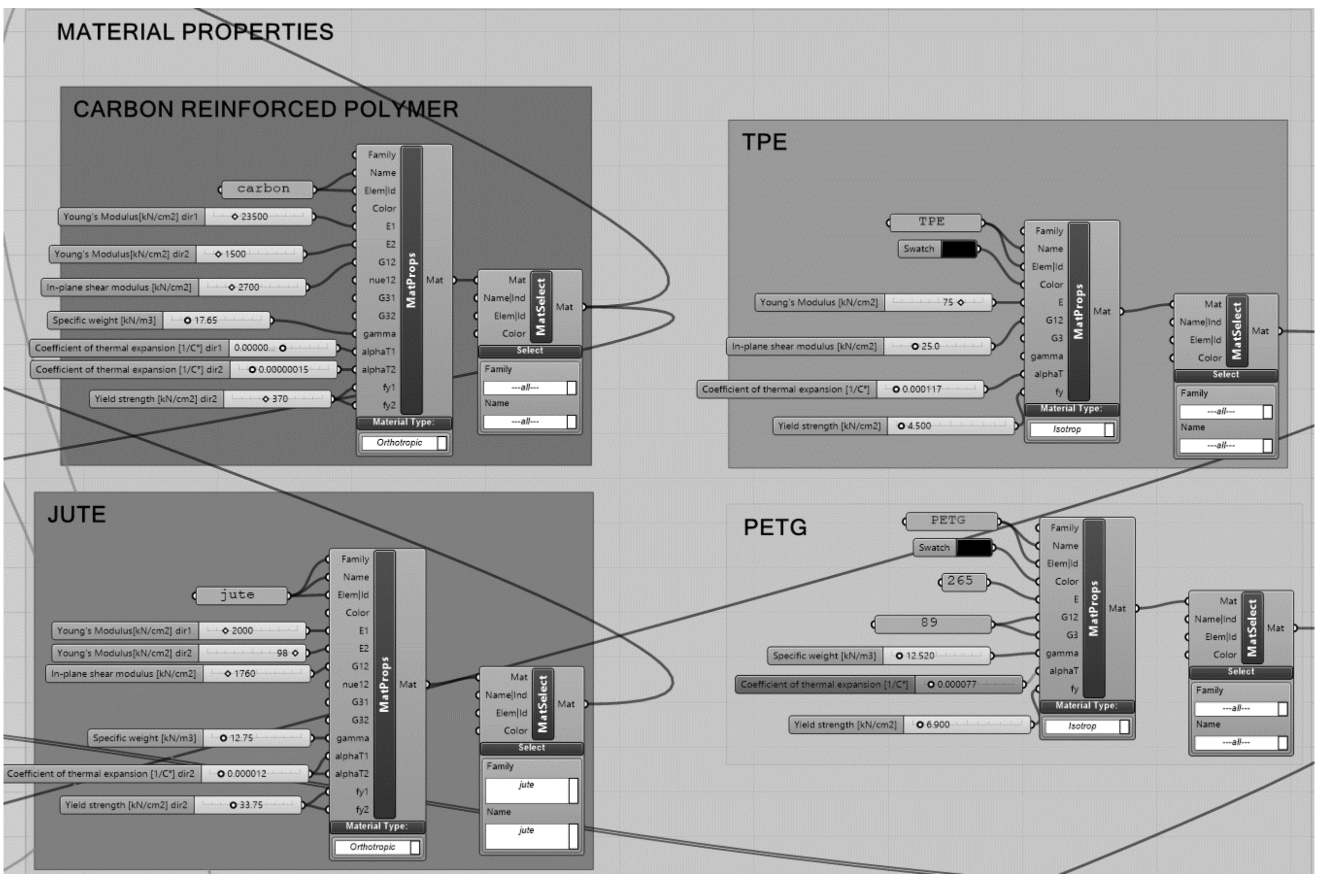


Figure 5- 3 Left: Orthotropic Material Settings Right: Isotropic Material Settings from Karamba

Load

After modeling the beam elements, Karamba asks users to determine support points. Fixed supports are selected to avoid translation and rotation in any direction. First, the initial strain load is applied to pretense the fabric. The fabric is pre-stressed by the frame, and Karamba 3D simulates the pre-tension effect on the fabric by adding an initial strain load. Therefore, pretension load (P) is calculated based on the equation mentioned below,

$$P = \frac{\Delta L \cdot A \cdot E}{L}$$

Equation 5- 1: Pretension Load Equation

where ΔL is the change in length, A is the area of the cross-section element, E is Young's modulus, and L is the length of the element. Therefore, pretension stress is calculated as 0.26 kips/ft^2.

Additionally, the loads that are calculated are supposed to reflect the loading conditions of a full-scale stool. Since this project focuses on the quarter scale stool, the vertical unit loads on 20 inches by 20 inches chair that withstands 250-pound person sitting is calculated, and the equation below is used to find an equivalent unit load that is applied on 5-inch and 5-inch stool. The steps of calculations are added below the equation. The unit load that is applied to a full-scale stool is 0.625 psi.

To transform the loads from a full-scale chair to a quarter-scale model, the loads must be transformed to be equivalent in both cases. Assuming fabric as a horizontal structure, the vertical reaction force (V) is the upward force (see Figure 5- 4) that is equal to half of the total vertical load applied to the fabric structure of the full-sized stool. This force is transmitted to the stool structure as a stress (i.e., the force divided by the cross-section area). Because of the nature of the quarter-scale model, this vertical reaction needs to be calculated as a force that generates the same stress in both stools.

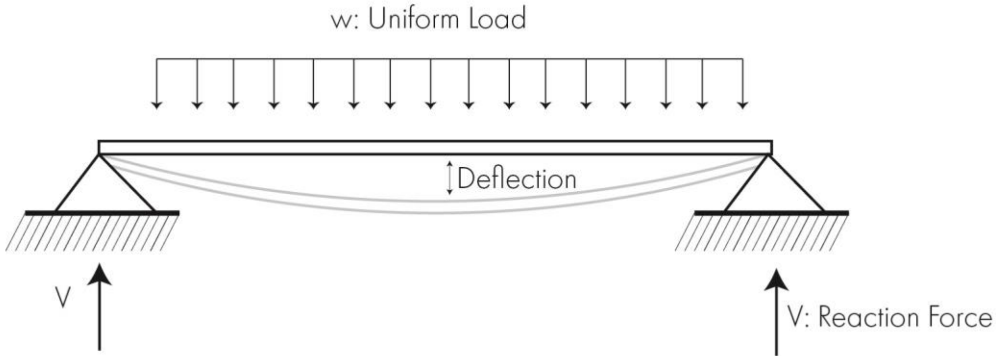


Figure 5- 4 Vertical Reaction Force Diagram

The vertical reaction force (V) is calculated as follows (Son, 2004):

$$V = \frac{wL}{2}$$

Equation 5- 2: Unit Load Equation

where w is the unit load, and L is the length of the structure.

Full-Scale Reaction Force: L=20 inch, w=250/20^2=0.625 psi → V= 6.25psi

Quarter-Scale Unit Load: L=5, V=6.25psi → w= 2.5 psi

This defines the uniform load for the design of the quarter-scale stool (w= 2.5 psi). A factor of safety of 3.0 is considered to set a maximum permissible load, resulting in a final maximum uniform load of 7.5 psi. Units are transformed to kips/ft^2 as per Karamba 3D requirement, as shown in Figure 5- 5.

