KNITTING BEHAVIOR:
A MATERIAL-CENTRIC DESIGN PROCESS

by

Carrie Lee McKnelly

BArch, Pratt Institute, 2008

Submitted to the Department of Architecture
in partial fulfillment of the requirements for the degree of

Master of Science in Architecture Studies
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 2015

© 2015 Carrie L. McKnelly. All rights reserved.

The author hereby grants MIT permission to reproduce and to distribute publicly paper and electronic copies of this thesis document in whole or in part in any medium now known or hereafter created.

Signature of Author:______________________________
Carrie L. McKnelly
Department of Architecture
May 21st, 2015

Certified by:______________________________
Lawrence Sass
Associate Professor of Design and Computation
Department of Architecture
Thesis Advisor

Accepted by:______________________________
Takehiko Nagakura
Associate Professor of Design and Computation
Chair of the Department Committee on Graduate Studies

Readers:

Brandon Clifford, Belluschi Lecturer, Department of Architecture, MIT
Caitlin Mueller, Assistant Professor in Building Technology, MIT

KNITTING BEHAVIOR:
A MATERIAL-CENTRIC DESIGN PROCESS

by

Carrie L. McKnelly

Submitted to the Department of Architecture on May 21st, 2015
in partial fulfillment of the requirements for the degree of
Master of Science in Architecture Studies

ABSTRACT

This thesis explores computation as a communicative device between the physical and the digital, establishing a conversation between a material assembly and a digital model as a tool to inform the logic of the assembly's internal organization. In this research, the material assembly, which is defined as a material whose properties derive from the programming of raw matter to form unique internal structures, manifests through the technique of knitting, a material practice defined by pattern as rule-based code.

A key contribution of this research is the development of a framework to help designers better understand how the topology of a knit structure can align with formal and structural motivations of tension activated architectural forms. This was accomplished through the identification of the knit pattern as code. Whereas traditionally the pattern is a static visual representation, in this research it is both the physical sequence of stitches and the dynamic properties of each stitch within a digital model. The dynamic properties of the physical material communicate through the knit pattern to the digital model, which explores the possibilities of form within the constraints of the material to remap the pattern's code and thereby re-informing the physical. This new framework may help designers create and evaluate material assemblies to better satisfy the local and global needs of form, structure, and aesthetics.

The play between the physical and the digital is recursive, experimental, and interpretative – each informs the other while never truly resulting in the same output.

Thesis Advisor: Lawrence Sass,
Title: Associate Professor Department of Architecture, MIT

ACKNOWLEDGMENTS

This thesis was possible by the support, guidance, and feedback from my advisors, mentors, classmates, and family; for each I am grateful. First, I thank my thesis advisor, Professor Larry Sass, for his insightful guidance, valuable advice, and heartfelt conversations about art, architecture, and life. Next, I thank my two thesis readers: Professor Caitlin Mueller for her enthusiasm, honesty, and feedback, and for inspiring many aspects of this research and guiding me to new territories; and Professor Brandon Clifford for his encouragement and thoughtful conversations -- although he is a man of mass, I hope to have excited him about thinness. Finally, I'd like to acknowledge several additional faculty members who have been key in forming the foundations of my inquiry in Design and Computation throughout my two years at MIT: Professor Terry Knight, Professor George Stiny, and Research Scientist Skylar Tibbits.

The administrative faculty of the Department of Architecture, MIT's writing center, and my SMarchS classmates were all instrumental in cheering me on. Your love and generosity will continue to inspire me. Deepest thanks to my classmates Nazareth Ekmekjian, Madeline Gradillas, Jeff Geisinger, and Nushelle de Silva, and my writing instructor Marylin Levine.

I am thankful for the Marvin E. Goody, Schlossman, and Bill Mitchell ++ awards supporting my ambitions and expanding the range of what was possible.

Finally, I thank my family and partner Ben Halpern. Your endless encouragement and love was essential day and night.

This thesis is dedicated to my parents, Steve and Rendy McKnelly. Your ambition, creativity, and sense of adventure is forever in my heart.

TABLE OF CONTENTS

CHAPTER 1
INTRODUCTION

While we construct our built environment from materials, we often do not program the materials from which we build. Historically, architects have been limited to materials with unprogrammed internal structures -- such as wood, stone, glass, steel, or concrete -- neglecting assemblies with properties that derive from a material and its internal organization. This thesis states a new architecture may emerge if the programming of material assemblies is within the control of the designer.

The research contained explores computation as a communicative device between the physical and the digital, establishing a conversation between a material assembly and a digital model as a tool to inform the logic of the assembly's internal organization. Currently designers lack a framework for understanding how true material properties -- including their active behaviors -- can inform a digital model which can then aid in the programming of material assemblies.

This manifests through the technique of knitting -- a material practice defined by pattern as rule-based code -- for application in tension-active forms. Whereas traditionally the pattern is a static visual representation, in this research it is both the physical sequence of stitches and the dynamic properties of each stitch within a digital model. The dynamic properties of the physical material communicate through the knit pattern to the digital model, which explores the possibilities of form within the constraints of the material to remap the pattern's code, thereby re-informing the physical.

This thesis aims to establish a framework for exploring how the knit pattern can be understood as the communicative device between the physical and the digital by reviewing key concepts and existing research (Chapter 2), then by detailing the process of material exploration from physical making to digital simulation (Chapter 3), followed by a detailed description of how that exploration manifests in a prototype demonstrating a tension-active form (Chapter 4), and finally by summarizing the contributions with intended applications and future work (Chapter 5). But first, I will motivate the research by my interests in the interdependence of form, material, structure, and fabrication.

1.1 Past Work

As a designer, researcher, and maker, I endeavor to understand form, material, structure, and production not as separate aspects, but rather as interrelated concerns that influence the way we construct our built environment. My work is motivated by form-found geometry, materiality, and construction logic, often gravitating towards minimal forms which are not easily understood until a logic emerges from within them. After many years of designing and fabricating large spatial installations, the distinction between form, structure, and material has blurred. I have developed a fascination with the dependency between these fundamental elements of building and am drawn to the role material plays in both defining form and embodying structure.

In my previous work with SOFTlab, a small design practice in New York City, each form was materialized from a patchwork assembly of thin, discretized panels, each shaped to specifically fit its precise location within the form. In a public artwork design for the San Gennaro festival in Little Italy, we constructed a form-found geometry through a digital particle-spring method that hovered between three Manhattan buildings while pointing to both the sky and a pedestrian walkway, as seen in Figure 1.1. The form was constructed from 4,224 discrete, laser-cut panels, each with a shape and assembly logic dependent on the global form and local needs within it. Each “x”-shaped panel allowed the forces to flow along the form similar to a cable-net structure. Form, material, and structure were unified as a result of the panel shape and construction logic.

My current research builds upon this knowledge, driven by a curiosity to explore whether a complex geometry can be made physical through a continuous material assembly with the specificities of form and structure. With this, the logic of construction is linked to the internal composition of the material assembly rather than the external shape of each panel.

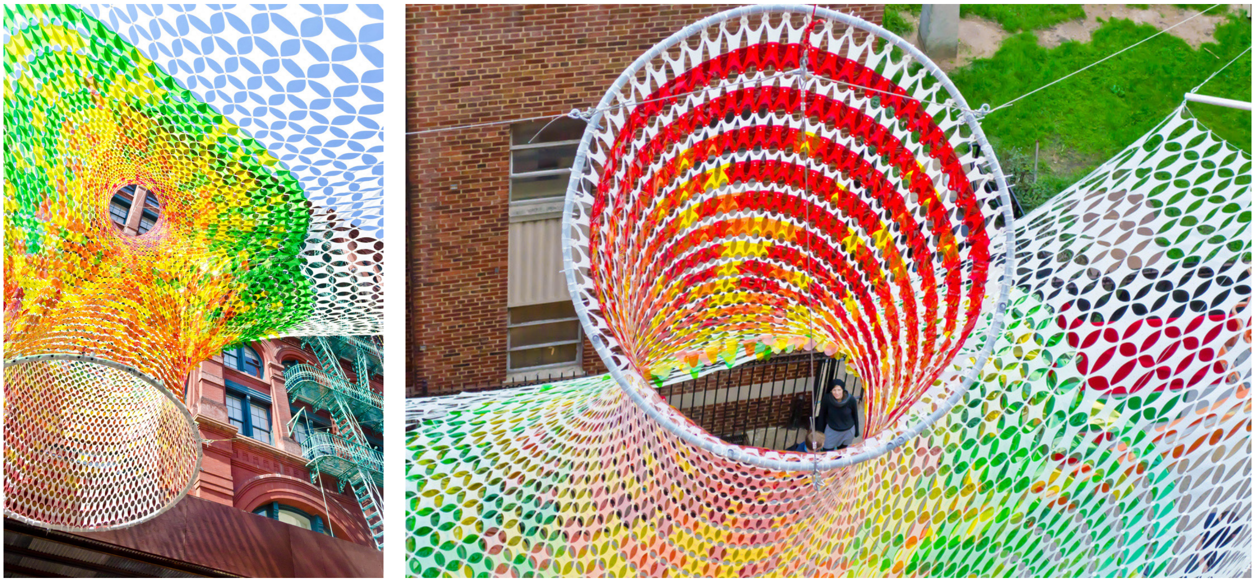


Figure 1.1: *Xtra Moenia, SOFTlab 2011; NYC*

1.2 Why Knitting and Tensile Forms

The research in knitting is motivated by an application in tension-active forms, and by a desire to ultimately create an architecture of minimal material means in which form, structure, and material are in harmony. Throughout his lifetime, Frei Otto constructed a range of sophisticated tensile structures of minimal material means, beginning with membrane structures and ultimately arriving at cable nets, which increased his structural spans and formal abilities (Drew 28,33). Otto's ephemeral architectural and form-finding methods inspire the formal motivations of this research; however, the material process is motivated more by the sophisticated logic of Nike Flyknit -- a knit athletic shoe also constructed of minimal material means. Nike reduced the typical athletic shoe from five or more panels to a single continuous shape by utilizing advancements in knitting technology to optimally loop each thread according to the requirements of form and structure. In a way, Nike's material system can be viewed as a hybrid of membrane and cable net structures; the fibers are programmed -- like the placement of cables in a cable-net -- according the the final geometry yet come together to form a textile enclosure (see Figure 1.2).

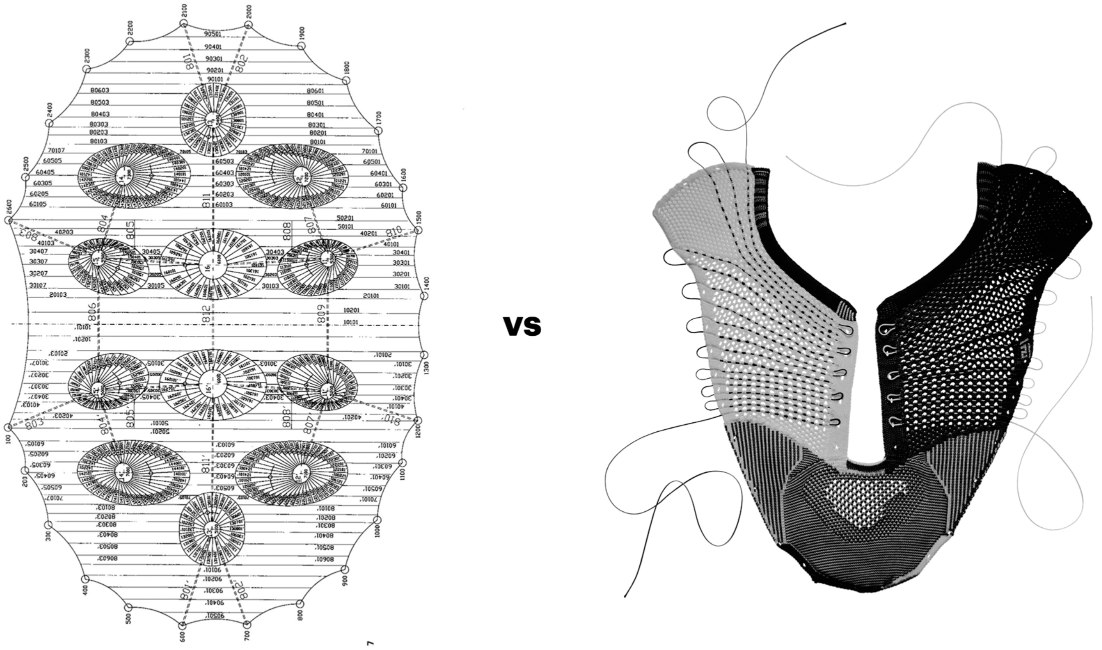


Figure 1.2: *Discrete pattern of membrane roof vs. Continuous material assembly of shoe (left: Koch 217; right: www.knittingindustry.com/)*

1.3 Challenges

The goals of this thesis are to establish a system that allows for a recursive investigation of both a physical knit assembly and a digital model through the computational device of a knit pattern, and then to apply the found material logic to tension-active architectural forms. Whereas traditionally the knit pattern is a static visual representation, in this research it is activated with true material values to better understand how the pattern behaves physically.

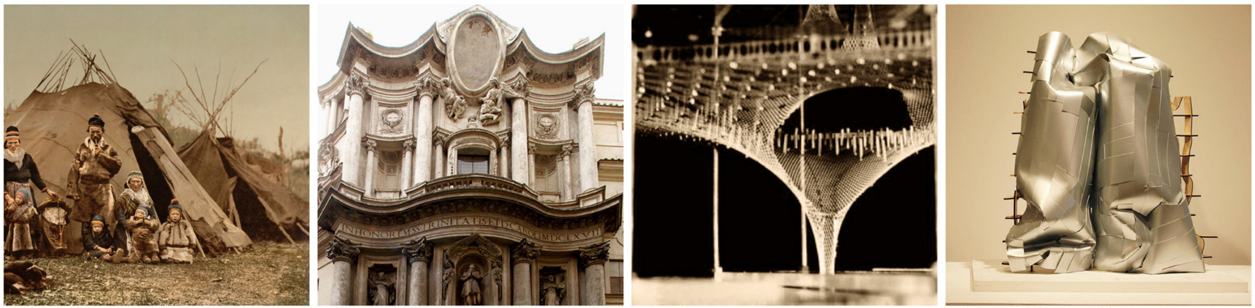
Additionally, this thesis explores the role of the pattern in creating three-dimensional forms through variation and difference. These challenges require establishing a framework or process for applying physical properties to digital models through (1) a means to fabricate physical knit material assemblies, (2) a way to understand their internal structure, (3) a system to test the physical material properties, and (4) a logic to digitally model a knit material assembly.

CHAPTER 2
BACKGROUND

This chapter critically examines the related contributions of others situates and also situates the thesis in the context of tensile architecture, material computation, and knitting. It is divided into two distinct sections: first, an overview of related work by researchers, artists, and architects studying similar problems of fiber assemblies and tension active forms; and second, the core concepts which motivate the research.

2.1 Fiber Assemblies as Materialization of Form

Textiles have a long history in architecture -- fluctuating between material as metaphor and material as structure as illustrated in Figure 2.1 (Garcia “Architecture + Textiles”, 8). As metaphor, the textile appears to be frozen in time like the elaborate constructions of the Baroque or the curved metal skins of Frank Gehry. As structure, the innate properties of the textile come to life in tension creating an almost ephemeral architecture of minimal material means.



Animal skin tent structure
Sami people of Arctic Europe

San Carlo alle Quattro Fontane
Francesco Borromini, 1646

Study Model
Frei Otto, 1960’s

Sonderborg Kunsthalle project model
Frank Gehry, 2010

STRUCTURE / METAPHOR / STRUCTURE / METAPHOR

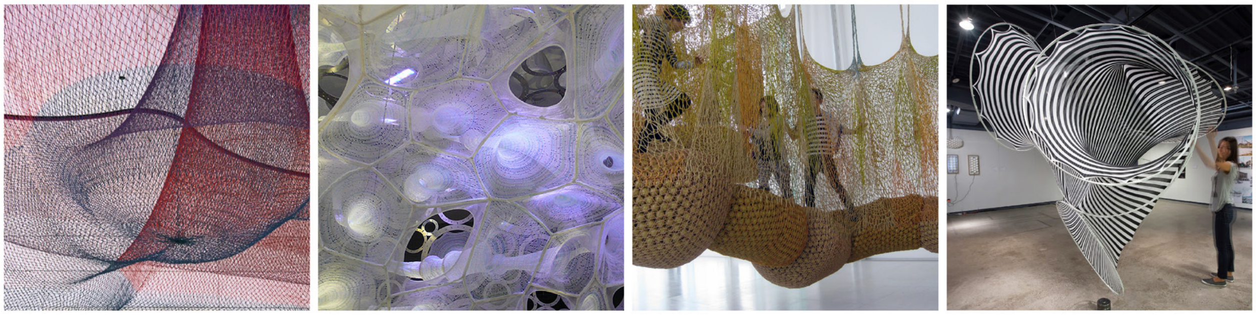
Figure 2.1: *Textiles in architecture deployed as structure or metaphor*

The use of textiles as form and structure has continued to inspire generations of architects, researchers, and artists. The four works shown in Figure 2.2 range in material and construction technique, yet each project employs fiber as the materialization of form and structure. Specifically, architectural researchers Jenny Sabin (Figure 2.2b) and Sean Ahlquist (Figure 2.2d) each use the technique of knitting to materialize tension-active forms, while artists Janet Echelman (Figure 2.2a) and Ernesto Neto (Figure 2.2c) use a technique of netting to construct forms which find their shape through gravity.