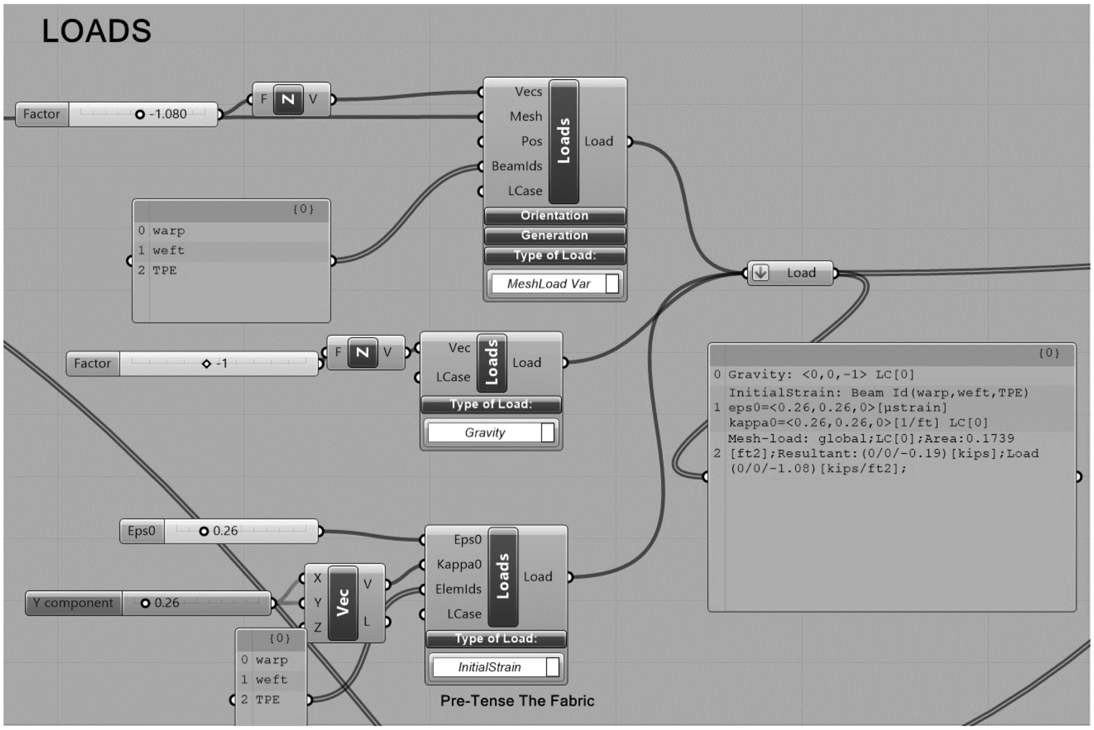


Figure 5- 5 Applied Loads

The calculated loading conditions are added to Karamba; that is why the simulation of pre-tensioned fabrics under vertical load and gravity demonstrates more realistic results. The correct calculations of loads are significant to receive a more accurate demonstration from the analysis part of the code. Consequently, designers can make better design decisions based on simulation analysis.

Analysis

After coding the beam elements, supports, and loads, the assembly definition in Karamba gathers all data and prepares the model for structural analysis, as shown in Figure 5- 6. The structural analysis provides values for deflection, maximum bending moment, tension force and compression force, shear strength, and reaction force in the fabric. The utilization component in Karamba calculates the maximum force that each element can bear according to the given safety factor. Additionally, the tool visually simulates the fabric structures under applied load conditions to show displacement, stress, and utilization. With this tool, it is possible to understand the structural capacity of different traditional weaving patterns, 3D printed plastics in specific toolpaths, and specific carbon fiber tows to jute ratio, making up fabric under given loading conditions.

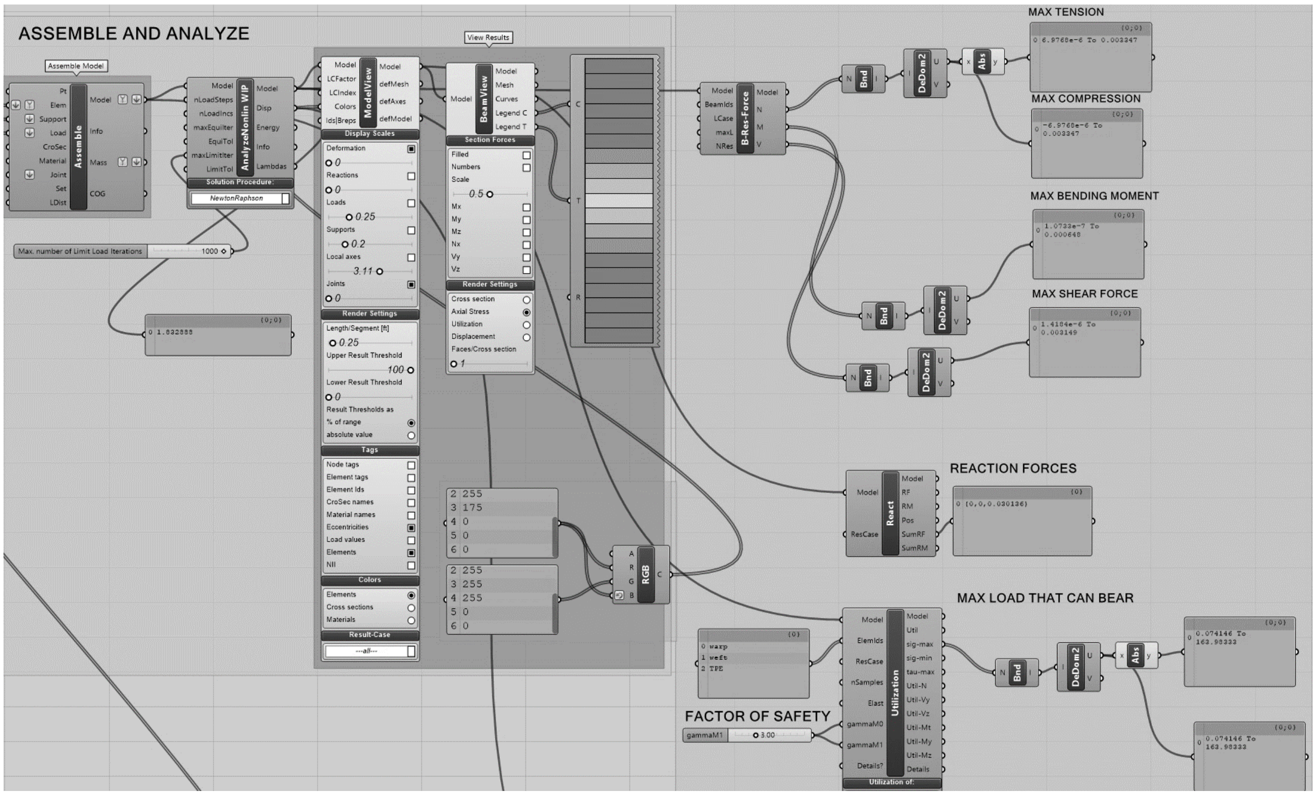


Figure 5- 6 Assembly and Analysis Part of the Tool

As mentioned earlier, Karamba 3D simulates the displacement of modeled geometries. It is important to compare different textile structures' displacement under loading to compare the behavior. The reason for choosing displacement as a design criterion is to understand how the fabric reacts when vertical loads are applied. The goal of the analysis is to avoid any failure with a large amount of displacement and uncomfortable seating surface with too little displacement.

There are three categories that are compared. These are different weaving patterns, carbon fiber to jute ratio, and 3D printed toolpaths. The first category that is compared are the different weaving patterns, and all of the fabrics are woven with jute fiber. Figure 5- 7 illustrates that the plain weave has shown the least displacement. Therefore, it is a good weaving pattern for structural purposes. On the other hand, a single gauze weave structure provides a better medium for 3D printing and undergoes the most tensile stress. Thus, the single gauze weave structure is an option for the surface components because it can be easily taped on the heat-bed without having problems with the extruder dragging the fabric.

The second category of analysis is to understand the impact of the carbon fiber to jute ratio on structural strength. Figure 5- 8 demonstrates that the increase in carbon fiber causes a decrease in displacement. The addition of carbon fiber results in higher tensile strength performed by the fabric. In the third category, the diamond shape and Voronoi toolpaths are tested (Figure 5- 9). The toolpaths are modeled on a single gauze woven textile that is made of jute. Even though the results do not show a significant discrepancy, the Voronoi toolpath has less deformation than the diamond tool path, and it can undergo more tensile stress.