A direct influence on the research contained in this thesis, Sabin in 2012 designed and fabricated a pavilion for Nike using their Flyknit technology. She extracted biological data from a runner's body in motion to generate the geometry and material pattern of the knitted structure (Sabin). Likewise, Ahlquist's ongoing research looks to biological systems, such as banana leaf stalks (Ahlquist 86), to inform the behavior of morphological, tension-active forms. He creates variegated knit material assemblies to embed the requirements of form and structure directly into the internal composition of the material. While Sabin and Ahlquist both generate forms from behavior, the formal motivators remain external, from sources like biology, rather than within the innate properties of the fiber and its composition. This research aims to generate form and structure from the behavior of a material's internal, intrinsic properties.

Equally motivating to this thesis are the fiber-based installations of Echelman and Neto. The American artist Janet Echelman creates ephemeral installations through large hanging nets. Each net is unique and precisely constructed according to the desired curved geometry and shaped through the environmental constraints of gravity. Echelman's work demonstrates the ability to guide form through the organization of material. In a similar manner, the Chilean sculptor Ernesto Neto creates large, immersive installations from an elaborate network of ropes. Suspended above the ground, his sculptures find their resting position through gravity and invite inhabitation. Their materialization mirrors the structural logic of the form by growing denser in zones of high force, therefore exhibiting a relationship between pattern and structure.

The materialization of these four precedents enable spatial constructs which embody form and structure through the composition of fibers. Whether constructed by artist or architect, by hand or machine, or through external or internal forces, the fiber assemblies are specific to the requirements of form and structure, even



(a) *(b)* *(c)* *(d)*

Figure 2.2: *Fiber as the materialization of form (a)* Every Beating Second, *Janet Echelman, 2011 (b)* myThread Pavilion, *Jenny Sabin 2012 (c)* A Trip into the Ludic, *Ernesto Neto 2012 (d)* Mobius Rib, *Sean Ahlquist 2014*

while their relationship is not always obvious. Currently designers lack a framework for understanding how the topology of a knit structure can align with formal and structural motivations. Thus the primary goal of this thesis is to establish a system that allows for a recursive investigation of form, structure, and material through physical and digital explorations.

The history of textiles in architecture paired with contemporary research and art practices has inspired a deeper investigation of tensile structures, material computation, and knitting as a means to materialize form. Each concept is further explained in the following sections.

2.2 Tensile Structures

This research is shaped by tension-activated structures due to their intrinsic interdependence of form, structure, and material and their well-understood methods of form-finding in both the physical and digital realms. Tension-active structures can be classified as either membrane or cable net by the technique of construction as illustrated in Figure 2.3.

Membrane structures, the first construction technique employed by Frei Otto from 1954-1968, are continuous, space-filling forms (Drew 28). Their form and structure derive from material properties and the geometry-defining construction pattern. According to Otto, the pattern allows the membrane to "autonomously assume its ultimate shape when it is stretched between its stipulated points" (Otto 20) while the material properties accommodate local, three-dimensional deformation. Unlike membranes, cable nets are open structures constructed from a series of high-strength, freely pinned cables. Following the principles of developable geometry, a cable net can assume the shape of any regularly curved surface by allowing each quad of the mesh to distort into a diamond-like shape. Cable nets are not limited by patterns or the properties of stretched fabric, allowing for a greater variation of forms spanning greater distances.

The majority of tensile structures derive their strength from doubly-curved geometry, allowing the material to achieve stiffness through "a sufficient degree of anticlastic curvature"(Nerdinger 18). As a result,

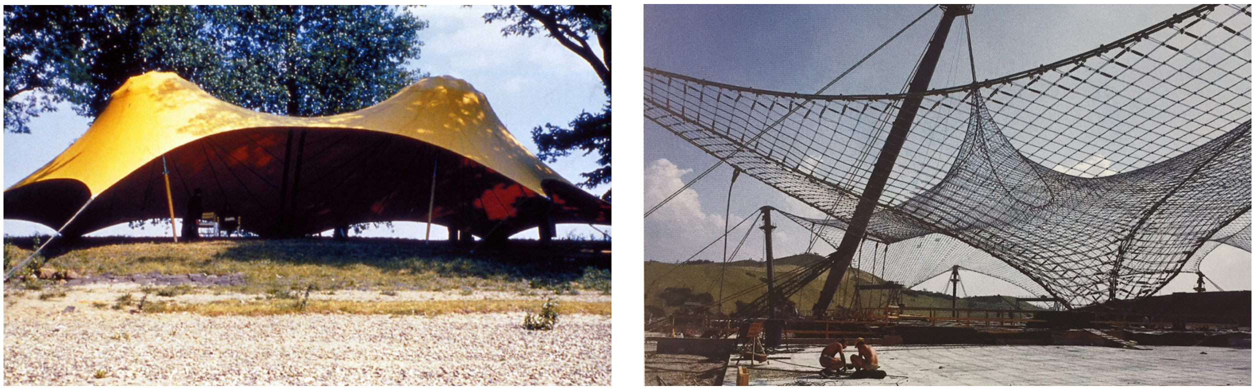


Figure 2.3: *Tension-active structures can be classified as membrane (left) or cable net (right) (Nerdinger 188, 268)*

plausible forms have been limited by the requirements of structure and homogenous material properties. But what if stiffness may be achieved through local manipulations to the material assembly in order to increase stiffness in specific locations? This thesis explores whether stiffness may be controlled through the patterning within the internal structure of a material, and whether a new range of tensile forms may thereby emerge.

2.3 Materials in Design

> “We may now be in a position to think about the origin of form and structure not as something imposed from the outside on an inert matter, not as a hierarchical command from above as in an assembly line, but as something that may come from within the materials, a form that we tease out of those materials as we allow them to have their say in the structures we create.” (Delanda 21)

Materials are often understood in terms of their internal structure -- homogeneous or heterogeneous, isotropic or anisotropic, predictable or unpredictable. Over time, the materials which construct our built environment have become standardized and understood, favoring the predictable. This taming of material behavior has led to static designs through a lack of tuning the internal structure to suit the demands of the application. How would our built environment change if we invest in understanding a new category of materials -- those which are not standardized or predictable? The focus of this research aims to compute and, therefore, better understand the innate properties of unpredictable, heterogeneous, or anisotropic materials assemblies, and to deal with variation as a creative force. In the context of this research, material assembly refers to a programmed material that depends both on the composition of its internal structure and on the raw matter from which it is composed.

Neri Oxman first defined material computation as “a design approach, a methodology and a technical framework, by which to model, simulate and fabricate functional material organizations with varying properties designed to correspond to multiple and continuously varying functional constraints” (259). Although Sean Ahlquist offers a definition more attuned to this research as “a means by which material make-up can serve as the primary agent for generating form” (“Development of a digital framework” 85). This research explores material computation by making, testing, and modeling knit material assemblies to better understand their internal logic and to establish a means by which it can be computed, thereby serving as the primary agent in generating form. Understanding the behavior of material assembles necessitates exploration across several modes of representation and simulation, from physical analysis to digital form-finding, ultimately resulting in a strategy for integrating form and structure into the material assembly. This research focuses on the ability to tune material behavior by programming its internal structure to correspond to multiple continuously varying functional constraints.

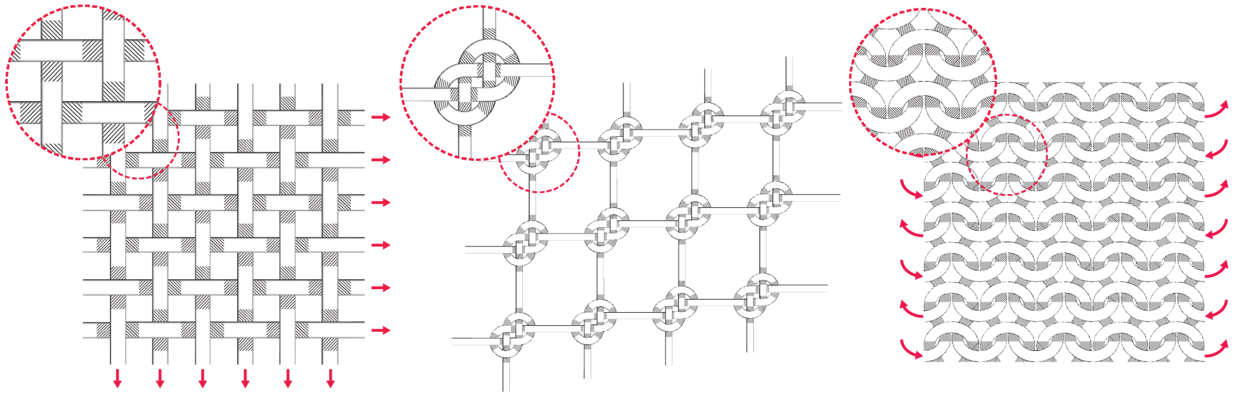
The methods utilize a particle-spring system for simulating the complex material behaviors of a knit material assembly. In a particle-spring system, springs are defined by the topology of a surface structure, where each edge of the subdivision represents a spring with attributes of stiffness and length (Kilian 132). Through the manipulation of spring parameters and surface topology, a multitude of formal variations are possible. This thesis specifically focuses on particle-spring systems as an abstraction of the knit material structure, as the complexities and fiber continuity of a knit assembly cannot be thoroughly accounted for through a system defined by a rigid structure of springs and nodes. However, the interdependence of each stitch with its adjacent stitches on all four sides is adequately simulated in the system by forming a relationship in which the stitches behave both individually and collectively.

Form-finding is a technique used to find force equilibrium surfaces through physical or digital means. There are two primary methods for form-finding: generating catenary curves through a hanging chain model and generating minimal surfaces through soap films (Drew 13). This thesis appropriates the soap film methodology utilized by Frei Otto to produce anticlastic geometry, or saddle-shaped surfaces curved in opposite ways in two directions. The physical soap film method, like the digital method which simulates it, produces a nearly ideal anticlastic minimal surface; however, “a mesh material or cable net can only approach but never achieve a true equal tension minimum surface” (Drew 14) due to the limitations of materialization. This research aims to investigate the tension between ideal (simulated) geometry and fabricated (physical) forms by designing programmed material assemblies with the characteristics of both membrane surfaces and cable nets.

For the purpose of this research, the particle-spring system is activated through Kangaroo -- an open source physics engine plug-in for Grasshopper, operating within the 3D modeling package Rhino -- to simulate the equilibrium of forces and ultimately the form-found geometry.

2.4 Knitting

Knitting is a material practice defined by pattern as rule-based code. A knit fabric is inherently heterogeneous, anisotropic, and unpredictable -- a material with performance directly linked to internal structure. The term



INTERLACE
WEAVE

INTERLOCK
NET

INTERLOOP
KNIT

Figure 2.4: *The material assembly produced through weaving is distinct from those of weaving, braiding, or knotting*

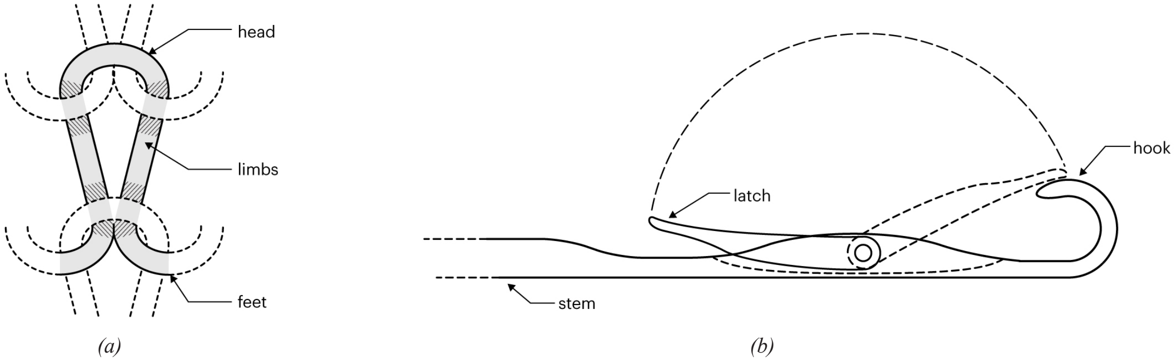


Figure 2.5: *(a) The simplest unit of a knit structure is a stitch (b) Self-acting latched needle commonly used in knitting machine*

"knitting" is used to describe the technique of constructing a textile by forming continuous lengths of fiber into vertically intermeshed loops. The resulting material assembly is distinct from weaving, braiding, or knotting, as diagrammed in Figure 2.4, by virtue of behaviors determined by the properties of the raw fiber and the organization of the stitches, with each dependent on its neighbors to all four sides.

A stitch, or loop, is the simplest unit of a knitted structure. It consists of a head and two side limbs as illustrated in Figure 2.5a. At the base of each limb is a foot which meshes through the head of the loop below it. When a single knitted stitch is inter-looped through its neighboring stitch, its side limbs are restricted at the base of the stitch by the head of the stitch above it. A basic stitch shares four loose points of intersection with its neighboring loops, two at the head and two at the feet (Spencer 34). As a result, each stitch distorts easily under tension, allowing the fiber to freely flow from one stitch to another and creating a material assembly which acts as a continuous, connected membrane in which local manipulations trickle through the global form as seen in Figure 2.6.

A sequence of stitches, looped by hand or machine, forms a textile. A knitting machine is an apparatus which applies semi- or fully-automated mechanical movement, ranging in human engagement and digital control, to produce knit material assemblies. As opposed to hand knitting in which two straight needles manipulate yarn one stitch at a time, a knitting machine coordinates the actions of a number of mechanisms and devices, each performing specific functions which contribute to the efficiency of the knitting action.

In its most elemental state, a knitting machine is a bed of needles and a carriage which slides across the bed, laying the fiber into each hook. The carriage activates the motion of the needle, principal element of any knitting machine, sending it forward to loop the yarn and complete a stitch or bypassing the needle to form a hole (Spencer 19). Most machines use a self-acting latch needle, sometimes termed an "automatic needle." On a latch needle, as diagrammed in Figure 2.5b, the hook is covered by an arm that pivots open as the needle slides forward within the carriage to receive a new loop, sending the old loop to the back of the needle. As the needle retracts into the bed, the old loop pushes the latch closed and slides off the needle over the new loop, thereby completing a stitch.

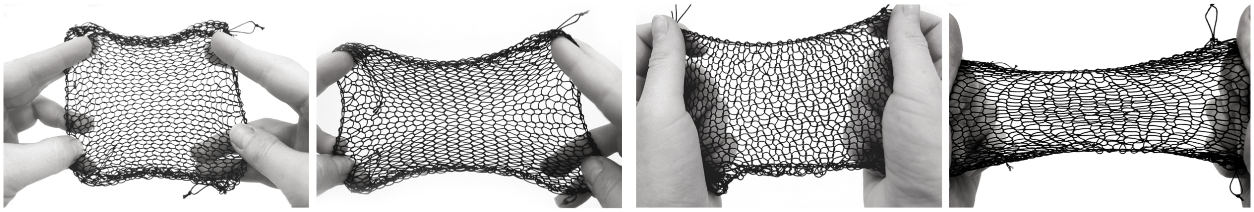


Figure 2.6: *A knit material assembly is interlooped and its properties are determined by the local relationship of each stitch within the global form.*

The knit pattern is the code which establishes the sequence of needles in a knitting machine. On a fully automated machine, the knit pattern digitally sets the needle's position via computerized numerical control (CNC). In contrast, a semi-automated machine requires each operation of the pattern to be set by hand manipulation of the needles. In this way, the pattern encodes the internal structure of the knit material assembly.

The following chapter aims to establish a framework to explore the knit pattern as the bridge between the physical and the digital by coding the static pattern with dynamic behaviors. The following process takes inspiration from the many researchers, architects, and artists working through the medium of fiber assemblies and applies the established concepts of tensile architecture, material computation, and knitting.

CHAPTER 3
PROCESS

Based on the limitations and motivations summarized in Chapter 2, this chapter proposes a new approach to exploring the dynamic behavior of knit material assemblies for the design and generation of tensile architectural forms. Currently designers lack a framework for understanding how the topology of a knit structure can align with formal and structural motivations. Therefore, the primary goal is to establish a system that allows for a recursive investigation of both the physical material assembly and the digital model through the computational device of a knit pattern.

Implementing the technique of knitting for tensile architectural forms requires an understanding of (1)

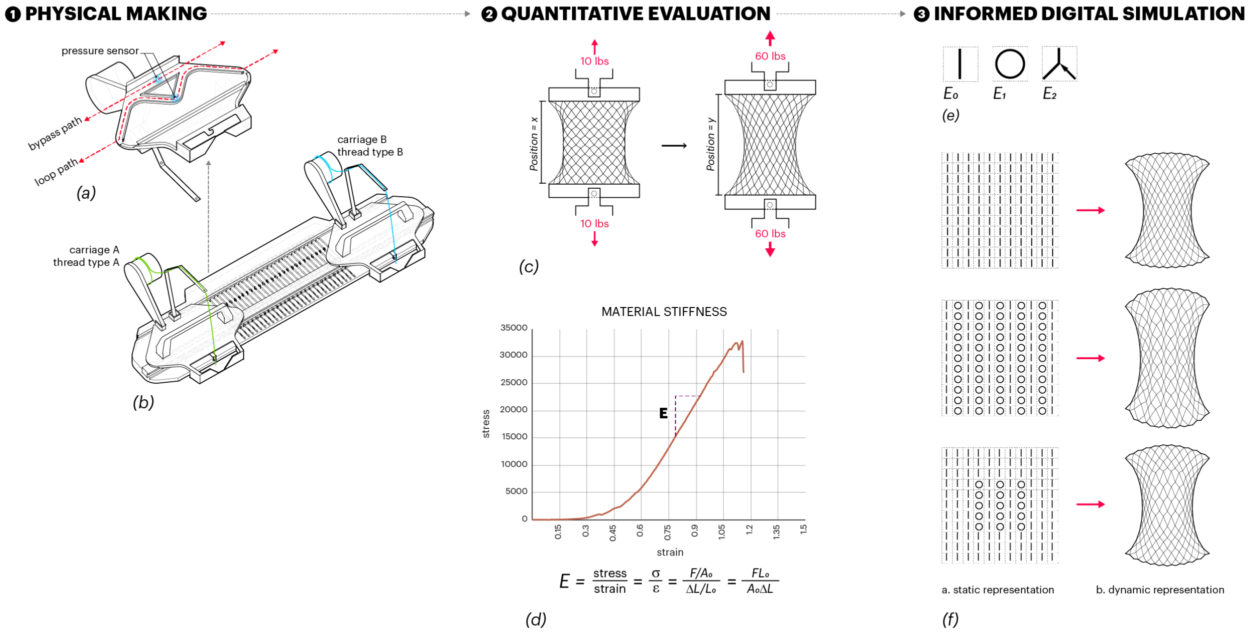


Figure 3.1: *Framework (1) Physical Making (2) Quantitative Evaluation (3) Informed Digital Simulation*

how to make knit material assemblies, (2) how variations to the composition of fibers affect the system's behavior, and (3) how static knit patterns can relate to the assembly's dynamic physical properties. This chapter details the design process through three distinct modes of exploration (figure 3.1) which allow for an experimental and recursive discovery of how physical making (3.1), quantitative evaluation (3.2), and informed digital simulations (3.3) can guide the design and generation of material to meet both the local and global needs of tensile architectural forms.

3.1 Physical Making

> "Acute knowledge of a medium's structure comes not by theory but through involvement." (McCullough 196)

In the process, the physical precedes the digital and material precedes form and structure. Understanding a knit material's behavior involves studying the relationships between the internal fiber composition and the rules from which it was constructed. This section documents the process of physically constructing a knit material assembly with a semi-automated knitting machine, establishes a set of stitch types with defined operations, and analyzes how these stitches proliferate into a pattern.

3.1.1 The Tool

A knitting machine, as detailed in Section 2.3, is a tool used to create knitted textiles in a fully- or semi-automated process ranging in human engagement and digital control. To summarize, fully-automated machines remove the human from direct material engagement and require a predetermined pattern to operate, while semi-automated machines allow the user to perform each operation and, therefore, better understand the construction of the material assembly as she knits. For this reason, the investigation utilizes a semi-automated machine.

Specifically, the knits are created on a re-purposed semi-automated flatbed knitting machine from the 1960s made by Kenner Products, an American toy company. As illustrated in Figure 3.2, the tool is comprised of minimal components including:

1. The bed, which provides support for the machines mechanisms. The width of the bed determines the maximum width of the textile.
2. The carriage, which coordinates the action of the needles with the feeding of the fiber.
3. The fiber supply and tensioning element, consisting of an arm attached to the carriage.
4. Twenty-eight latched knitting needles, which rest within the bed.

The tool is the means by which to translate the knit pattern -- the code which assigns the local arrangement of stitches -- into a physical material assembly. Each row of the pattern informs the position of the needles within the bed of the machine, as each needle performs a single operation within the code to construct one

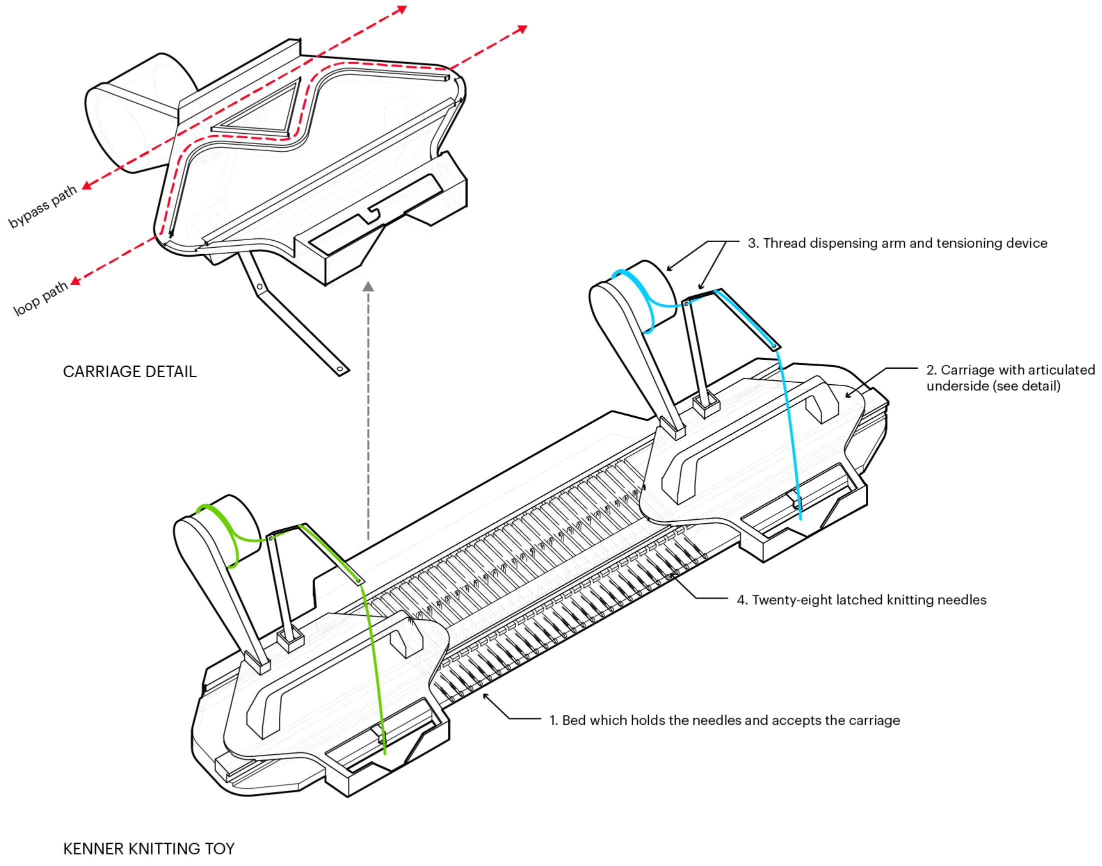


Figure 3.2: *The Tool: Semi-automatic knitting machine*

stitch of the material assembly. To operate the machine, the needles are first engaged in position according to the pattern of loops and holes by sliding each forward or backward respectively. Next, the carriage is guided over the bed of needles, sending them forward within a “V”-shaped track either to loop the fiber and complete a stitch, or bypass the needle and form a hole. Further, the initial functionality of the tool has been altered with the addition of a second carriage to enable the simultaneous knitting of two materials by feeding different fiber types through the thread dispensing arm and guiding each across the bed of needles in the desired sequence.

Although limited in automatic functionality, the tool affords a high level of direct user control unlike a fully automated CNC knitting machine. Through operating this tool and physically manipulating the loops which form the material assembly, insight is granted into the topology of each stitch type within the overall textile. For example, a transfer stitch (detailed in the next section), requires the user to physically shift a loop from one needle to another. Performing this simple maneuver makes apparent that the new needle now contains a redundancy of material. As each row of the material assembly is constructed with the tool, observable, tactile, and behavioral feedback establishes a new understanding of the system’s internal logic.

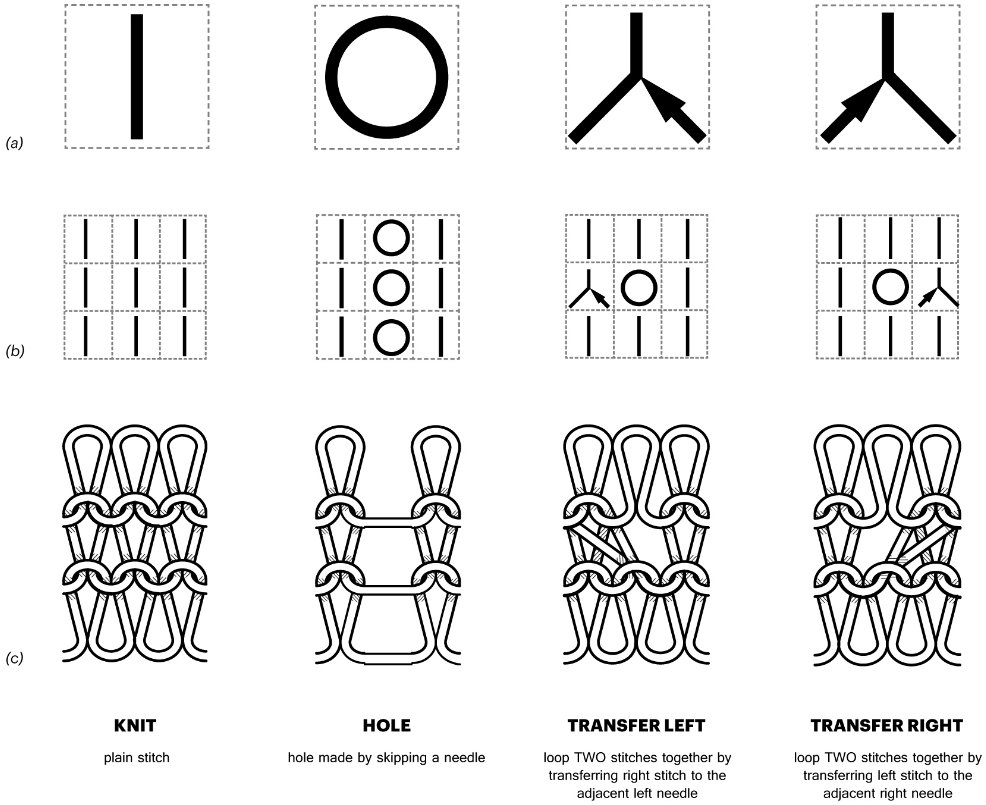


Figure 3.3: *Fundamental stitch types: knit, hole, and transfer (a) symbol (b) pattern (c) representation*

3.1.2 Fundamental Stitch Types

The performance and aesthetics of the material assembly derive from the types of stitches that construct the internal logic. A single stitch is the simplest unit of a knit material assembly and represents a single operation in the rule-based code knit pattern. A stitch, as detailed in Section 2.3, consists of a head, two side limbs, and feet at the base of each leg. Each stitch is continuous, attaching to its side neighbors at its feet and intermeshing with the row above at its head. The continuous nature of the stitch creates a unit with unfixed size and proportions, allowing for slippage into its adjacent neighbors as well as expansion or contraction under tension.

Using the machine, many patterns ranging in complexity may be constructed from three fundamental stitch types diagrammed in Figure 3.3: a knit, a hole, and a transfer. A knit is defined as the basic stitch. To create a knit using the tool, the latched needle is simply moved into knitting position and the fiber is allowed to loop through the stitch below it. A hole is a void in the pattern, created by moving the needle out of action and ultimately causing it to bypass the knitting “V”-shaped track. And lastly, a transfer stitch moves a loop from one needle onto a neighboring needle using an external stitch transfer tool, creating a redundancy of fiber on a single needle.

Each stitch operation guides the flow of fiber within the overall material assembly. As diagrammed in Figure 3.3c, a pattern of knit or hole stitches will create a predominantly horizontal and vertical flow of material; however, a transfer stitch disrupts the orthogonal flow and introduces an angle into the material assembly. Likewise, a basic knit stitch overlaps its neighboring stitches at four distinct points, while a transfer stitch overlaps the neighboring stitch along its limb to create a fifth point of intersection. Additionally, the transfer stitch further disrupts the assembly by creating a localized redundancy of material when placed on top of an existing stitch.

3.1.3 Elemental Material Assemblies

A sequence of single stitches creates a knitted material assembly. For each needle spanning the width of the knitting machine, the stitch type may vary to form a unique pattern, and to direct the flow of fibers. Using the three fundamental stitch types described in Section 3.1.2 in repetitive sequences, four distinct material assemblies were created as shown in Figure 3.4.

The first elemental pattern, the knit, (a) is a continuous sequence of loops, creating a normative, orthogonal material assembly. The second elemental pattern, the open knit, (b) alternates between a stitch and a hole by skipping every other needle while knitting. This sequence also creates a normative assembly, albeit less dense than the first. The third elemental pattern, the diagonal, (c) creates a 45 degree angle in the material assembly, disrupting the orthogonal flow of the previous two samples. This pattern is created by transferring every other stitch to the neighboring needle while alternating between even and odd needles on each

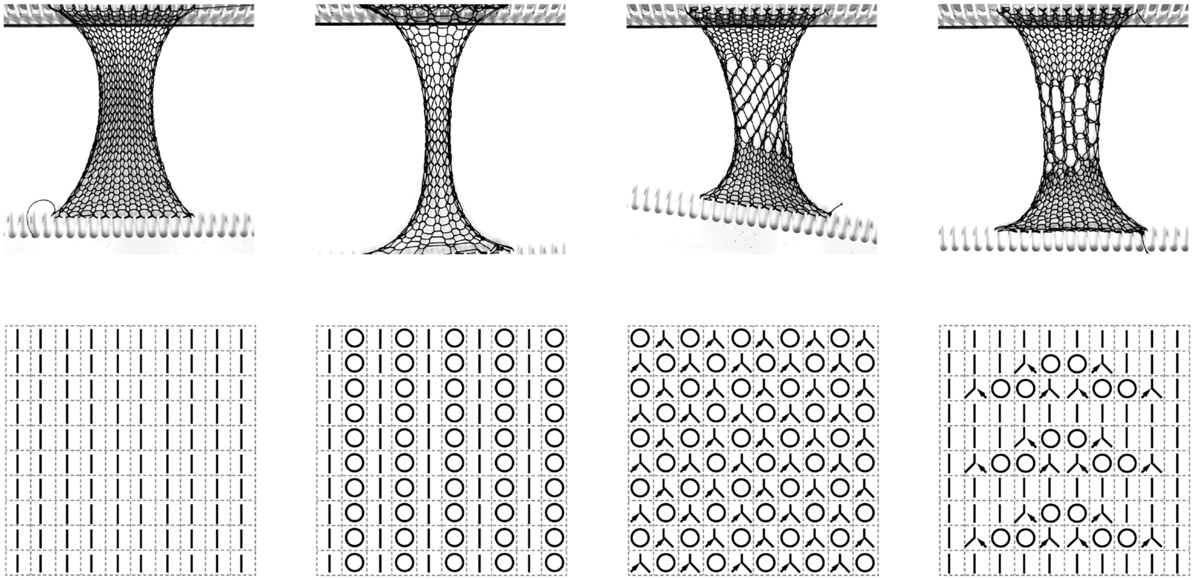

(a) (b) (c) (d)