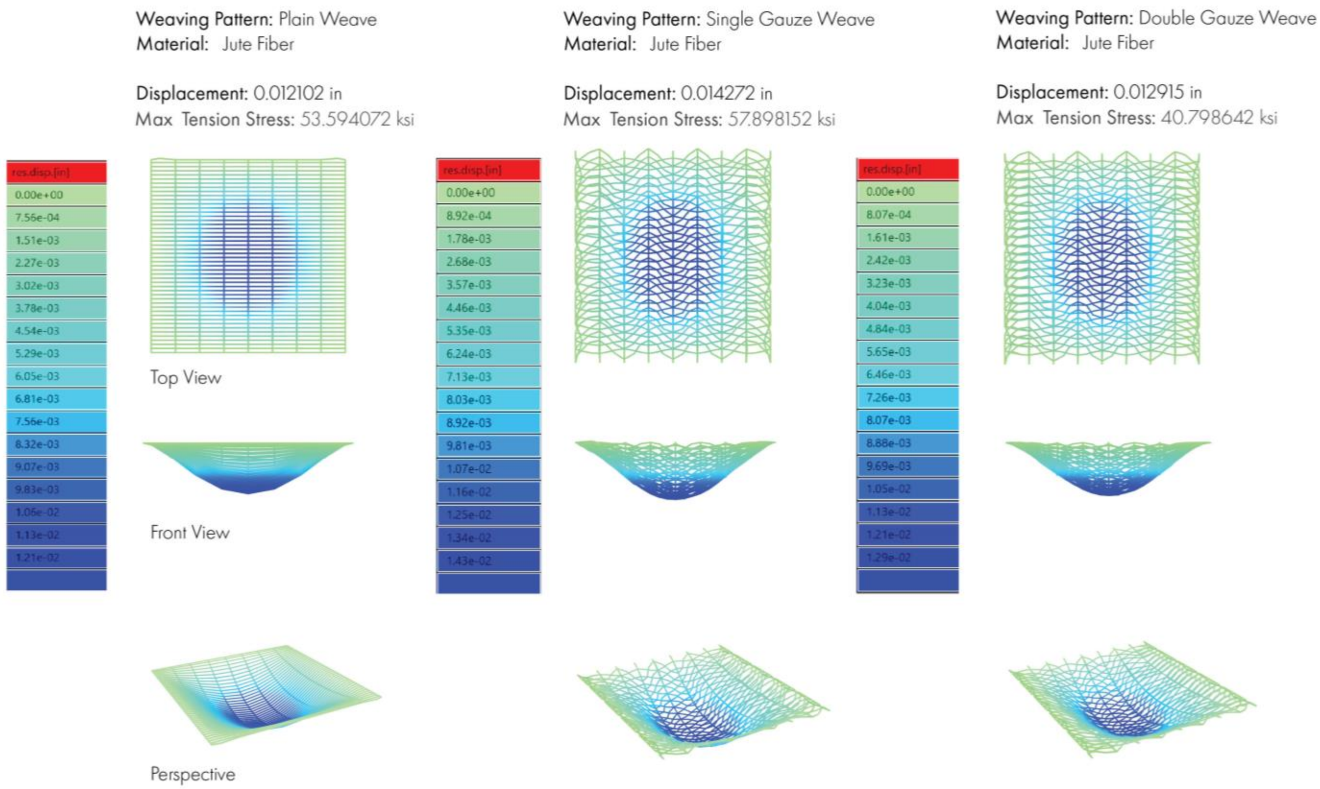


Figure 5- 7 Vertical Displacements of Three Different Weaving Patterns with All Jute Yarns, Under Uniform Pressure Load and Pretension Stress on the Fibers

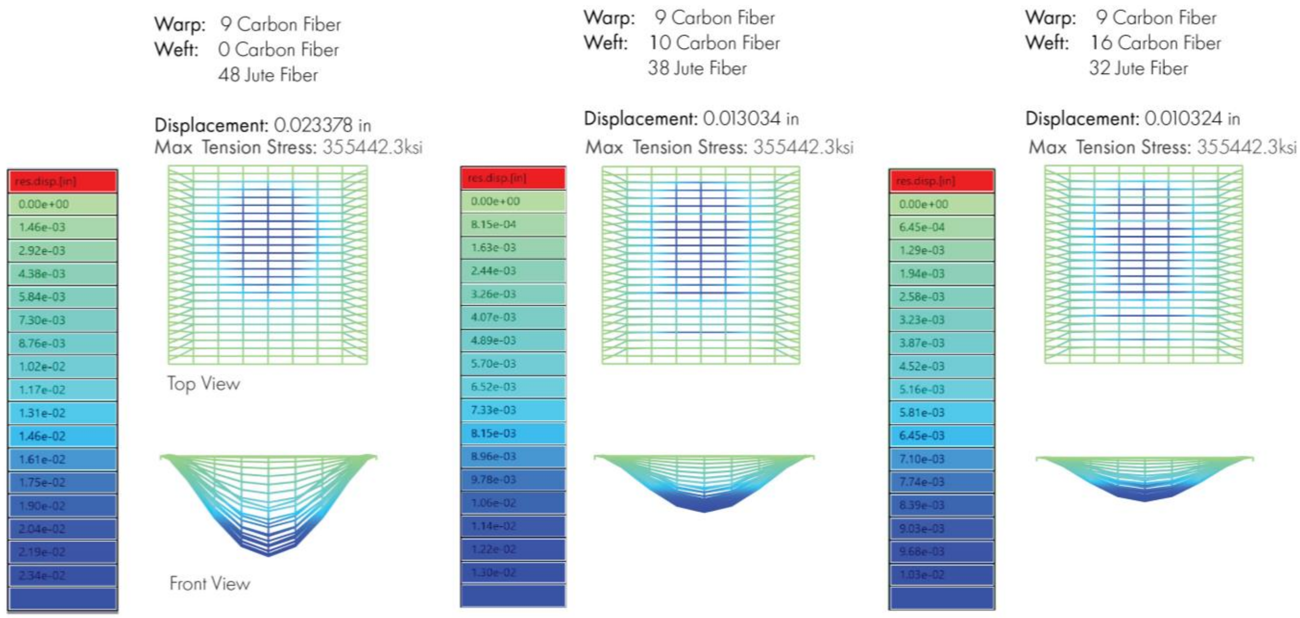


Figure 5- 8 Displacement Vertical Displacements of Three Different Carbon Fiber to Jute Fiber Ratio, Under Uniform Pressure Load and Pretension Stress on the Fibers

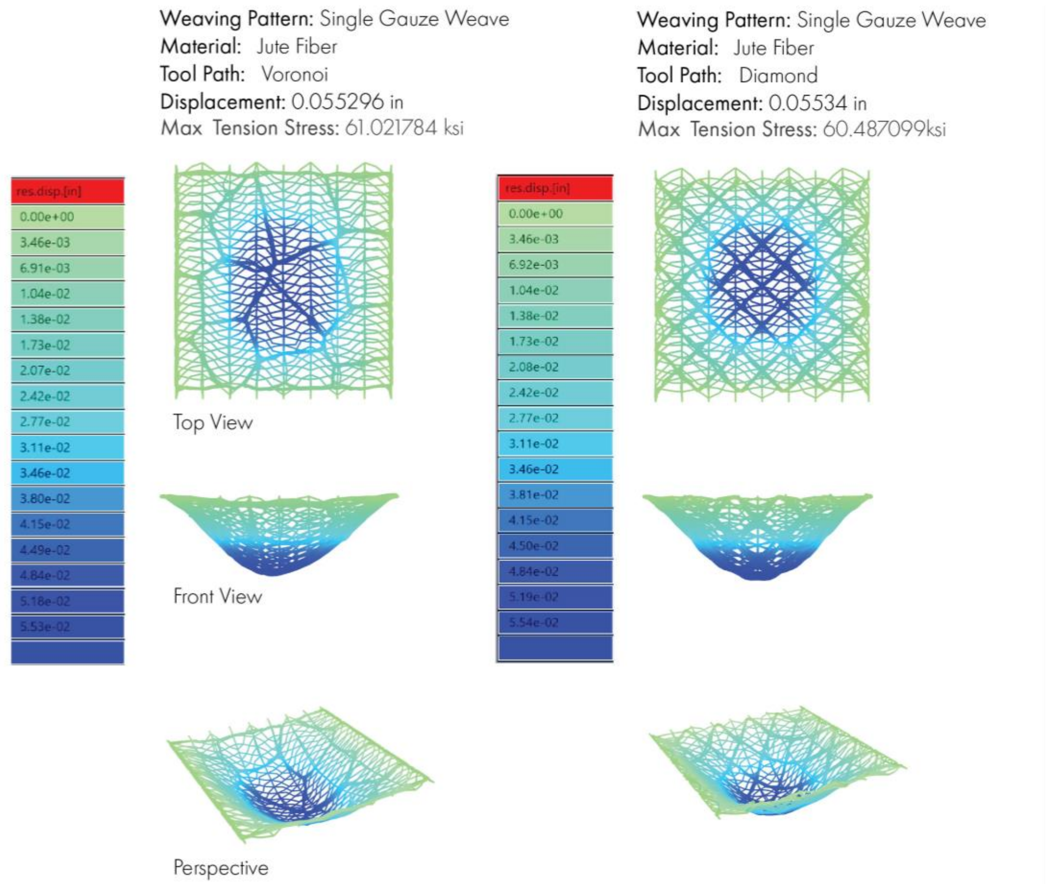


Figure 5- 9 Displacement Vertical Displacements of Two Different Toolpaths of Voronoi and Diamond Pattern That is 3D Printed with Thermoplastic Elastomer on Single Gauze Jute Fabric, Under Uniform Pressure Load and Pretension Stress on the Fibers

Table5- 2 Summary of Simulation Results: Displacement and Maximum Tension Stress

Weaving Pattern:	**Displacement (in)**	**Max. Tension Stress (ksi)**
Plain Weave	0.121 in	53.6 ksi
Single Gauze Weave	0.014 in	57.9 ksi
Double Gauze Weave	0.012 in	40.8 ksi
Carbon Fiber to Jute Ratio:		
Warp: 9 Carbon Fiber Weft: 0 Carbon Fiber/ 48 Jute	0.023 in	355442.3 ksi
Warp: 9 Carbon Fiber Weft:10 Carbon Fiber/ 38 Jute	0.013 in	355442.3 ksi
Warp: 9 Carbon Fiber Weft: 16 Carbon Fiber/ 32 Jute	0.010 in	355442.3 ksi
Tool Path:		
Voronoi	0.055 in	61.02 ksi
Diamond	0.055 in	60.49 ksi

In short, the simulation of the fabrics demonstrated the structural capacity of each fabric structure. The plain weave has a higher resistance to the applied load compared to other patterns. There is a direct relationship between carbon fiber to jute ratio and strength of the fabric. Therefore, the fabric with a higher carbon fiber to jute ratio has less displacement. Lastly, 3D printed plastic with a toolpath of Voronoi and diamond tool path has the same displacement results. These results are reflected in the Synthesis section, where design decisions are made.