Figure 3.4: *Elemental Patterns (a) knit (b) open knit (c) diagonal (d) hexagon*

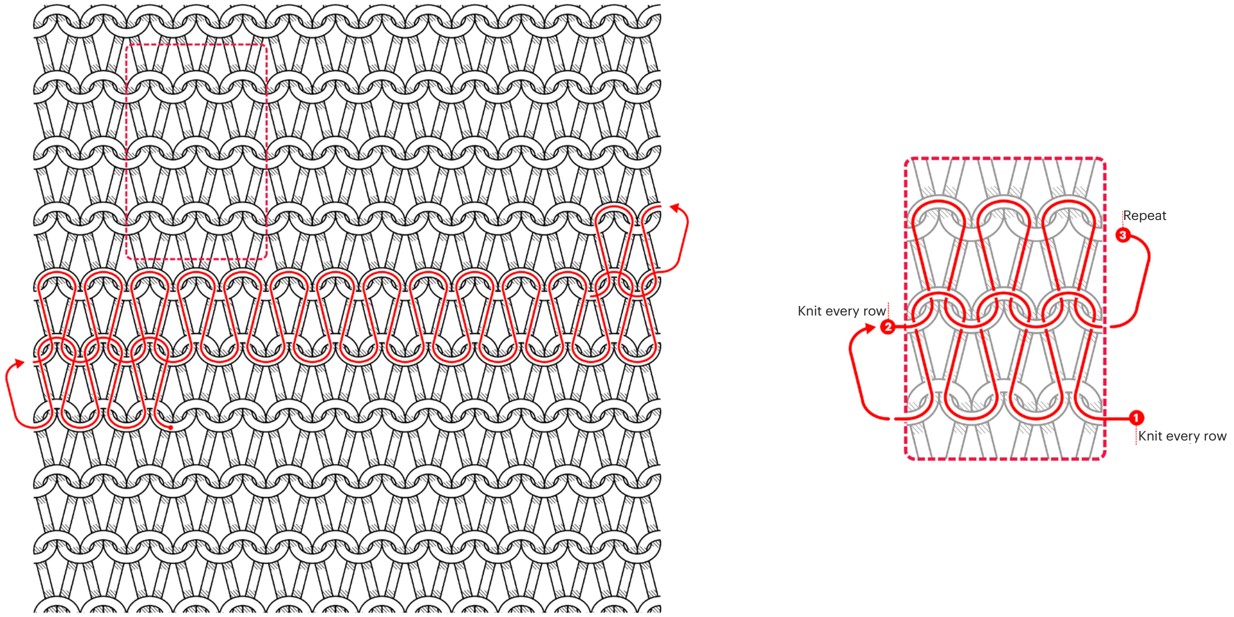


__Figure 3.5:__ Knit pattern : fiber path

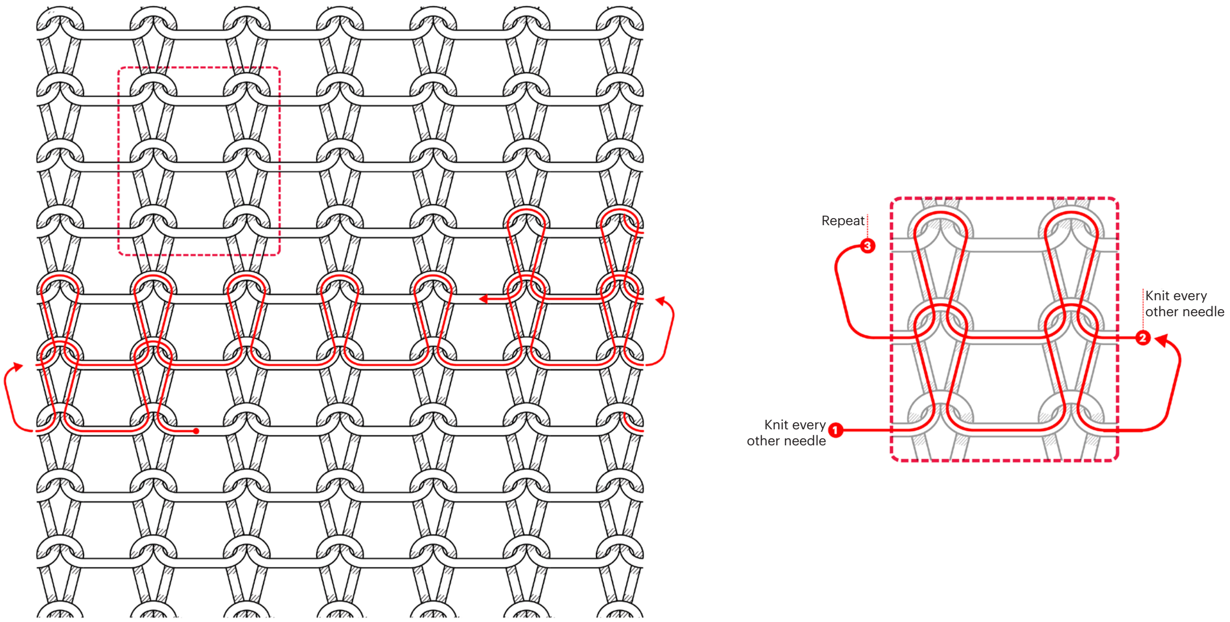


__Figure 3.6:__ Open Knit pattern : fiber path

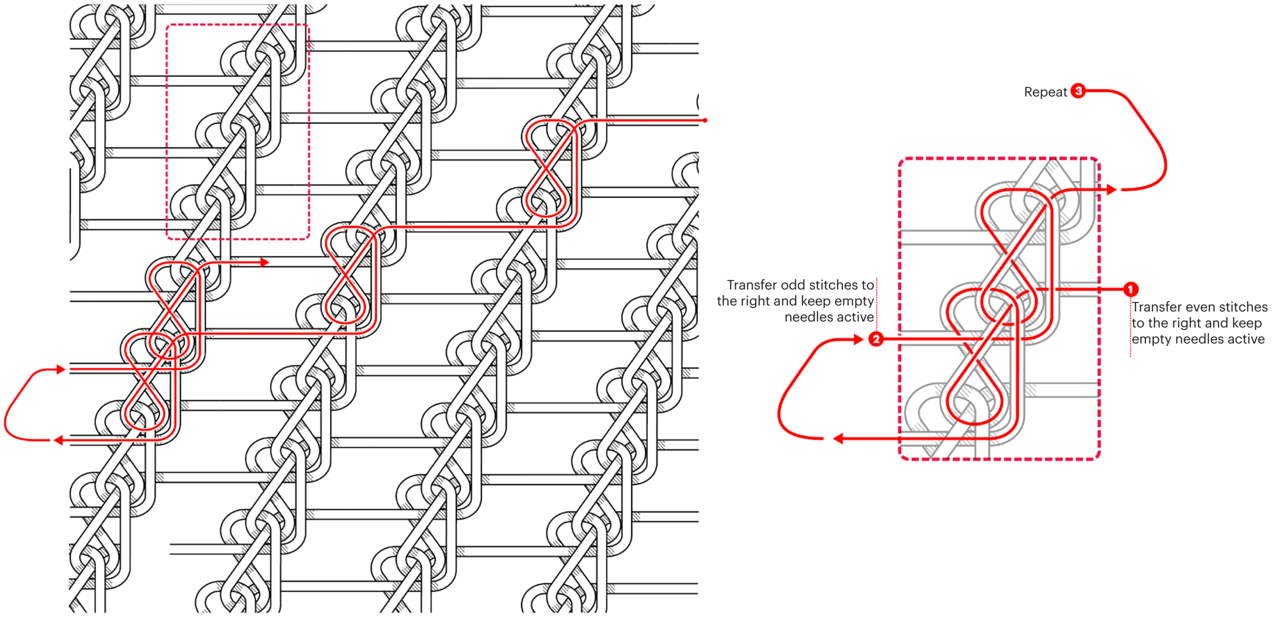


Figure 3.7: *Diagonal pattern : fiber path*

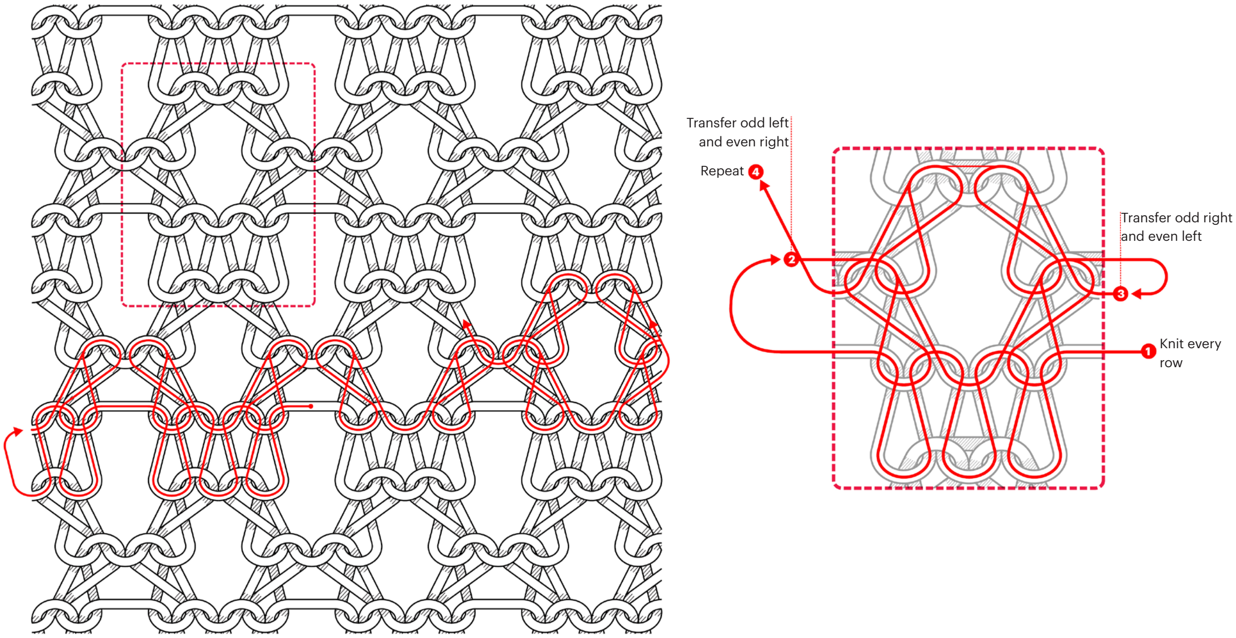


Figure 3.8: *Hexagon pattern : fiber path*

constructed row. The fourth elemental pattern, the hexagon, (d) establishes a repetitive sequence of gaps, transferring the loops away from each other to create a double wide void and moving them back together to close the gap. Visually, this pattern creates both meandering vertical lines and staggered horizontal lines.

To better understand the topology of the knitted material assembly without the distortion of physical forces, each pattern is analyzed in its static representation in Figures 3.5-3.8. This diagrammatic view of the material assembly allows for an understanding of the path the fiber takes through the textile and highlights the moments of irregularity. The drawings also display areas of redundancy, points of overlap, and the dominant direction of the fiber. The diagrams are meant to simplistically reveal the topology of the material system, absent of the dynamic environmental conditions.

3.1.4 Physical Making Discussion

The process of physical making and its analytical representation reveal that knit patterns lack the dynamic properties of the materials' behavior. Exploration and engagement with the semi-automated knitting machine establish a language -- or a set of operations -- which forms the basic components of the knit pattern, including fundamental stitch types and elemental patterns. While the simplicity of the machine may limit more complex operations, direct user engagement is essential to understanding the internal logic of the knit material assembly in order to apply dynamic behaviors to the static knit pattern.

In the next section, Quantitative Evaluation, each elemental material sample is tested for dynamic behaviors to explore whether variations to the sequence of stitches can create distinct performance characteristics.

3.2 Quantitative Evaluation

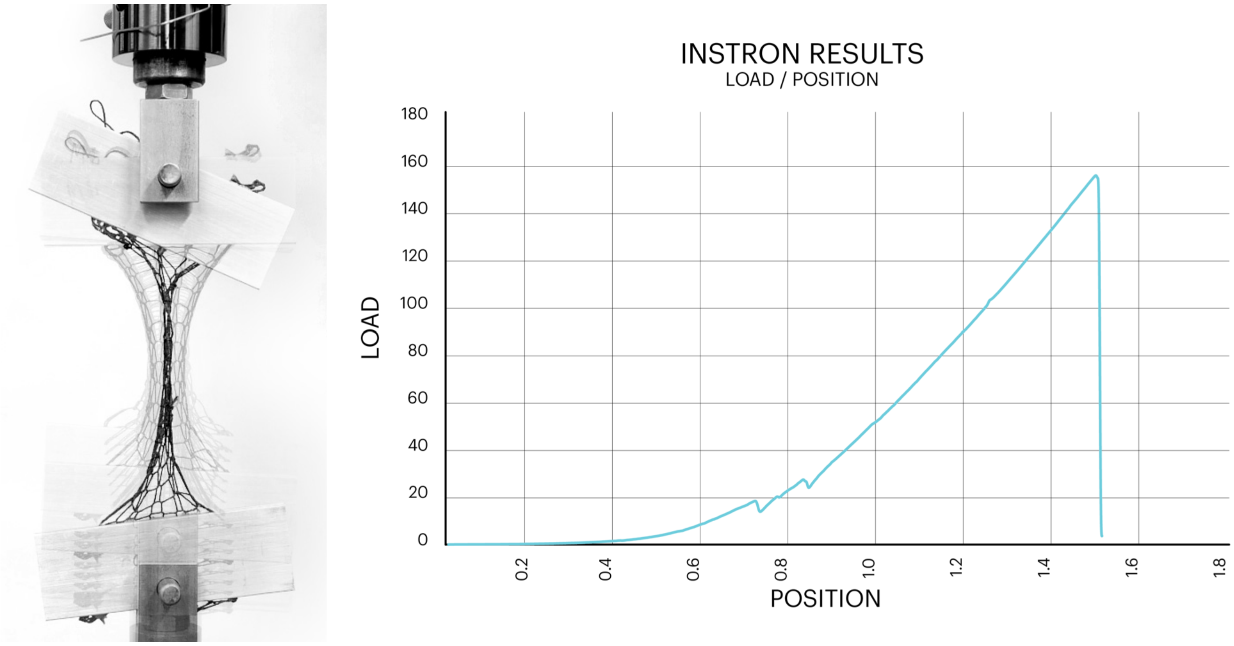
A primary goal of this thesis was to test whether variations to the material assembly, such as its density and direction, could produce a range of performative characteristics, such as increased stiffness or flexibility, to aid in the three dimensional necessities of tension-active architectural forms. Programming the knit pattern to align with formal motivations, however, requires a quantification of the physical material assemblies. The strength of a material, however, is not easily determined; as Frei Otto explains, "it cannot be measured in absolute terms -- and, strictly speaking, it does not really exist. All one can do is use standardized equipment to apply loads for comparison purposes to objects which have standardized shapes." (Nerdinger 34) Therefore, in this research each elemental material is subjected to comparative structural loading tests to evaluate the relative stiffness of the knit patterns.

To standardize the tests, each material sample is constructed of similar relative proportions using the same heavyweight polyester thread. In addition, the force is applied uniaxially, parallel to the knit columns, and the boundary edge perpendicular to the loading direction is fixed to prevent failure at the connection. First, each elemental material assembly was constructed to match consistent measurements: 13 needles wide by

13 rows long. Next, the top and bottom edge of each sample was sandwiched between 1/8” aluminum bars with an epoxy fastener. Finally, each material specimen was tested on an Instron tensile loading machine. The machine converts an applied load into a proportional electrical signal, incrementally stretching the material until it fails. The prepared material samples were placed in the machine using a pin connection, as seen in Figure 3.9a, allowing it to freely pivot into its resting position. As the material is stretched, the machine records the applied load in relation to displacement as documented in Figure 3.9b.

In order to quantitatively characterize each material sample, the elastic modulus -- a constant used to characterize the stiffness of a material -- was calculated using the recorded data along with specific material attributes such as fiber diameter and cross-sectional area. Figures 3.10-3.13 document the relationship between stress and strain on each elemental material sample in order to extrapolate its stiffness from the steady slope of the curve. The open knit material assembly exhibits the highest stiffness at 141,000 psi and the knit assembly exhibits the lowest at 55,500 psi. As a comparison, steel exhibits a stiffness of 29.0x10^6 psi, as the knit material assemblies perform closer to the stiffness of plastics.

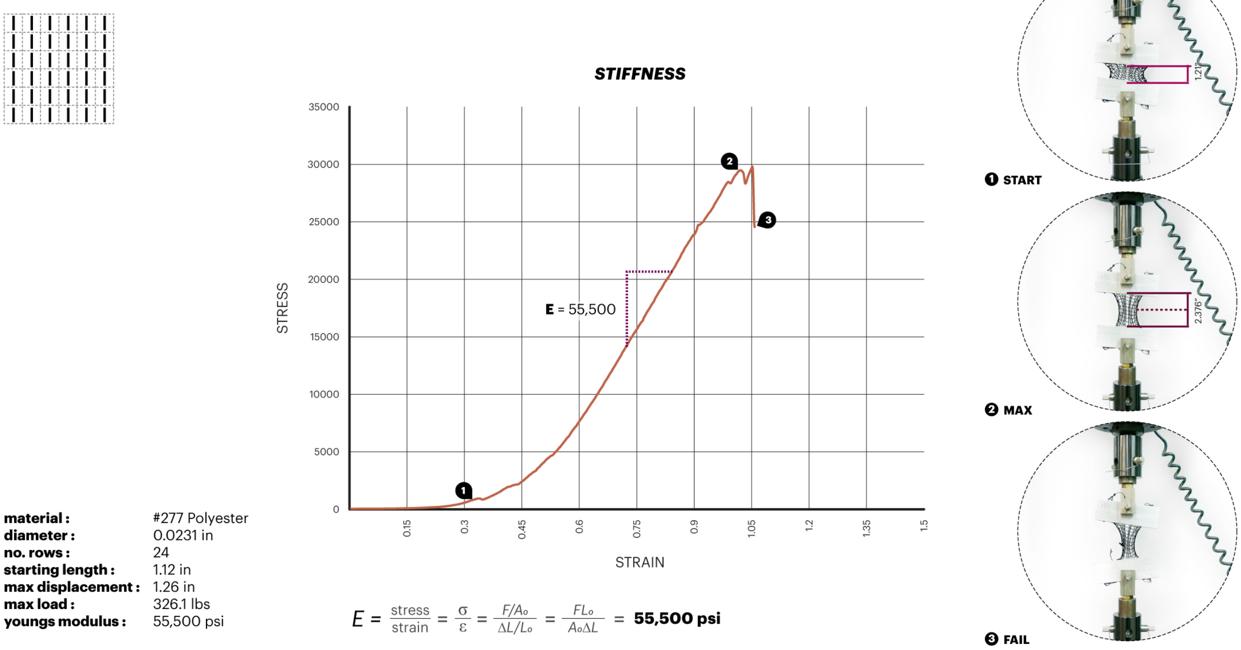
The measure of stiffness is the primary behavioral attribute extracted from each material sample due to its importance in many structural applications, including tension-active structures. In most tensile forms, doubly curved geometries are required for the fabric to achieve the stiffness needed to withstand internal and external loads, limiting the range of global forms possible. These tests suggest that stiffness may be achieved from within the material assembly to expand the possibilities of form.



(a) *(b)*

Figure 3.9: *(a) Comparative structural loading on Instron (b) Recorded Load/Position*

01_KNIT

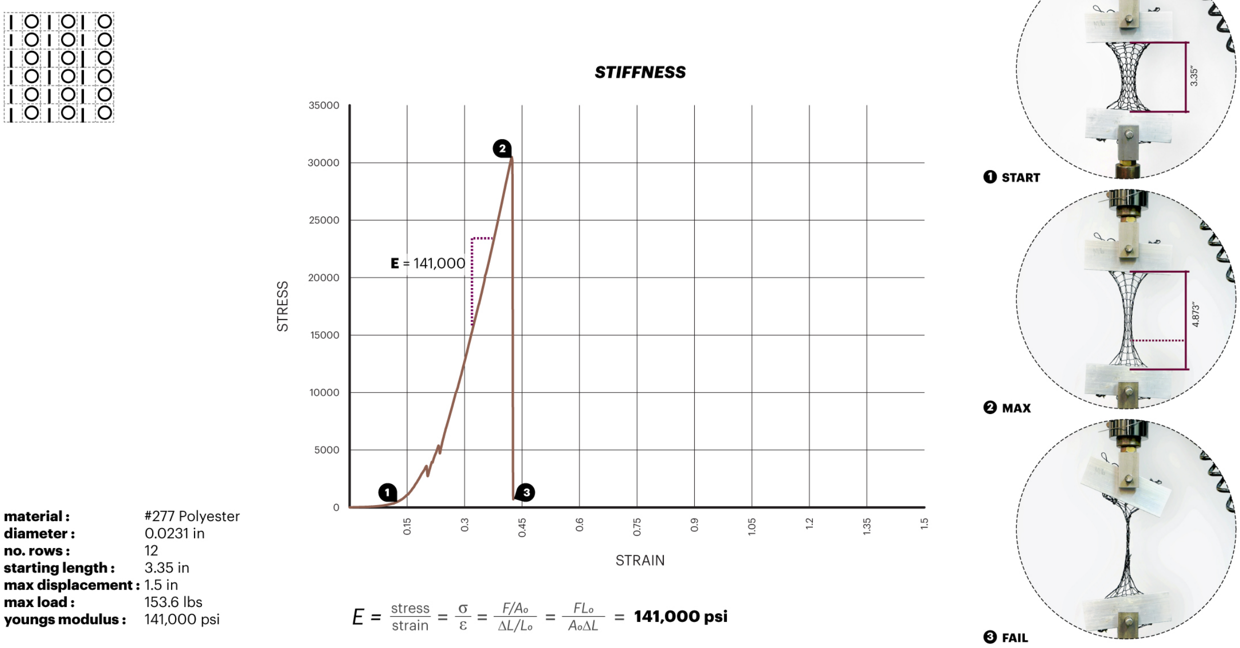


material :	#277 Polyester
diameter :	0.0231 in
no. rows :	24
starting length :	1.12 in
max displacement :	1.26 in
max load :	326.1 lbs
youngs modulus :	55,500 psi

$$E = \frac{\text{stress}}{\text{strain}} = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{FL_0}{A_0\Delta L} = \textbf{55,500 psi}$$

Figure 3.10: *01_KNIT Instron Material Test*

02_OPEN KNIT

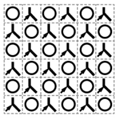


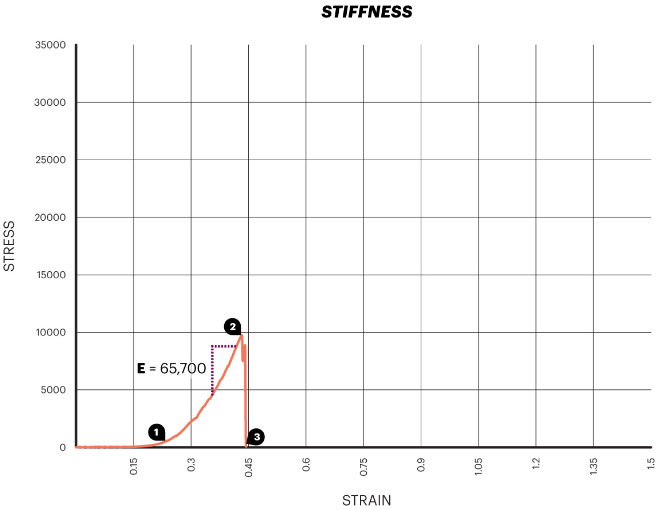
material :	#277 Polyester
diameter :	0.0231 in
no. rows :	12
starting length :	3.35 in
max displacement :	1.5 in
max load :	153.6 lbs
youngs modulus :	141,000 psi

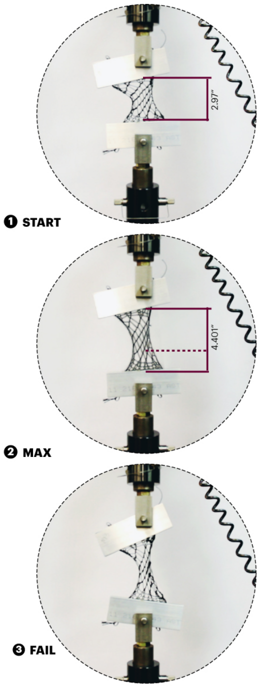
$$E = \frac{\text{stress}}{\text{strain}} = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{FL_0}{A_0\Delta L} = \textbf{141,000 psi}$$

Figure 3.11: *02_OPEN KNIT Instron Material Test*

03_DIAGONAL





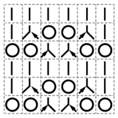


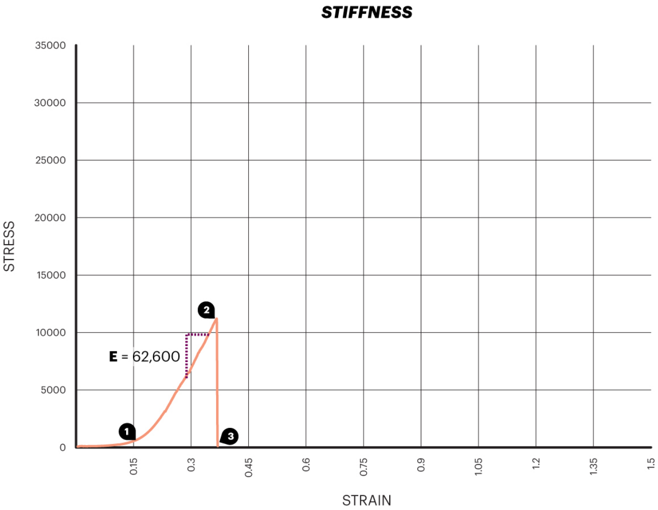
material :	#277 Polyester
diameter :	0.0231 in
no. rows :	24
starting length :	2.9 in
max displacement :	1.4 in
max load :	107.7 lbs
youngs modulus :	65,700 psi

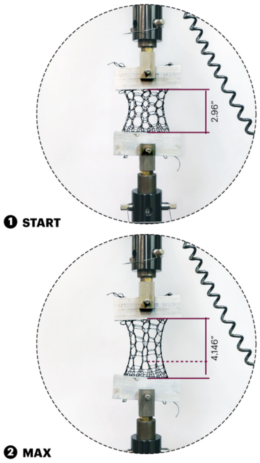
$$E = \frac{\text{stress}}{\text{strain}} = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{FL_0}{A_0 \Delta L} = \mathbf{65{,}700\ psi}$$

***Figure 3.12:** 03_DIAGONAL Instron Material Test*

04_HEXAGON



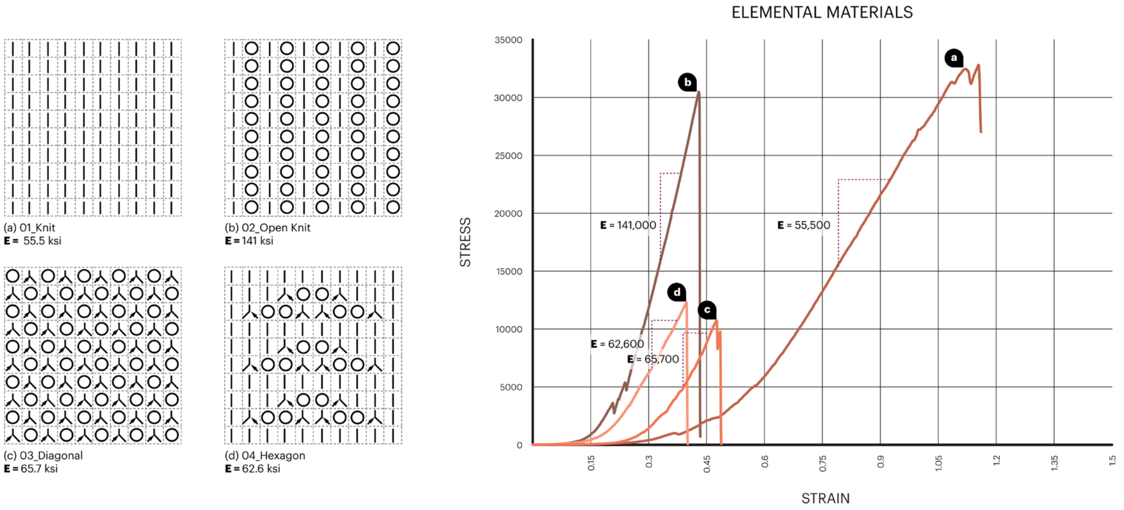




material :	#277 Polyester
diameter :	0.0231 in
no. rows :	24
starting length :	2.96 in
max displacement :	1.2 in
max load :	123.5 lbs
youngs modulus :	62,600 psi

$$E = \frac{\text{stress}}{\text{strain}} = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{FL_0}{A_0 \Delta L} = \mathbf{62{,}600\ psi}$$

***Figure 3.13:** 04_HEXAGON Instron Material Test*


(a) 01_Knit
E = 55.5 ksi

(b) 02_Open Knit
E = 141 ksi

(c) 03_Diagonal
E = 65.7 ksi

(d) 04_Hexagon
E = 62.6 ksi

Figure 3.14: Comparison between four elemental material assemblies

3.2.1 Quantitative Evaluation Discussion

As seen in Figure 3.14, the open knit assembly composed of plain knit stitches exhibits the highest stiffness, while the knit assembly composed of plain knit stitches, albeit more dense than the open knit, exhibits the lowest stiffness yet highest strength. The two material assemblies containing transfer stitches, the diagonal and the hexagon, have relatively low stiffness and strength values. The reasons for the plain knit assembly exhibiting such low stiffness in comparison to the open knit assembly are not immediately clear, and additional tests are necessary to further explore the behavior of each pattern and should include multiaxial load testing to uniformly stretch the material in all directions, thus accounting for the complex flows of fiber within each knit material assembly.

Additionally, the material samples tend to fail along the unconstrained boundary. This may be a result of improper placement of the material during the sandwiching process or due to the fact that the fibers along the edges tend to be stiffer than fibers in the interior structure. This can be resolved by testing a complete cylinder in order to eliminate the boundary, or by devising a new system to accurately constrain the fixed boundary.

For the advancement of this design framework, testing the elastic modulus for each material assembly validated that variations to the sequence of stitches may create unique stiffness properties. In the next section, the unique stiffness value for each material assembly is interpreted to embed the knit pattern with dynamic data from which a digital model can be constructed.

3.3 Informed Digital Simulations

The stiffness properties of the physical material, extracted from the comparative structural loading,

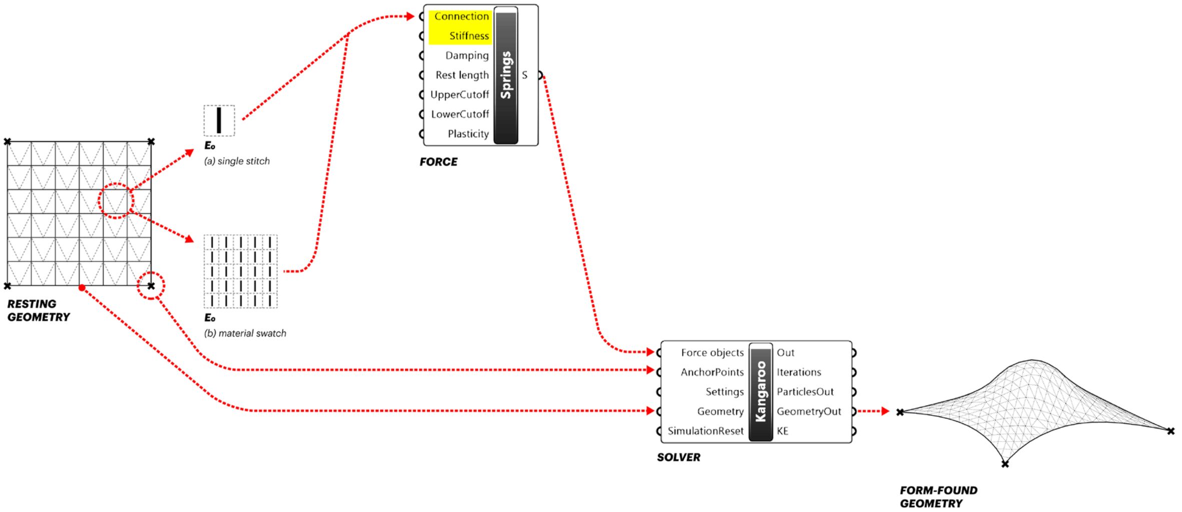


Figure 3.15: *Digital work flow using particle-spring system*

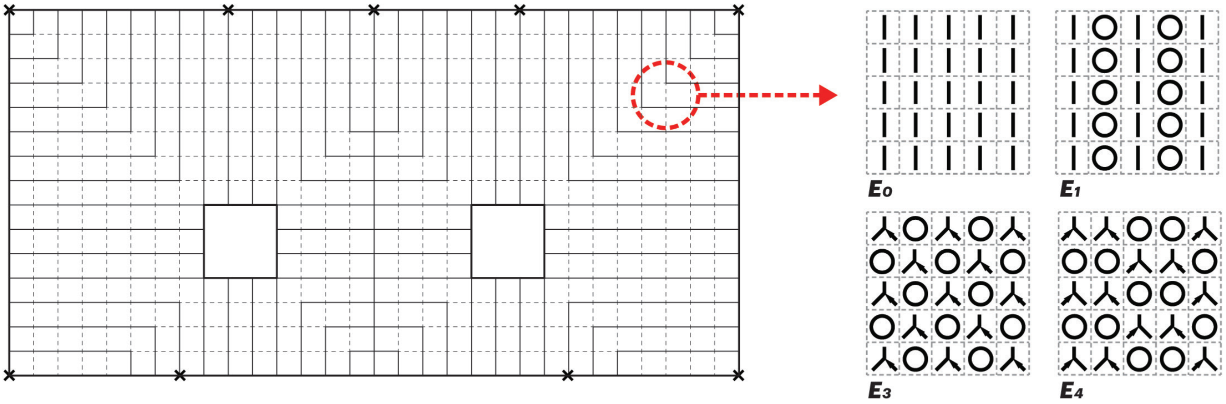
communicate through the knit pattern to a digital model in order to explore the possibilities of form within the constraints of the material. The complexities of a knit material system have yet to be implemented into an accessible simulation software. Therefore, a novel contribution of this research is the development of a workflow within Kangaroo to explore an abstraction of a knit material assembly through a particle-spring method that form-finds through an equilibrium of forces as illustrated in Figure 3.15. It should be noted that the proposed workflow does not account for the complex behaviors of a knit material assembly, such as the ability for each loop to slip between its neighbors and often distorting under tension beyond recognition.