SYNTHESIS

Chapter 6: Design of a Stool

Handwoven and 3D printed Fabric

This part of the thesis aims to translate the knowledge gained from bone analysis and fabrication and material experiments into a stool design. The design of the stool evolved throughout the process of experiments, and it consists of two parts that are handwoven and 3D printed fabric and the stool frame. The woven textile that is stiffened and stabilized with 3D printing techniques has a significant role in providing strength to frame and comfort to the users. After analyzing the fabric and 3D printed structures, two layers of fabric are overlayed with an orthogonal angle to improve the mechanical properties of the textile. Figure 6- 1 shows each element that is used for the fabric part of the chair. The first layer is considered as a structural component with a plain weave that combines jute yarn with carbon fiber tow. Carbon fiber is used for nine warp, and sixteen wefts elements and jute fiber is used for thirty-two weft elements. The second layer is the surface component where human interacts with fabric that is made of all jute fibers with gauze weave structure. The 3D printing pattern is inspired by bone surface and composed of Voronoi cells. The cells concentrate where pressure concentrates while a person is sitting.

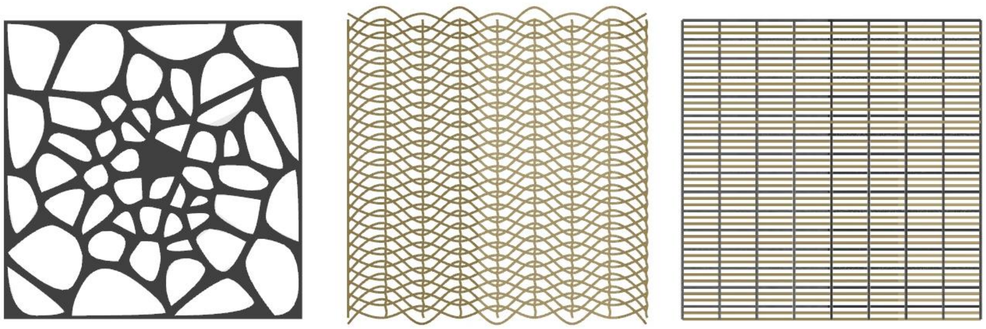


Figure 6- 1 Elements of the Overlayed Fabric Structure

The Voronoi pattern is 3D printed on the front and then the backside of each fabric to add stiffness to the textile and prevents distortion on fabric. Figure 6- 2 illustrates how the materials are overlayed with a 90-degree angle. This structure results in a comfortable and strong seating surface where deflection is controlled. The concept of this design applies to other architectural elements such as interior walls, façade systems, and ceiling structures, etc.

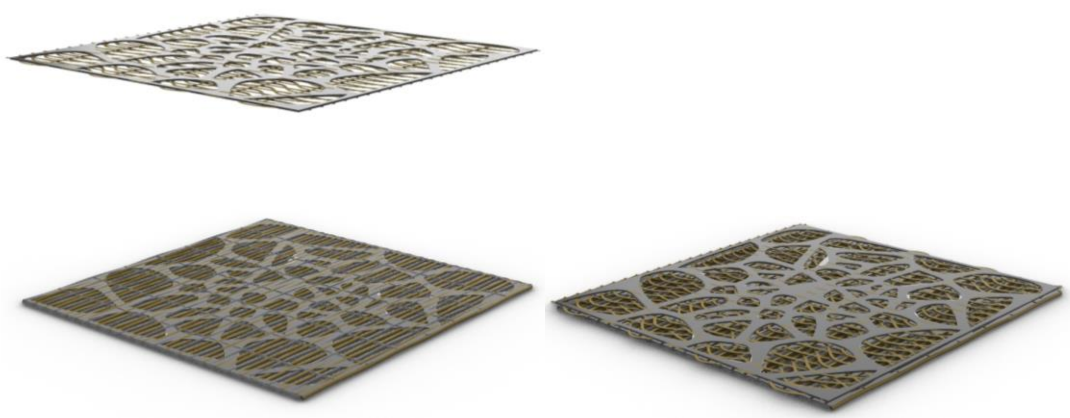


Figure 6- 2 Overlayed Fabric System

Stool Frame

The relationship between trabecular alignment and micro-geometries in trabecular bone structure is applied to a stool frame design. The initial iterations reflect the trabecular surfaces that are composed of Voronoi cells (Figure 6- 3). The first iteration has a cubic shape, and the embroidery hoop attaches the fabric to the top of the frame. However, the textile and frame are seen as two separate elements, and the concept of mimicking bone structure is not reflected well with the first iteration. Thus, the second iteration had a more organic shape and has holes in the bottom of the surface to connect the fabric to the bottom of the frame with knotting the threads. The second iteration needed to have inner structural elements to provide more strength to the outer surface.

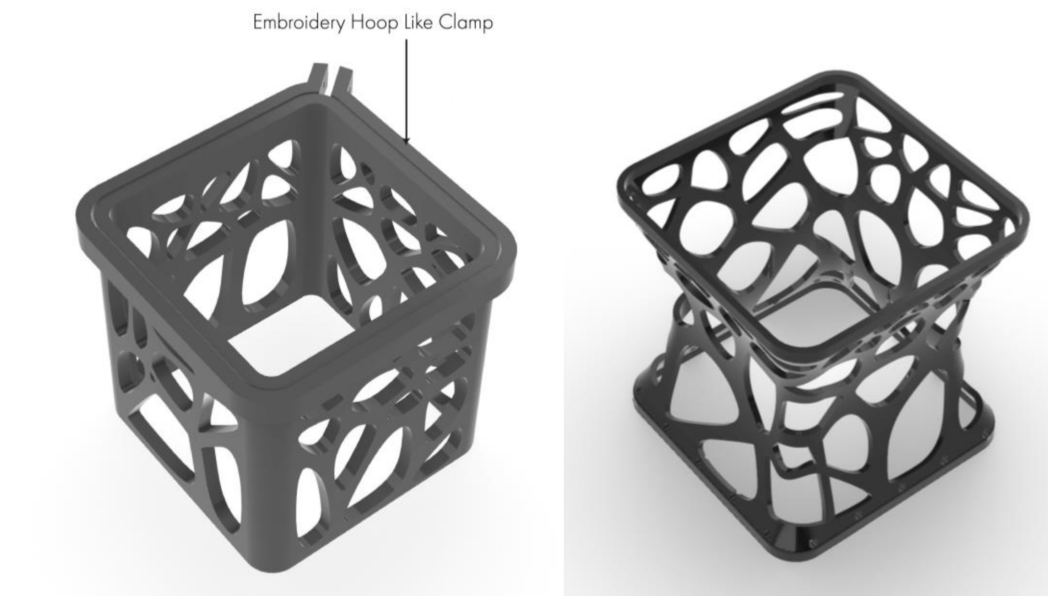


Figure 6- 3 Initial Frame Iterations Left: First Iteration Right: Second Iteration

Hence, the third iteration of the frame has a porous surface with supporting inner beams (Figure 6- 4). The beams and Voronoi cells concentrate on where weight distribution is. The connection between fabric and frame is inspired by darbuka that is a traditional drum and originated in Egypt. The frame provides holes in the bottom and the sidewalls. The bottom holes allow the warp and weft threads to be attached to the frame with knotting (Figure 6- 5). This design solution causes the fabric to be pre-tensioned.

Figure 6- 4 Third Iteration Left: Top View Center: Bottom View Right: Front View

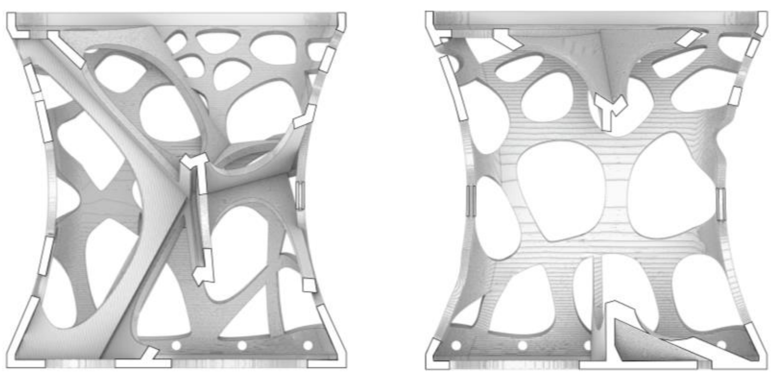


Figure 6- 5 Third Iteration - Section View of Frame

Figure 6- 6 shows the final chair design that is inspired by cow bone structure and traditional drums to connect textiles to the chair frame. The fibers going through the Voronoi cells to attach the bottom of the frame demonstrate the rods in the Nanoscale trabecular structure. The continuous structure of bone is reflected on stool design by using Voronoi tessellation on the frame and fabric, and the strings, which goes within the frame, unites the frame structure and fabric top. The fabric with 3D printed Voronoi pattern has a small amount of displacement that is shown in Chapter 5 to provide comfort to the users.

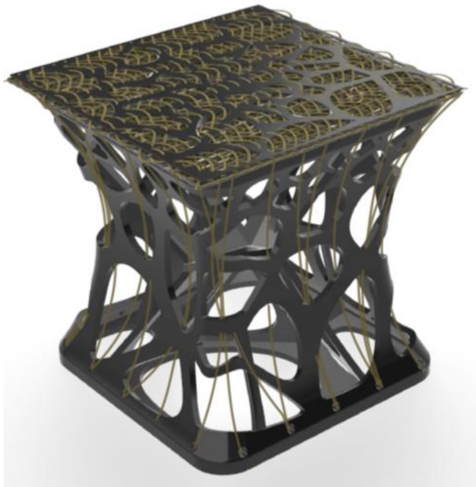


Figure 6- 6 Connection of Fabric to Frame

Although a small amount of displacement is acceptable with fabric structure, the frame needs to be rigid enough to have the least displacement as possible. Consequently, the frame is 3D printed and made of PETG. The infill density settings, which determine the amount of filament printed inside the object that is directly related to the ultimate strength, are increased to 40%. This setting makes the frame stronger to avoid possible height changes while a person is sitting to prevent the loss of tension on the fabric because the frame provides tension in fabric by the fabric-frame connection.

The weft and warp strings of the fabric are going through the frame, as it is shown in Figure 6- 7. The strings have entered the channels and then inserted into the holes in the bottom of the frame. Then, the strings are knotted in the bottom of the frame to keep the fabric in tension. The fabric on top deforms slightly when a person sits as the displacement is shown in Figure 5- 8. The next section, titled Computational Testing of Final Stool Frame, explains the structural analysis of the frame structure with more details.

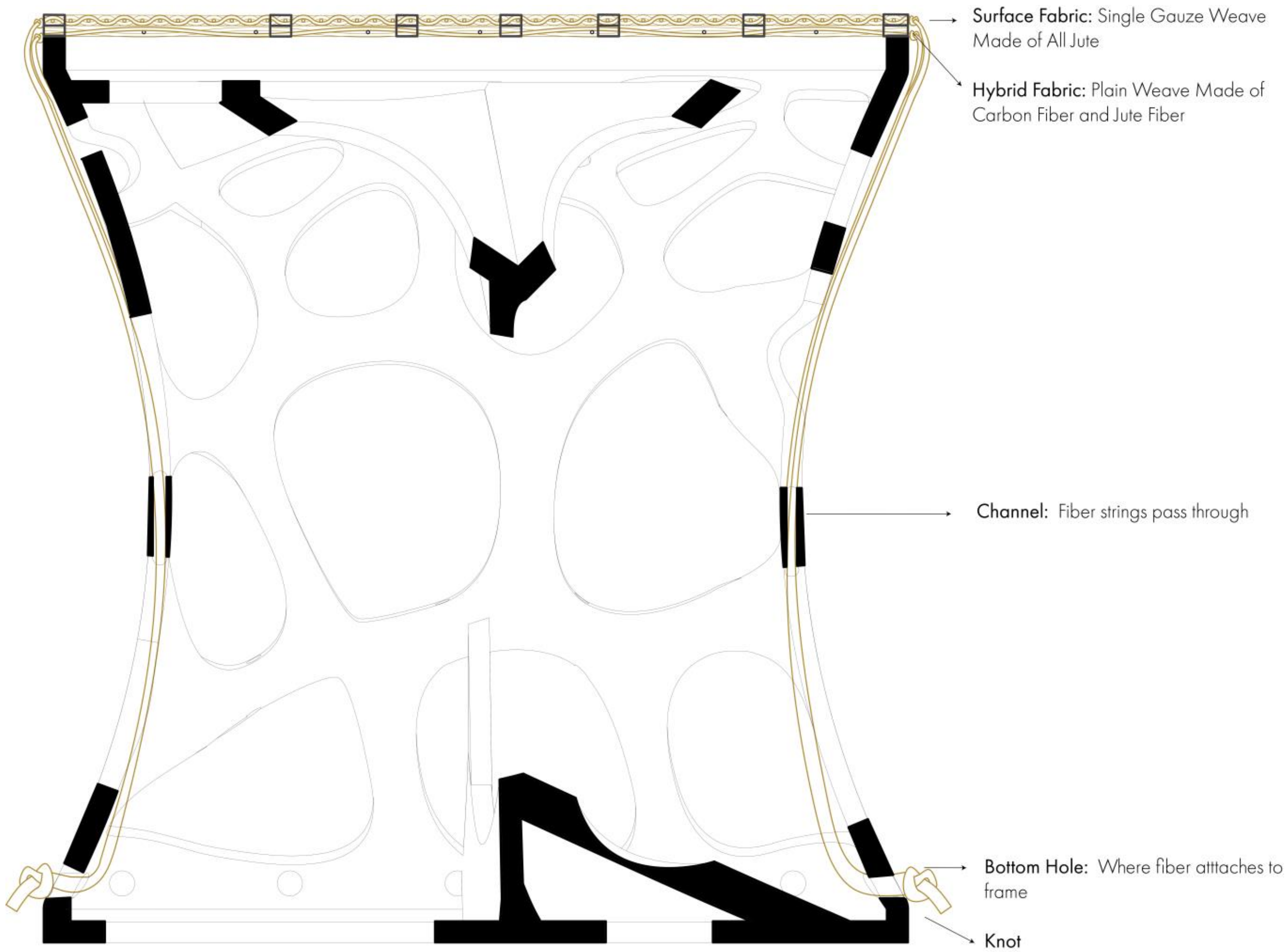


Figure 6- 7 Detailed Section Drawing of Stool

Computational Testing of Final Stool Frame

The rigidity of the stool frame is significant in retaining the tension of the fabric structure. Thus, the frame is tested with the Finite Element Method to understand how the frame structure reacts under loading conditions. The frame is modeled as a poly-surface in Grasshopper and modified in Rhinoceros. Then, the poly-surface is set as reference geometry in Karamba 3D. The frame structure is defined as a shell, which is a structural element characterized by its three-dimensional solid geometry. The bottom part of the frame, where touches the ground, defined as support. The vertical load of 1.08 kips/ft^2 (7.5 psi) on quarter-scale stool, which is calculated by dividing a human bodyweight of 250lbs by the size of the area of the fabric to support that person and gravity load are applied to the frame.

The finite element analysis tool requires a description of the material. The material properties of PETG are received from the MatWeb database and plugged into to cross-section component of the tool. The properties of PETG are:

Young’s Modulus: 265 kN/cm^2

Shear Modulus: 89 kN/cm^2

Specific Weight: 12.52 kN/m^3

Coefficient Thermal Expansion:0.0000770 1/°C

Yield Strength: 6.9 kN/cm^2

The first frame and final frame are compared to comprehend the role of the inner trabecular structure of the stool frame. The criterion is to have a vertical displacement of less than 1inch on the outer surface, which keeps the fabric in tension. Figure 6- 8 shows that the outer surface has more displacement without the internal part. This displacement on the outer frame directly impacts on the fabric tension provided by connecting to the bottom of the frame. Thus, it is significant to decrease the deformation on the surface. Once again, the ultimate intent is to mimic the bone structure, which is continuous in its structure for the solution, and beam-like elements are added to the inner part to support the outer surface.

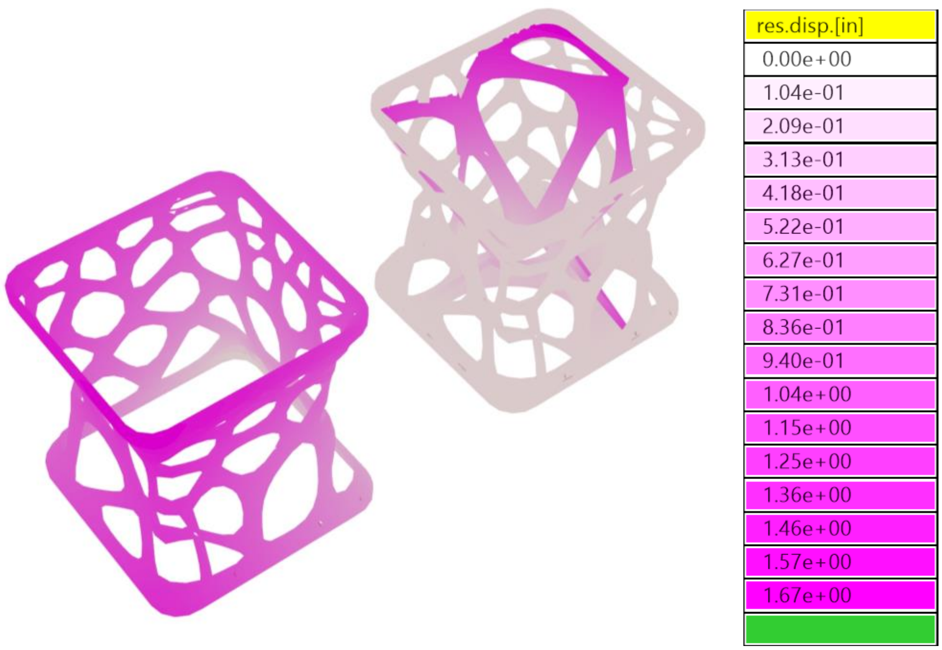


Figure 6- 8 Displacement Comparison of Frame 1 (Left) and Frame 2 (Right)

Additionally, the finite element analysis simulates the force flow lines on the shell to understand the movement of the load when vertical loads and gravity are applied (Figure 6- 9). The other feature that Karamba 3D renders is utilization values, which are the maximum tensile and compressive stress that is carried by the structural element. Figure 6- 10 illustrates how the frame output utilization by calculating the force on the element, cross-sectional, and material properties. The negative values that are in red are tensile stress, and the positive values that are in blue are compression stress. The inner beams undergo more tensile stress than outer surface.