For the purpose of this research -- digital explorations informing the generation of knit patterns -- the intention was not to find the most structurally optimal form or mimic the complex behaviors of the material system, but rather to establish a workflow that could allow digital form finding to generate knit patterns according to the distribution of internal forces. The stiffness values interpreted from the comparative structural loading activate a digital model as a particle-spring system that form-finds via an equilibrium of forces. Below, two methods of simplifying the complexities of the physical knit material assembly into a discrete particle-spring system are explored with each spring, or mesh edge, representing a patch of material or an individual stitch.

3.3.1 Springs as Material Assembly

In this study, each spring of the mesh topology represents one of the four elemental materials diagrammed in Figure 3.16. The goal was to visualize the formal differences between a uniform material distribution where each spring is defined by the same stiffness and a specific material distribution where each spring is defined by a stiffness which relates to the values obtained in Section 3.2.

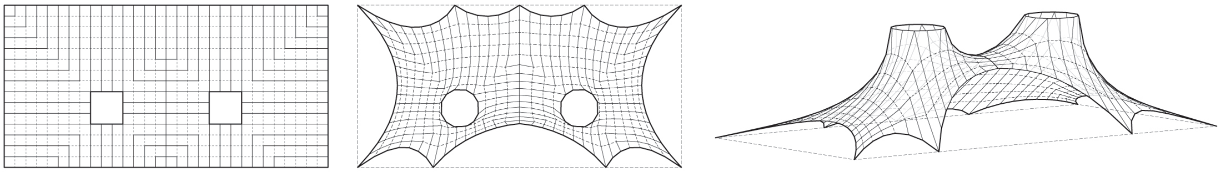
The initial geometry was anchored at nine points and lifted at two discrete openings as illustrated in Figure



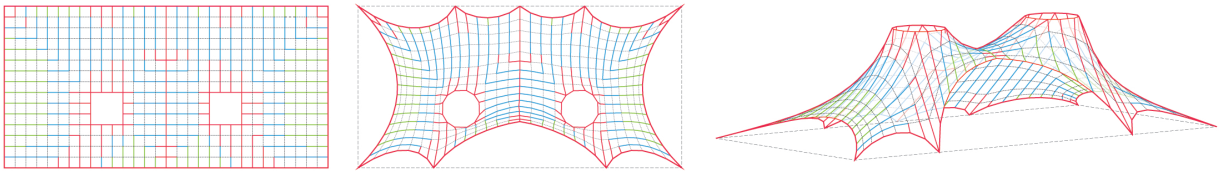
(a) boundary plan

(b) material swatch

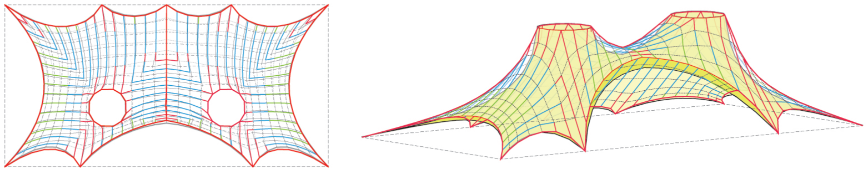
Figure 3.16: *Spring as material assembly*



(a) uniform marerial stiffness



(b) sorted material stiffness



(c) difference in geometry

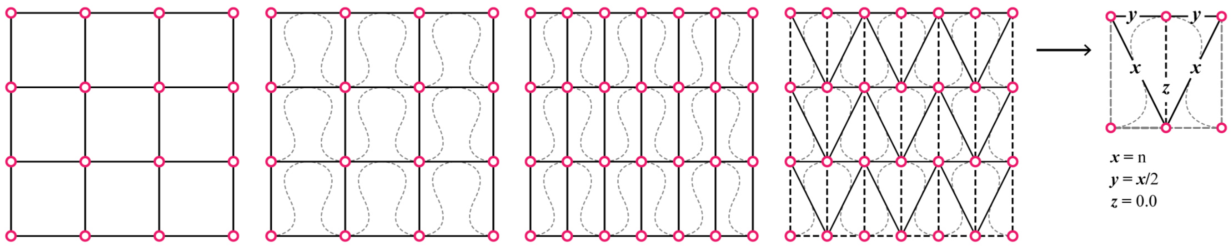
Figure 3.17: *Difference between uniform material assembly and material assembly specific to flow of force*

3.17. First, each spring was defined with a uniform stiffness and the particle-spring system found the resulting form based on the sum of all the internal and external forces, Figure 3.17a. Next, the change in the spring length between the two-dimensional initial position and the form-found geometry was calculated. Hooke's Law states that the change in length of a spring is proportional to the force exerted on that spring, and therefore, by calculating the difference between the springs initial position and solved position, the flow of forces may be visualized. With a new understanding of the forces exerted on each spring under a uniform material distribution, the springs were grouped into four categories based on exerted force. From the initial resting position, a new stiffness value was assigned to the springs in each group, which derived from the physical material assemblies, Figure 3.17b. For example, the springs with the most force were assigned a material assembly with the highest stiffness, while the springs with the least force were assigned that with the most flexibility. The difference between the uniform and variegated material assemblies can be seen in Figure 3.17c.

Using this method, the resulting form is a patchwork of material assemblies, in which each spring is a swatch of fabric. The geometry is modeled at 15"x30" and the maximum displacement between the uniform material distribution and the varied material distribution is 1.93". The form exhibited the greatest local differences in curvature where the stiffness was increased. This study serves as a proof of concept that a form can be guided to the desired curvature through local variations to the material properties.

3.3.2 Springs as Stitch Type

In this study, the springs of the particle-spring network resemble the internal structure of a knit material system as illustrated in Figure 3.18. While there are a number of approaches to abstracting the topology of a mesh to approximate a knit structure, this thesis represents a single stitch as five springs which form a triangle like shape corresponding to the wide head at the top of a stitch and the pinched feet at the bottom Each digital stitch is assigned a stiffness value extrapolated from the comparative structural loading to characterize one of the three stitch types summarized in Section 3.1.2: a knit, a hole, or a transfer. Now, each symbol of the knit pattern may be activated with an explicit stiffness value, therefore creating a dynamic simulation of the previously static representation.



(a) spring and node mesh topology

(b) interface with knit topology

(c) divide spring and node topology

(d) refine spring and node topology

Figure 3.18: *Using particle-spring system, a new topology is constructed where five springs are a single stitch*

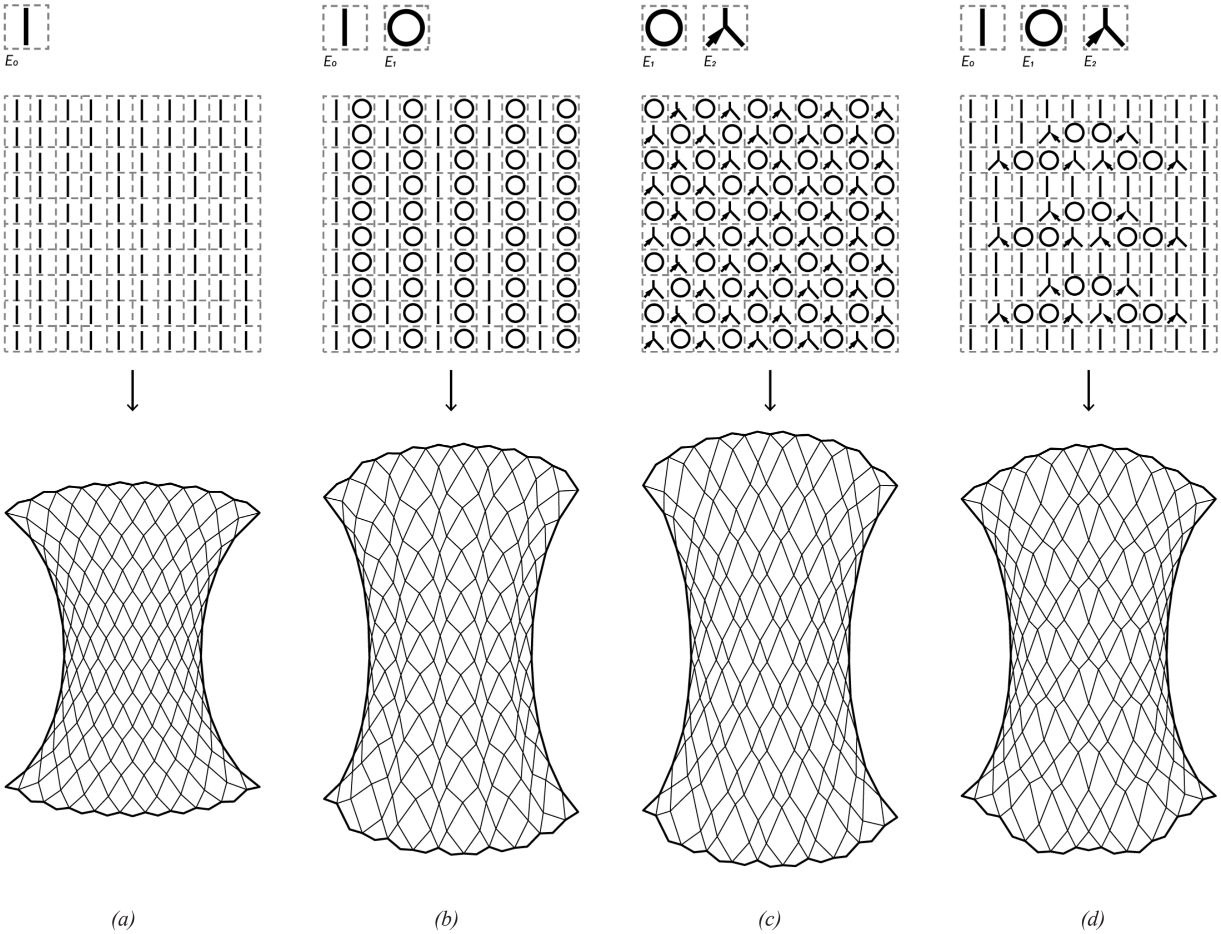


Figure 3.19: *Knit patterns activated using particle-spring system (a) 01_Knit (b) 02_Open Knit (c) 03_Diagonal (d) 04_Hexagon*

As diagrammed in Figure 3.19, each of the four elemental material tests outlined in Section 3.2 is digitally simulated, where each cell of the knit pattern represents a single physical stitch. To model the action of the Instron tensile loading machine, each knit pattern is digitally pulled from anchor points along the top and bottom boundaries and the particle forces are constrained to single degree of freedom. The force exerted to stretch each knit pattern is proportional to the load the physical material assembly can hold before failing. While the resulting figures do not visually resemble the physical materials, they represent certain behaviors, ultimately informing how the knit pattern behaves.

The knit pattern is now the code which assigns the local arrangement of stitches to the physical material assembly and which activates the global characteristics of the form in the digital model. The force exerted on each spring in the digital model can now be used to generate a new knit pattern according to the unique behaviors of the form, shifting the stitch topology of the knit material assembly to better suit the formal motivations.

3.3.3 Informed Digital Simulation Discussion

By incorporating the stiffness properties of physical material assemblies into digital simulations, the knit patterns may both generate form and remap their coded patterns according to internal forces. While the simplified digital workflow falls short of truly modeling the complexities of a knit material system, it is nonetheless an initial step towards working within an established simulation technique and is not intended to mirror physical properties. With this in mind, the digital model successfully generates unique forms, expressing behavioral differences through variations of stitch type or material property. In Steering of form, Axel Kilian suggests the topology of a particle-spring system is the "main interface for specifying the final form" (135), however, this study suggests the curvature of a form can be guided through variation to the material properties.

The most compelling discovery of the digital workflow is the potential for use as a generative tool. By calculating the force exerted on each spring -- representing a stitch type or a material assembly -- a knit pattern may generate according to the requirements of form and structure. Next steps for the method are to more accurately and iteratively solve for the most optimal stitch type according to the flow of fiber in relation to the local flows of force across the global form. In addition, future work will incorporate a difference in spring topology for each stitch type, as currently each stitch is digitally represented by the same symmetrical five spring system, whereas in reality each stitch in the physical material assembly has a unique topology. For example, the transfer stitch shifts the flow of fiber to disrupt the symmetrical nature of the knit stitch. The incorporation of unique stitch topologies will aid in establishing a flow of material according to the flow of internal forces.

3.4 Summary of Contributions

In this chapter, I have thoroughly described the process to establish a framework that allows for a recursive investigation of both a physical material assembly and a digital model through the computational device of a knit pattern. This process fills the needs identified in Section 2.1 and addresses the challenges identified in Section 1.3 by (1) establishing a tool, fundamental stitch types, and a range of elemental patterns for physical making, (2) devising a method for physically testing knit materials to extract quantitative measures, and (3) inventing two methods for simulating knit material assemblies in a computational model.

This process reveals that physical and digital methods can be used to (1) better understand the complex and often unpredictable behaviors of knit material assemblies and (2) to program their internal logic to suit the global needs of form and structure.

CHAPTER 4

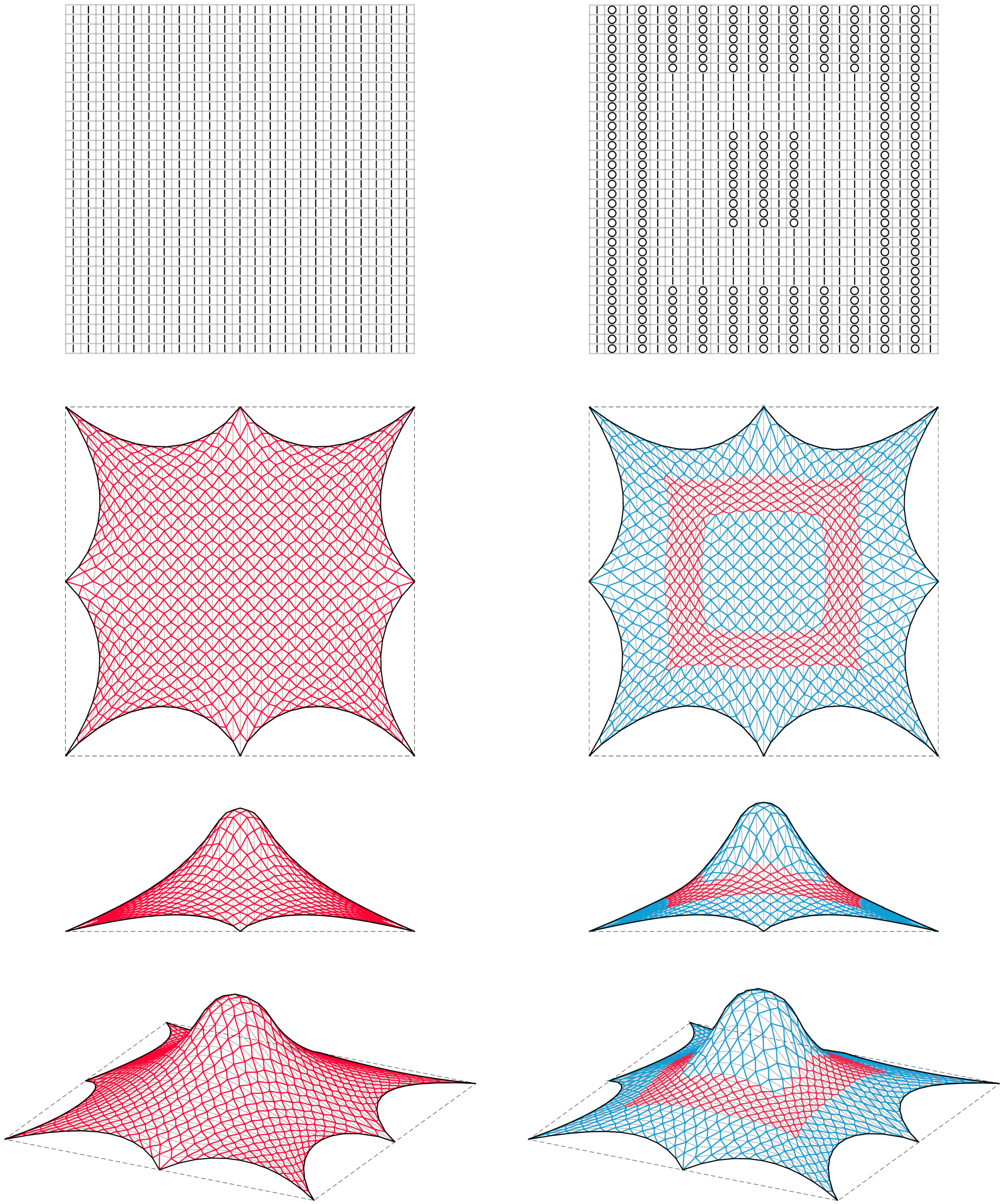
PROTOTYPE

This chapter demonstrates how the framework established in Chapter 3 may be applied to the design and generation of tension-activated forms. The framework is tested through a small prototype of a simple anticlastic geometry anchored at nine points along the perimeter with a force applied to a grid of nine points at the center. The knit pattern is 23 stitches wide by 36 stitches long, which results in a flat knit 6”x6” square. The test uses the three fundamental stitch types and four elemental patterns established in Section 3.1 and applies the stiffness values extracted from the quantitative evaluation in Section 3.2. Finally, the prototype implements the springs as individual stitches in the digital model as explained in Section 3.3.2.