In short, this simulation tool shows how the stool frame reacts under an applied load. The outer surface becomes rigid with the addition of the inner beam elements. Therefore, the connection of the fabric to the frame doesn't affect the tension on the fabric. The frame is illustrated as a stable and strong structure that can withstand a bodyweight of 250 pounds.

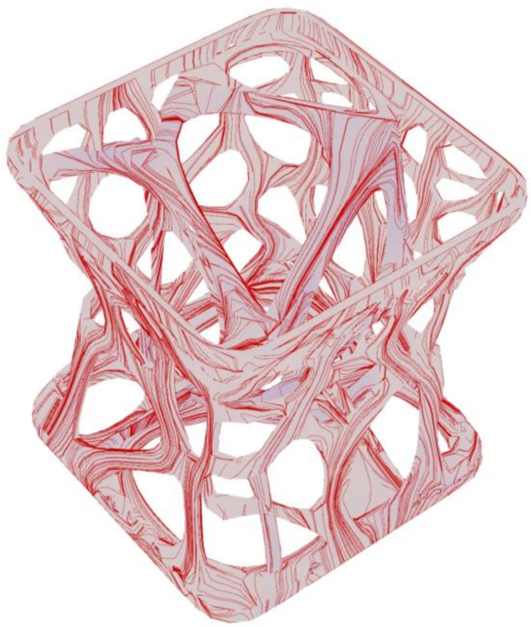


Figure 6- 9 Force Flow Lines

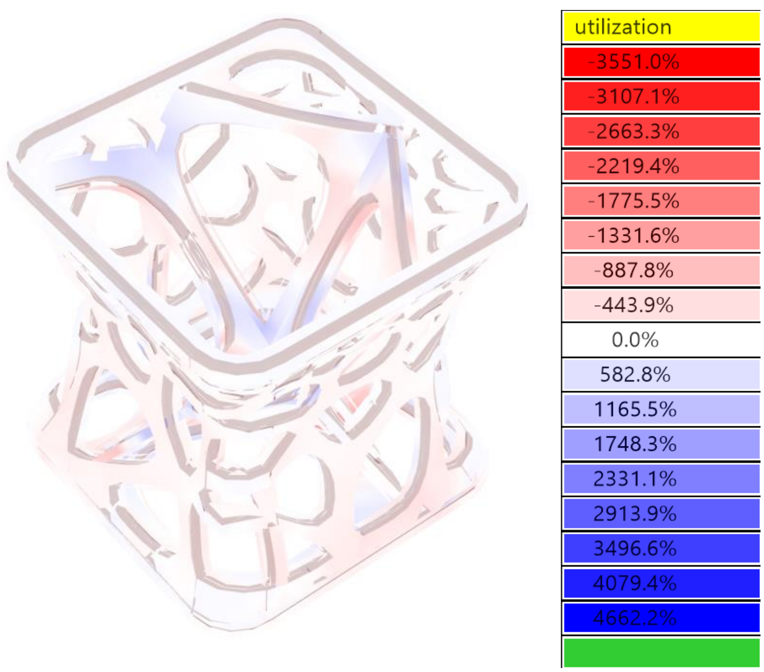


Figure 6- 10 Utilization Structural Diagram

CONCLUSION

Chapter 7: Conclusion

In conclusion, this author of this thesis places emphasis on problems about conventional fabrication techniques and limited digital platforms for textile design. For instance, manufacturing methods of fiber structures are mostly concentrated on using molding techniques, which requires mold fabrication. This method causes a waste of material and time. Additionally, chemical resins are applied to stiffen fabric structures that have various negative environmental and health impacts. As a solution, this thesis presents a fabrication method that integrates traditional weaving and 3D printing techniques and a digital tool. This method of fabrication starts with weaving on a pegboard loom and then removing the fabric from loom to 3D printing Thermoplastic Elastomer (TPE) on the top and bottom of the fabric structure. Voronoi and diamond shape patterns prevent the fabric from deforming in a specific direction. It stabilizes the warp and weft location and adds compressive strength to the textile.

The other problem is a lack of digital platforms for designers to model their textile design and test it structurally. Therefore, a generative algorithm is built within Karamba 3D, which is a plug-in Grasshopper to provide a parametric platform to model the fabrics and 3D printed patterns to test the structural resistance of the 3D printed woven textiles. This digital tool allows designers to simulate 3D modeled textiles under an applied load. Designers using this tool can increase or decrease the number of warps and wefts, *and* the density of 3D printed patterns to achieve the desired resistance. It creates a platform for designers to test different carbon fiber to jute fiber ratios; to test three different weaving structures; and to test two different 3D printed TPE patterns. The results of these tests show maximum tension and compression force, maximum bending moment, and deflection. As a result of the developed digital tool which allows parametric textile modeling and testing, designers and architects can reduce the amount of material used to construct architectural and structural elements such as barrier walls, columns, beams, structural ceiling, and, indeed, furniture construction which has woven hybrid fabric structure.

Moreover, the idea of using graded material is derived from bone structure. Bone structure analysis shows how a trabecular structure is aligned and concentrated in response to specific loading conditions. The visible geometries and structures in micro and Nanoscale analysis inspire the overall chair design. The stool frame and 3D printed fabric reflect the Voronoi cells, and the threads of the fabric, which goes through Voronoi cells and connects to frame at the bottom, represent the rod structures in the trabecular bone structure. The chair is designed to hold a human body weight up to 250 pounds. Additionally, the chair frame is tested in the digital platform by using Karamba 3D.

Overall, the integrative fabrication method of weaving and 3D printing improves the use of textiles in architecture. For instance, the 3D printed woven fabrics can be used as ceiling and floor where the walls are 3D printed of concrete or earth. The strings can go through in between walls and attach to the vertical elements. Furthermore, the 3D printed fabrics can be used as formwork for 3D printing walls, shells, and roofs. In 2018, Zaha Hadid Architects and ETH used knitted fabric as formwork for concrete shell construction. They used human labor for adding concrete; however, 3D printing concrete or earth with a robotic arm is more time and cost-efficient option. The digital tool that is introduced in this thesis can be beneficial to understand loading conditions to optimized the design of structures that are made with 3D printing and weaving techniques. The number of carbon fibers in hybrid fabric and weaving patterns can be adjusted according to the results that are received from the digital tool.

In short, the stool design shows a novel relationship between textiles and 3D printing. First of all, both techniques have an additive approach to manufacturing. It allows optimization of stool design by load analysis. The fabric is an absorbent material; therefore, the 3D printing on the fabric works well and adds stiffness to the woven structure. Additionally, 3D printing on woven fabric can be used for form-finding purposes in larger-scale projects.

Furthermore, the stool design reflects the complex relationship between horizontal and vertical elements. Bone structure is studied to convert the complexity into the continuity of these two elements by allowing the seating surface to stay in tension by going through a 3D printed vertical stool frame. Trabecular bone provides a formal shape and structural method into the stool design. The knowledge that is gained from the bone analysis is applied to the stool design that is made with integrative fabrication methods of weaving and 3D printing.

Limitations

The first limitation is the problem of accessing laboratories due to COVID-19, which has been announced as a pandemic by the World Health Organization in March 2020. The action towards this health crisis requires social distancing and closure of institutions and businesses. Therefore, the quarter-scale chair and woven fabrics are not tested in a controlled laboratory, and all the results are received by the simulation tool, Karamba 3D.

The second limitation is Karamba 3D has limited libraries for material selection. Hence, material properties are edited manually for more accurate results. The other issue with the tool is that it does not convert curves into polylines that become structural elements. Therefore, the warp and weft curves are transformed into polylines for finite element analysis.

The third limitation are time-constraints that impact continuous fiber printing experiments. The robotic arm portion of the thesis stayed in an experimental stage. The second version of the extruder shows that the fiber needs to be preheated and treated before entering the extruder. The material choice of extruder affects the movement of the fiber. The pieces of the extruder are 3D printed of PETG. The inner surface of the extruder is not smooth enough because of the fabrication method; therefore, it influences the movement of fiber. As a solution, the extruder pieces can be made of metal to have a smoother fiber movement.