4.1 Digital Generation of Knit Patterns

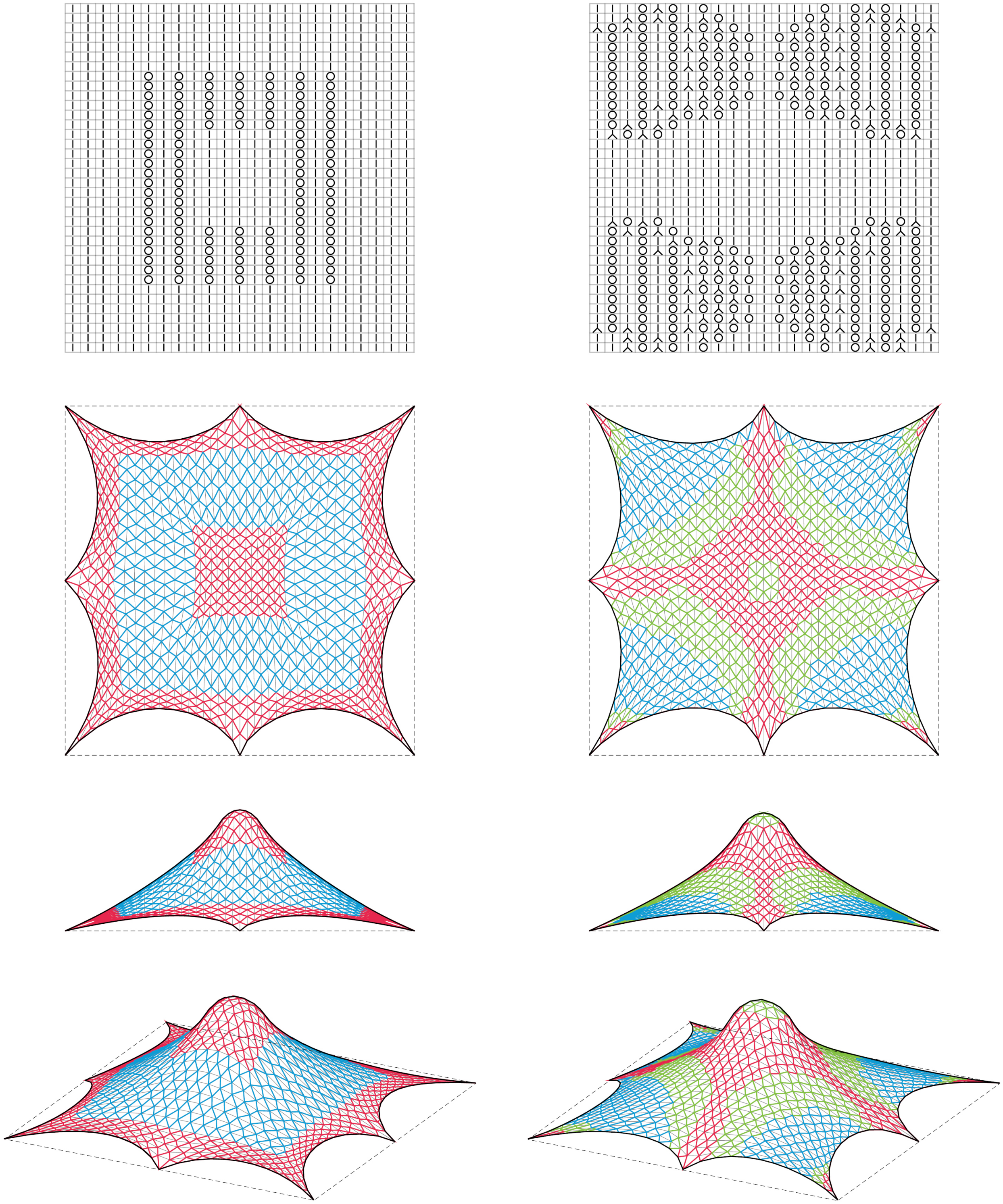
Building upon the discoveries of the physical making and quantitative evaluation established in Chapter 3, the prototype reverses the process to begin with an informed digital simulation. The initial resting geometry is first simulated from a plain knit pattern -- a uniform material assembly -- in which each stitch has the properties of a knit stitch as seen in Figure 4.1a. The vertical force exerted on the central points allows the form to find its resting height according to the internal constraints of the stitch stiffness.

Following the initial simulation, the knit pattern is altered by grouping stitches according to their position within the form. Stitches along the perimeter and in the center comprise the first group while those along the central perimeter form the second. As illustrated in Figure 4.1b, stitches within the first group are assigned stiffness values for an open knit pattern, while the stitches in the second group are assigned values for a plain knit pattern. Then a third sample is created by reversing the patterns and placing the tighter knit pattern in the first group and the open knit pattern in the second (Figure 4.1c). The elevation view in each diagram clearly exhibits the difference in form which results from local manipulation to the material composition. In the first simulation, the tightness of material around the middle of the pattern matches the flexibility of the open knit pattern in the center to create a geometry of more extreme curvature, unlike the



(a) (b)

Figure 4.1: *Results for particle-spring form finding for different stitch types (a)Uniform stiffness (b)Perimeter sorted stiffness A*



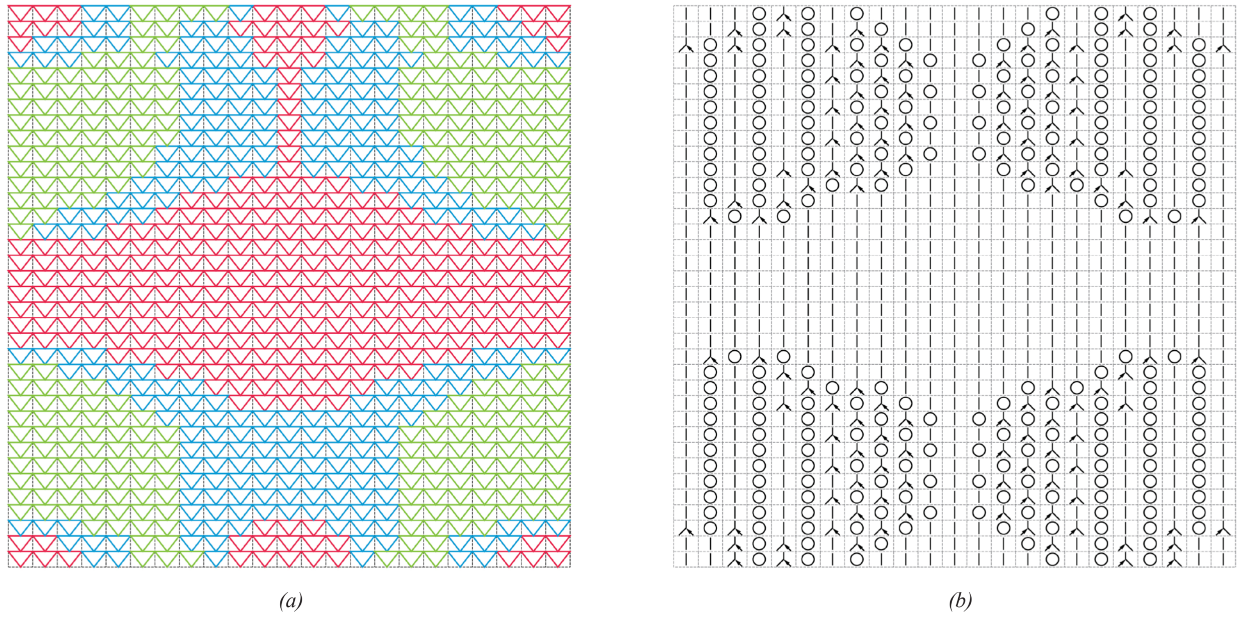
(c) (d)

Figure 4.1: *Results for particle-spring form finding for different stitch types (c)Perimeter sorted stiffness B (d)Force sorted stiffness*

reverse simulation which exhibits a more steady slope.

The digital tests culminate in a final simulation to generate the knit pattern according to forces within the geometry (Figure 4.1d). To accomplish this, each cell of the digital knit pattern is assigned a uniform spring stiffness that represents a basic knit pattern. Once the three-dimensional geometry finds a resting position, the length of each stitch is calculated to determine the force exerted on the spring, similar to the method implemented in Section 3.3.1. According to Hooke's Law, the difference between the initial and the resultant spring length is proportional to the force exerted on that spring. Therefore, the flow of forces within the material assembly is visualized by three groupings from most to least stressed. Consequently, a new knit pattern is generated by assigning a knit pattern to the most stressed stitches, an open knit pattern to intermediate stitches, and a diagonal pattern to the least stressed stitches. The model is then simulated a second time to test the behavior of the global form as a result of varying the pattern locally. This process -- calculating the forces exerted by each stitch and regrouping the cells accordingly -- may be exercised recursively until the desired form is achieved or the distortion between each cell is minimized.

The digital simulation serves as a tool to explore the possibilities of form within the constraints of the physical material. By calculating the forces within the form-found geometry, the digital model can also serve as a tool to re-map and therefore generate the knit pattern as seen in Figure 4.2. Each generated knit pattern may then guide the creation of physical material assemblies.


(a)

(b)

__Figure 4.2:__ Knit pattern generated through particle spring form finding (a) Stitches sorted by force (b) Resulting knit pattern

4.2 Physical Generation of Knit Patterns

The framework in Chapter 3 establishes the knit pattern as the bridge between the physical and the digital. Therefore, the knit patterns generated from the digital simulations serve as the set of operations -- or the code -- to knit physical material assemblies. Following the code, each of the four digital simulations has been constructed on the Kenner knitting machine discussed in Section 3.1.1 and documented in Figure 4.3. From the knitting machine the appearance of the of the first three tests were predictable, following the orthogonal organization derived from the stitch type. The fourth test, however, produced unexpected visual results. As the material assembly emerged from the knitting machine, the flow of fibers within the stitch pattern hinted towards the ultimate three-dimensional form.

Each of the four flat material assembles were anchored to a solid base at the nine pre-defined points before a force was applied at the center of the textile by pushing upwards with a sphere until the material assembly resisted. As documented in Figures 4.4, each material assembly produced a unique formal result. The elevation of each view most clearly exhibits subtle changes in form as a result of a unique material assembly. For example, similar to its digital counterpart, Figure 4.4b exhibits more extreme curvature than its inverse, Figure 4.4c. The knit material assembly generated through the flow of forces within the digital model (Figure 4.4d) creates the most unique physical local and global conditions. The flow of fibers seems to follow the curvature of the resultant geometry as the knit pattern, unlike the digital simulations, produces a highly asymmetrical form.

The physical tests demonstrate that the flexibility of a knit material assembly may easily accommodate the requirements of the simple prototypical form; each stitch slips past its neighbors, creating local distortions to fit the global form. As previously noted, the continuous nature of fiber in the material assembly produces a slippage that cannot be accounted for in the digital model, resulting in an obvious -- and perhaps even desired -- discrepancy between the physical and the digital. The knit pattern, as the bridge between the physical and the digital, is interpretative and experimental; it allows each to inform the other while never truly resulting in the same output.