Next Steps

The goal of this project is to design a chair that withstands a human body weight of 250 pounds and fabricating it with weaving and 3D printing techniques. The further development of this research is to construct a full-scale chair. The future steps include:

1. Testing the physical woven fabrics and quarter-scale final chair in a highly controlled laboratory and compare the results of deflection, tension, and compression with the results received from the digital tool.
2. Improving the connection between fiber and frame by making a thread as a part of the inner trabecular tense structure in the quarter-scale prototype.
3. Developing a g-code to control robotic arm motion and taking advantage of the six-axis motion to fabricate a full-scale chair frame with spatial 3D printing.
4. Exploring other weaving patterns combining natural fibers with synthetic fibers and evaluating the strength of these hybrid fabric structures.
5. Understanding the problems that happened in continuous fiber extruder.
6. Solving those issues to print structural elements.

Contributions

This thesis has the following contributions:

1. **An integrative fabrication technique**. This technique combines traditional weaving and 3D printing to stiffen the fabric and add stiffness to the woven fabric structure.
2. **A digital tool.** This tool models parametric fabric structures with different weaving patterns and analyzes the structural resistance of textiles in various loading conditions.
3. **Textile designs.** Designs that used combined natural and synthetic fiber overprinted with Thermoplastic Elastomer
4. **Stool design.** Design using the textile top and 3D printed base inspired by cow bone trabecular structure.
5. **Design for continuous fiber extruder.** A first draft design for a continuous fiber 3D printing extruder that attaches to the robotic arm for larger-scale architectural element fabrication.
6. **A literature review and experiments.** Understanding various resources and experimenting with different fabrication and simulation techniques to design textiles and a chair that is inspired by bone structure and explaining future architectural applications.

In short, this thesis presents a mixed fabrication method of weaving and 3D weaving and simulation methods of parametric fabric modeling and testing. These methods result in textile and stool design inspired by cow bone trabecular bone after acknowledging literature review and experiments.

APPENDIX

3D Printing with a Robotic Arm

This appendix includes an alternative approach to integrate printing and textile design. This is to use continuous fiber printing. Markforged invented a 3D printer that extrudes fiber with filaments. However, the build volume is 320mm x 132mm x 154 mm; it does not allow larger-scale printing. My experiment suggests continuous fiber printing with a robotic arm to expand the printing size.

The first step of this experiment is modeling extruder pieces and 3D print the parts with Polyethylene terephthalate (PETG), adjusting higher infill density. The first design of extruder has two stepper motors for fiber and PLA. The nozzle diameter is 2 mm to be able to extrude two materials at the same time. It includes two fans to cool the printed objects while exiting the hot end. The fiber and PLA enter to extruder from different tunnels and meets in the hot end, as shown in Figure A- 1. However, this design was not successful because the motor cannot push the fiber into the extruder.

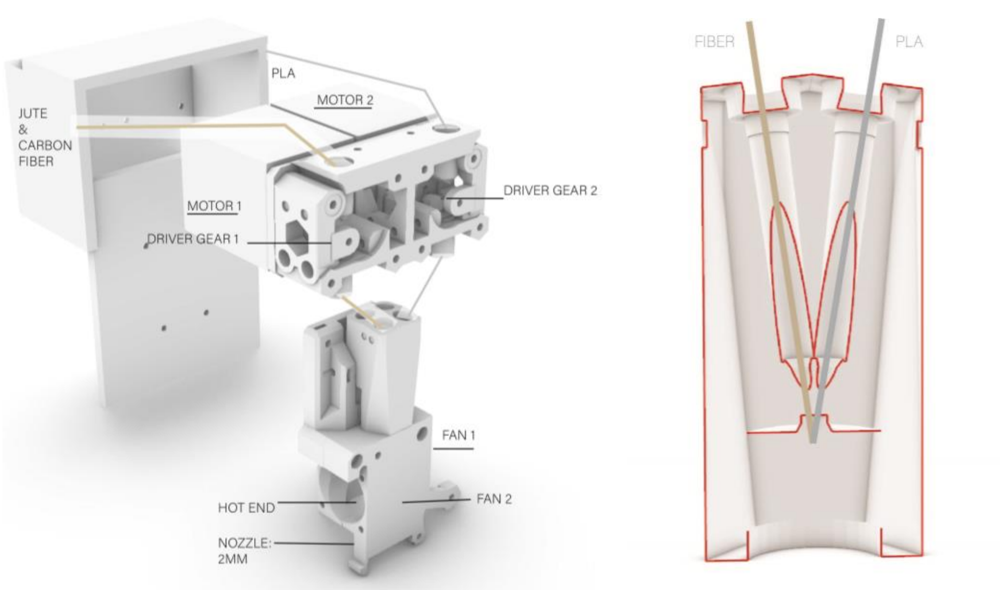


Figure A- 1 Left: Full-Assembly Right: Section View

The next iteration allows the thread to be inserted from the sidewall and dragged by PLA entered from above, as shown in Figure A- 2. For this design, only one motor is needed for PLA. The tunnel where PLA and fiber meet is narrowed to exaggerate the push effect of PLA, yet it is not enough to get the two materials together in the nozzle. Fiber needs to bepreheatedd and treated to control fuzz before insertion.

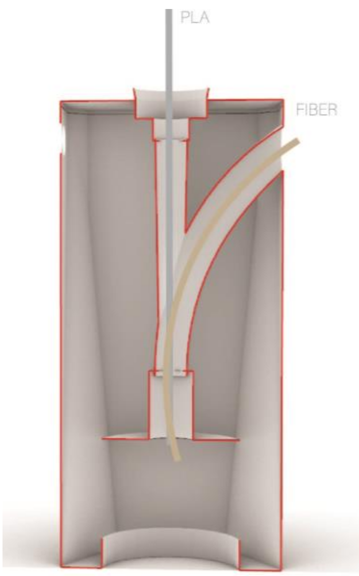
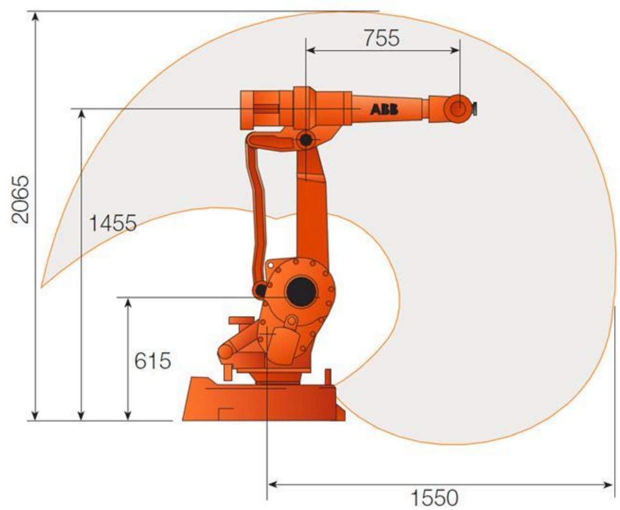


Figure A- 2 Test 2-Section View

Meanwhile, the bracket for IRB 2400 robotic arm is designed according to information that is taken from ABB’s official website. The bracket made of PETG attaches to the robotic arm, the stepper motor, and extruder, as illustrated in Figure A- 3.



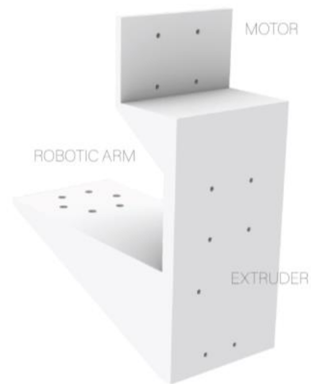


Figure A- 3 Left: Robotic Arm Dimensions Right: Bracket Design

After finishing the hardware assembly, the process of wiring electronics was started. For this project, Arduino Mega 2500 microcontroller and RAMPS 1.4 controller board are used for the electronic controlling system. Longrunner Nema 17 is selected as a stepper driver for the motors. The electronic board is received power by a 12 V switching power supply. Figure A- 4 demonstrates the details of wiring and electronics that are installed on the board. The Arduino board is configured with Marlin Firmware. The electronics are tested by Pronterface, which is a host of 3D printers to check if the wiring system is working as desired.