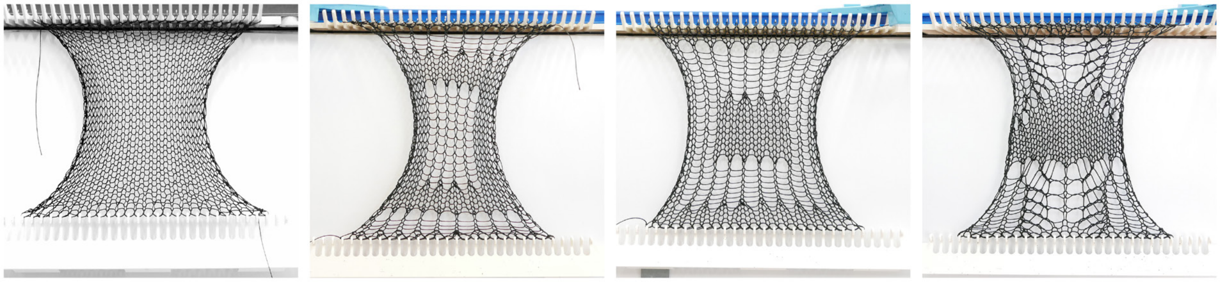
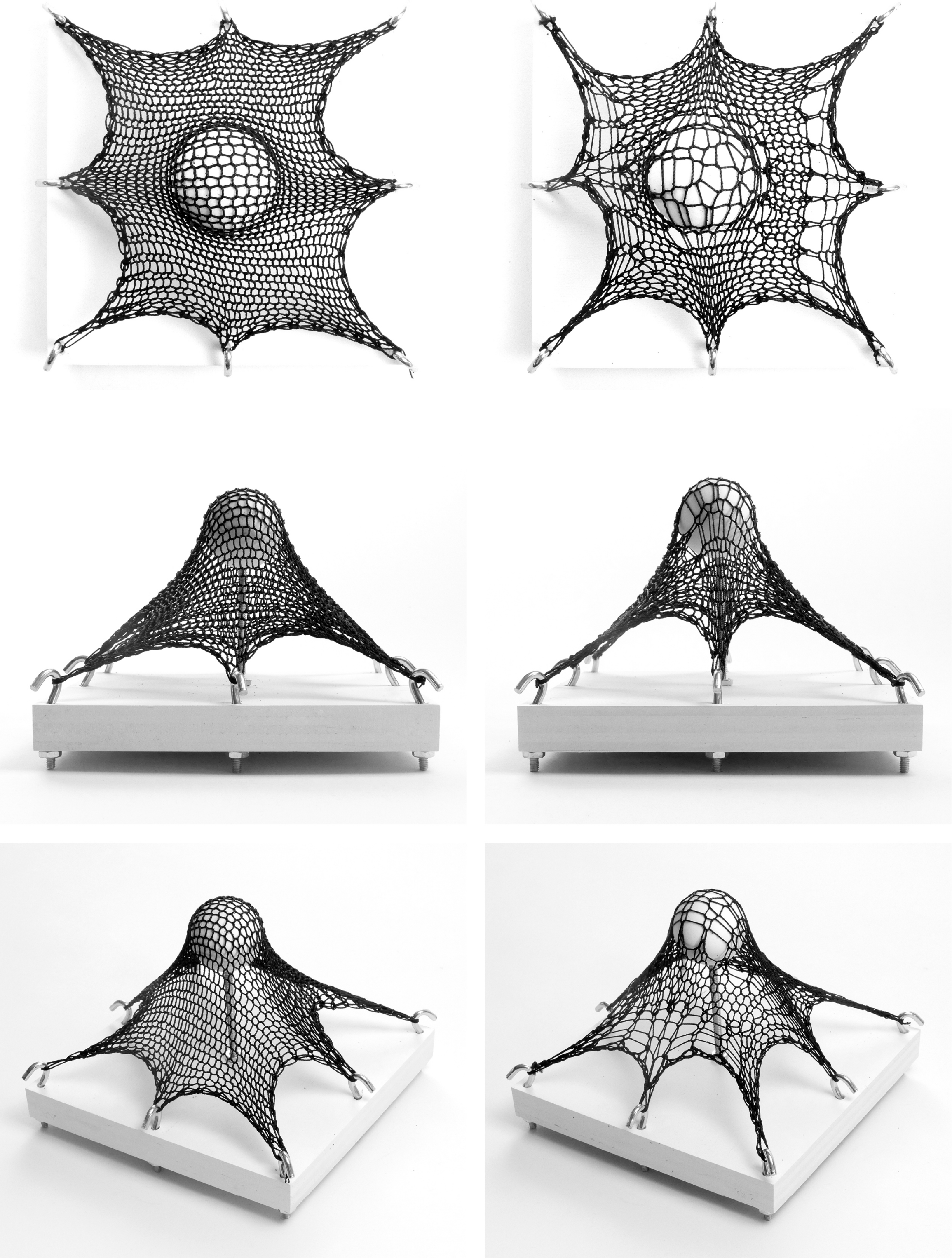
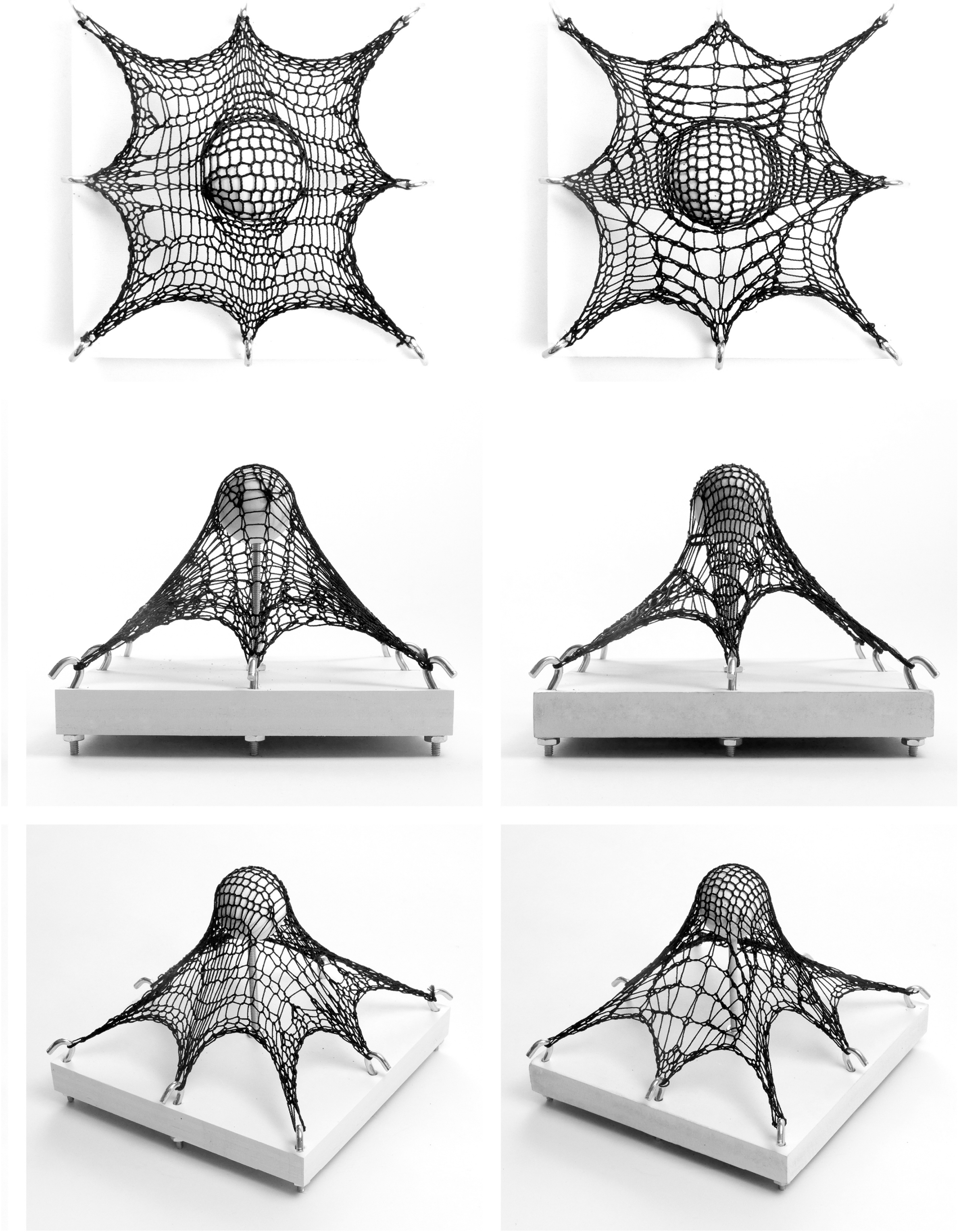

(a) *(b)* *(c)* *(d)*

Figure 4.3: *Two-dimensional physical knit material assemblies following digital simulations (a)Uniform stiffness (b) Perimeter sorted stiffness A (c)Perimeter sorted stiffness B (d)Force sorted stiffness*



(a) (b)

***Figure 4.4:** Three-dimensional physical knit material assemblies following digital simulations (a)Uniform stiffness (b)Perimeter sorted stiffness A*



(c) *(d)*

Figure 4.4: *Three-dimensional physical knit material assemblies following digital simulations (c)Perimeter sorted stiffness B (d)Force sorted stiffness*

CHAPTER 5
CONCLUSION

This chapter summarizes the contributions of the thesis, discusses potential applications, and speculates on future work. This thesis has established an unmet need in architectural design practice for the programming of materials within the control of the designer, focusing on knit material assemblies for their unique internal structure and constructability with accessible tools. In response to this need, this thesis has identified the knit pattern as the interface between the physical and the digital and has proposed a new framework for making, evaluating, and simulating material assemblies for tension-active forms. First, this research established the language of the code by identifying fundamental stitch types and elemental patterns. Next, the code, or knit pattern, was embedded with dynamic data extrapolated from comparative loading tests. Finally, the embedded code was activated through a particle-spring network, simulating the knit patterns with unique behaviors. The framework institutes a non-linear, iterative, and recursive process in which discoveries found at each stage transmit through the knit pattern.

5.1 Applications and Potential Impact

The aim of this research is to help designers conceive of custom material assemblies early in their design process. By understanding the knit pattern as the interface between physical making and digital exploration, designers can work through many modes of making and testing to program materials -- specifically knitted textiles -- according to the requirements of form, structure, or aesthetics. Variations in the two-dimensional pattern produce distinct three-dimensional properties which can aid in the production and construction of large structures. The ability to program material assemblies can be seen as a shift away from mass-produced, often homogenous, materials, towards materials designed to suit specific needs, which may further reduce material consumption and waste. Moreover, the customization of materials can lead to new architectural forms and design solutions that are inconceivable within contemporary material practice.

The main contribution of this thesis is the new framework which establishes a process to make, evaluate, and generate knit material assemblies. This was accomplished through the identification of the knit pattern as code. Whereas traditionally the pattern is a static visual representation, in this research it is both the physical sequence of stitches and the dynamic properties of each stitch within a digital model. The dynamic properties of the physical material communicate through the knit pattern to the digital model, which explores the possibilities of form within the constraints of the material to remap the pattern's code and thereby re-informing the physical. This new framework may help designers create and evaluate material assemblies to better satisfy the local and global needs of form, structure, and aesthetics.

The primary application of the new framework is in the exploration and development of custom knit textiles for tension-active forms, although the principles apply to any material assemblies that derive from a pattern as a rule-based code. Based on a continued interest in fiber-based assemblies in art and design, as identified in Section 2.1, contemporary practice may benefit from a better understand of programming a material according to the requirements of form and structure, and how to design with a material that offers such customization. Therefore, the framework is a means to explore and understand the active, and often complex, behaviors of custom material assemblies.

5.2 Future Work

There are many important areas for future research in custom knit material assemblies and their effectiveness in tension-active architectural forms, including incorporating varied fiber types into a single material assembly, producing knit textiles on a robust automatic knitting machine, expanding the tensile tests to include uniaxial loading, developing the digital workflow to accommodate shifts in topology, and implementing a measure to test differences in performance.

Each material assembly in this research is constructed from a uniform heavyweight polyester. During a stage of experimentation, other fiber types were tested, including Kevlar, metal-reinforced Kelvar, and steel cable, and a second knitting carriage was added to the machine to accommodate multi-material construction. Each of these fibers produced visual and tactile differences. Immediate future work involves testing new materials and exploring possibilities of a multi-material framework.

Second, the materials in this thesis were produced on a hand-held, semi-automatic knitting machine. This technique of knitting was motivated by the industrial infrastructure which surrounds it, meaning that the discoveries found at the scale of the prototype could potentially grow in scale. This research will next test how the material operations behave when manufactured on a machine with higher resolution and precision.

A third and necessary next step for this research is to expand the range of material loading tests to include multiaxial loading. Currently, the stiffness and strength of each material is a measure of uniaxial loading which favors material assemblies with an orthogonal, or knit, internal structure. Multiaxial loading will test if assemblies with transfer stitches that shift the path of fibers exhibit a higher stiffness than the previous tests.

A fourth area for investigation includes the development of the digital model, particularly incorporating the springs as a single stitch workflow. Currently the topology of the mesh is subdivided into five springs to mimic one interpretation of a knit structure. There are potentially infinite solutions to the subdivision of springs in the digital model, which may more accurately represent a stitch. Furthermore, the topology can be customized to represent one of three fundamental stitches: the knit, the hole, and the transfer. The current model implements the same topology -- that of a knit -- for every stitch type and varies the spring stiffness to integrate their differences. Future work will continue varying spring stiffness and incorporate changes to the mesh topology.

The final next step will be to loop the physical three-dimensional tests back into the framework to test their physical behaviors. Future tests should incorporate a performance metric to measure how each pattern differentiates itself from the others and from its corresponding digital tests. The measure may be visual, structural, or any other metric to evaluate how the pattern aids or hinders the three-dimensional form.

Beyond these specific steps, an important and broad challenge includes the scale and range of forms possible with a knit material system. This work concentrates on the scale of the prototype to deeply understand the material assembly at the scale of a single stitch; however, the application of this research aims to eventually be applied at the scale of a building. Future tests may implement CNC knitting at the scale of a pavilion to explore how the material would behave when increased in scale.

5.3 Concluding Remarks

As the fields of art and architecture grow more connected to digital technologies that allow for high levels of specification, the desire to design with infinitely more resolution and customization is inevitable. The design process can incorporate a new range of methods, frameworks, and workflows which may affect how we understand and design with materials -- especially those which can be programmed according to the requirements of form, structure, and design intent. This thesis has focused on knit material assemblies for their unique ability to be easily produced and highly customizable. A primary goal was to develop a framework to not only explore their implementation in design practice, but also how variations to the material assembly relate to three-dimensional forms. The research presented in this thesis is an important first step of the ongoing design exploration.

REFERENCES

Adriaenssens, Sigrid et al., eds. *Shell Structures for Architecture: Form Finding and Optimization*. London ; New York: Routledge, 2014. Print.

Ahlquist, Sean, and Moritz Fleischmann. “Elemental Methods for Integrated Architectures: Experimentation with Design Processes for Cable Net Structures.” *International Journal of Architectural Computing* 6.4 (2008): 453–475. Print.

Ahlquist, Sean, and Thomas Speck, eds. “Development of a Digital Framework for the Computation of Complex Material and Morphological Behavior of Biological and Technological Systems.” *Computer-Aided Design* 60 (2015): 84–104. Print.

Ahlquist, Sean, and Achim Menges. “Behavior-Based Computational Design Methodologies: Integrative Processes for Force Defined Material Structures.” *Integration Through Computation*. Ed. Joshua M. Taron. University of Calgary: Association for Computer Aided Design in Architecture, 2011. 82–89. Print. ACADIA.

---. “Frameworks for Computational Design of Textile Micro-Architectures and Material Behavior in Forming Complex Force-Active Structures.” *ACADIA 2013 Adaptive Architecture : Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture*. Ontario, Canada: Toronto : Riverside Architectural Press, 2013. 281–292. Print. ACADIA.

Bach, Klaus, Ernst Kullmann, and Ilse Schmall. *Netze in Natur Und Technik*. Stuttgart-Vaihingen: Inst. für Leichte Flächentragwerke, 1975. Print.

Bamberger, Jeanne, and Donald A. Schon. “Learning as Reflective Conversation with Materials: Notes from Work in Progress.” *Art Education* 36.2 (1983): 68–73. Print.

Bassett, Richard J., Ron Postle, and Ning Pan. “Experimental Methods for Measuring Fabric Mechanical Properties: A Review and Analysis.” *Textile Research Journal* 69.11 (1999): 866–875. Print.

Beesley, Philip, Michael Stacey, and Omar Khan, eds. *ACADIA 2013 Adaptive Architecture : Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture*. Toronto : Riverside Architectural Press, 2013. Print.

De Landa, Manuel. “Material Complexity.” *Digital Tectonics*. Ed. Neil Leach. Chichester, West Sussex, U.K. ; Hoboken, NJ: Academy Press, 2004. 14–21. Print.

Drew, Philip. *Frei Otto : Form and Structure*. Boulder, Colorado: Westview Press, 1976. Print.

Garcia, Mark. “Architecture + Textiles = Architextiles.” *Architectural Design* 1 Nov. 2006: 5–11. Print.

---. “Prologue for a History and Theory of Architextiles.” *Architectural Design* 1 Nov. 2006: 12–20. Print.

Glaeser, Ludwig. *The Work of Frei Otto*. New York: Museum of Modern Art, 1972. Print.

Gordon, J. E. *The Science of Structures and Materials.* New York : Scientific American Library : , 1988. Print.

Ingold, Tim. “Of Blocks and Knots.” *Architectural Review* Oct. 2013: 26–27. Print.

---. “The Textility of Making.” *Cambridge Journal of Economics* 34.1 (2010): 91–102. Print.

Kilian, Axel. “Steering of Form.” *Shell Structures for Architecture: Form Finding and Optimization*. London ; New York: Routledge, 2014. 131–139. Print.

Koch, Klaus-Michael, and Karl J. Habermann, eds. *Membrane Structures : Innovative Building with Film and Fabric.* Munich ; New York: Prestel, 2004. Print.

Leach, Neil, David Turnbull, and Chris Williams, eds. *Digital Tectonics.* 1 edition. Chichester, West Sussex, U.K. ; Hoboken, NJ: Academy Press, 2004. Print.

McCullough, Malcolm. *Abstracting Craft : The Practiced Digital Hand*. MIT Press, 1998. Print.

McQuaid, Matilda, and Philip Beesley. *Extreme Textiles : Designing for High Performance*. New York : Smithsonian Cooper-Hewitt, National Design Museum : Princeton Architectural Press, 2005. Print.

Nerdinger, Winfried, ed. *Frei Otto : Complete Works : Lightweight Construction, Natural Design.* Basel ; Boston: Birkhäuser, 2005. Print.

Otto, Frei, and Bodo Rasch : *Finding Form : Towards an Architecture of the Minimal*. Germany: Axel Menges, 1995. Print.

Oxman, Neri. “Material Computation.” *Manufacturing the Bespoke: Making and Prototyping Architecture*. Ed. Bob Sheil. 1. Chichester: Wiley, 2012. Print.

Peters, Brady, and Terri Peters, eds. *Inside Smartgeometry : Expanding the Architectural Possibilities of Computational Design*. United Kingdom: John Wiley & Sons Ltd, 2013. Print.

Sabin, Jenny. “myThread Pavilion.” *Portfolio*. Jenny Sabin Studio. n.p., 15 Sept. 2012. Web.

---. “myThread Pavilion: Generative Fabrication in Knitting Processes.” *ACADIA 2013 Adaptive Architecture : Proceedings of the 33rd Annual Conference of the Association for Computer Aided Design in Architecture.* Ed. Philip Beesley, Michael Stacey, and Omar Khan. Ontario, Canada: Toronto : Riverside Architectural Press, 2013. 347–354. Print.

Spencer, David J. *Knitting Technology : A Comprehensive Handbook and Practical Guide to Modern Day Principles and Practices.* Oxford ; New York : Pergamon Press, 1989. Print.

Taron, Joshua M. *ACADIA 2011 : Integration through Computation : Proceedings of the 31st Annual Conference of the Association for Computer Aided Design in Architecture*. United States ; Association for Computer Aided Design in Architecture, 2011. Print.

Thomsen, Mette Ramsgard, and Martin Tamke. “Digital Crafting: Performative Thinking for Material Design.” I*nside Smartgeometry : Expanding the Architectural Possibilities of Computational Design.* United Kingdom: John Wiley & Sons Ltd, 2013. Print.