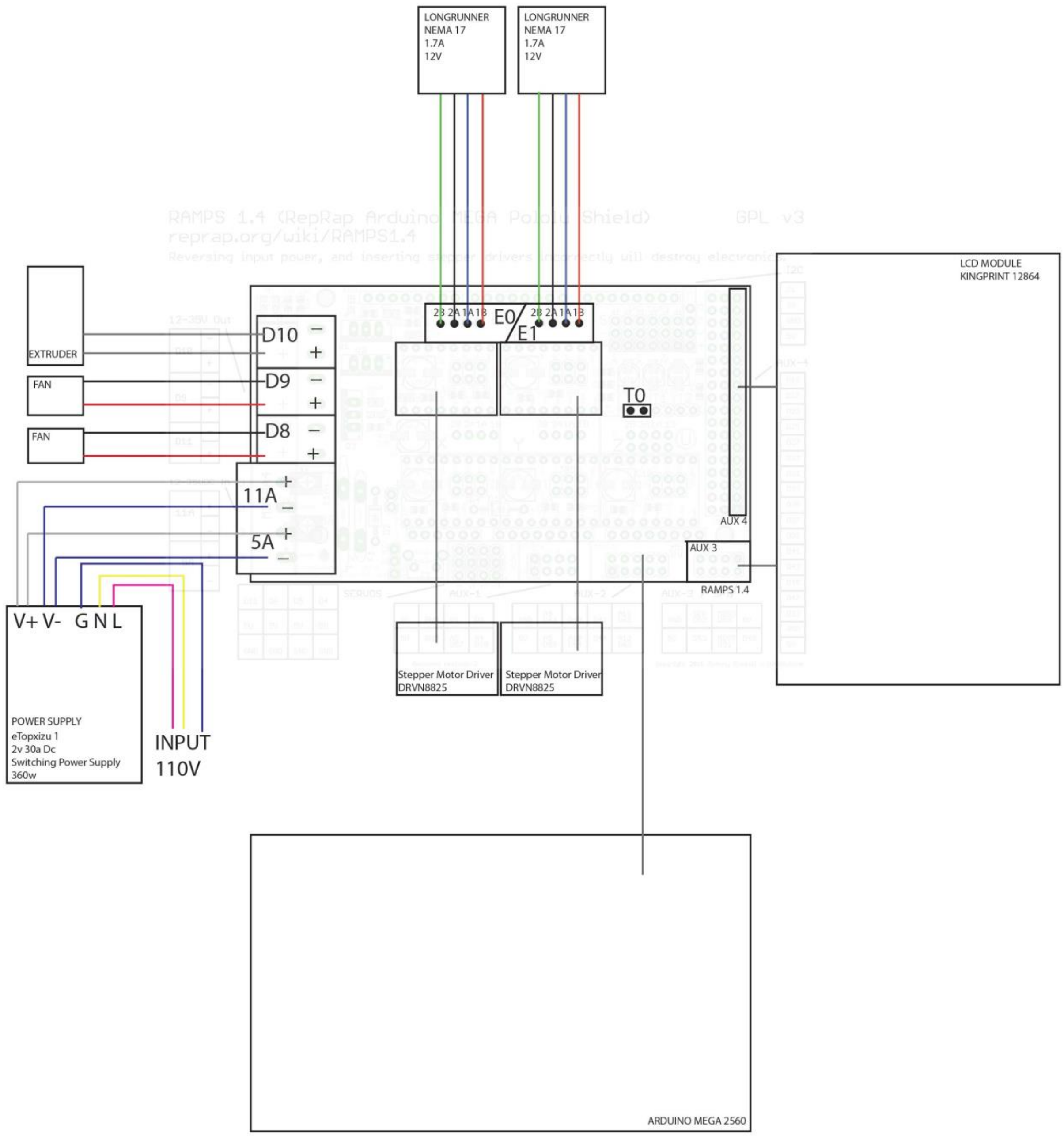


Figure A- 4 Electronic Wiring Diagram

In short, the electronics work well; however, there are hardware related issues that occurred in the experimental stage of continuous fiber printing, which can be solved in the future for full-scale chair fabrication. In Chapter 6, design ideas for continuous fiber printing are discussed.

Initial Design Concepts

During the experiment to print continuous fiber with the robotic arm, the stool concept was designed using an extruded 2D Voronoi Pattern to mimic channel elements found in micro-scale bone SEM images. Figure A- 5 illustrates the starting point of the stool design. However, the surface for seating is not ergonomic, and there is an excessive amount of Voronoi structures that the robotic arm would not be able to print because of complex geometry.

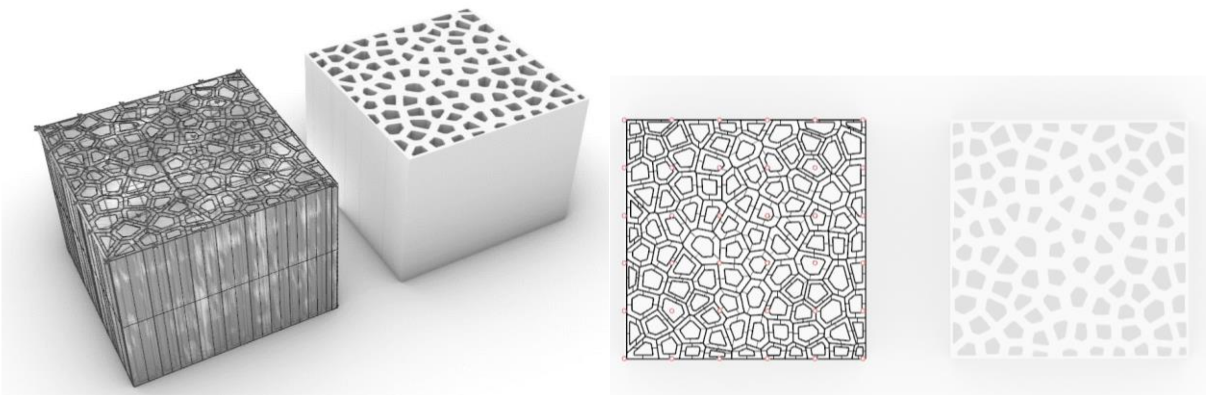


Figure A- 5 Staring Point of Stool Design

The next step was to reduce the number of Voronoi cells and curve the cell boundaries to simplify geometry for the robotic arm. (Figure A- 6). The upper part is trimmed to create a more comfortable surface to sit. The wall thickness of the center of the stool is increased, and the channels that touch the ground are increased to optimize the stool design with material efficiency. The toolpath of continuous fiber printing is studied, as shown in Figure A- 7. The main challenge of the toolpath is remaining the continuity of the fiber and not cutting the material during production. Therefore, the channels would have rod-like elements while moving from one channel to another channel.

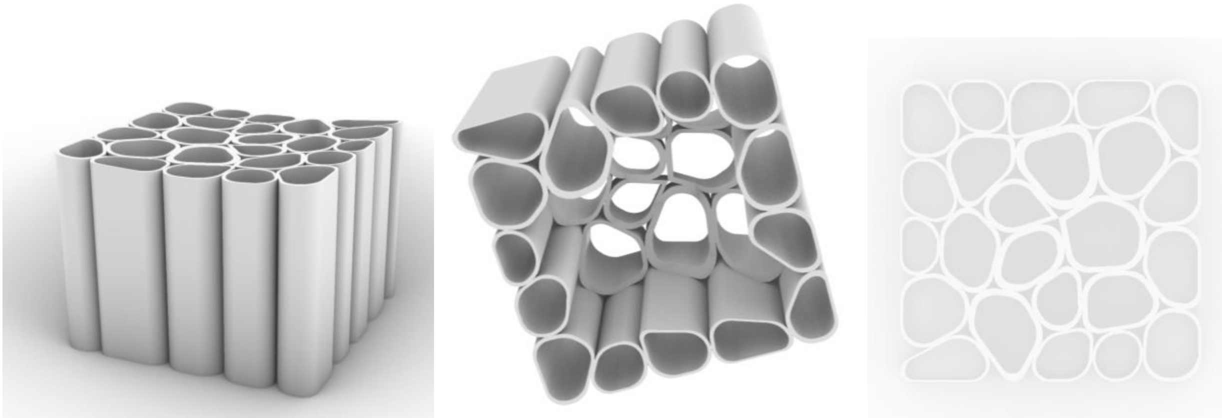


Figure A- 6 Left: Perspective View Center: Bottom Perspective View Right: Top View

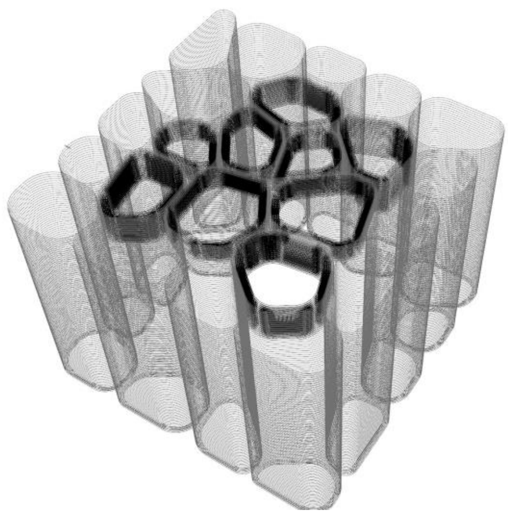


Figure A- 7 Toolpath for Continuous Fiber Printing

After all experiments with continuous fiber printing on the robot were interrupted, this thesis focused on the integration of weaving and 3D printing methods. Therefore, the stool design has altered with the change of fabrication method. The final stool design consists of two parts: handwoven and 3D printed fabric and a stool frame made of PETG. The details of the synthesis of experiments and understanding with stool design are explained in this chapter.

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