Laminate-Like Behavior of An Additively Manufactured Polymer with Underlying Bioinspired Architecture

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ABSTRACT

LAMINATE-LIKE BEHAVIOR OF AN ADDITIVELY MANUFACTURED POLYMER WITH UNDERLYING BIOINSPIRED ARCHITECTURE

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Laminates are a class of composite materials in which several unidirectional laminae are stacked together to create a material with a clear layer-by-layer architecture. Traditionally, each lamina is itself a composite consisting of aligned fibers, such as cellulose, graphite, or glass, embedded within a polymer, ceramic, or metal host matrix. These materials are unique in the sense that their engineering properties can be greatly varied simply by changing the stacking order of lamina within the laminate. While there are several traditional manufacturing approaches for laminates, recent research has focused on assessing the feasibility of using additive manufacturing techniques to create these materials. Additive manufacturing, commonly referred to as 3D printing, is one of the most innovative technologies for manufacturing polymer and metal components.

Replicating a traditional laminate using these manufacturing approaches, however, would require 3D printing two materials simultaneously. Although this is possible, in this work we instead aim to investigate the ability to impart laminate-like behavior (i.e. tunability of mechanical properties through changing internal material architecture) to a homopolymer sample. Our hypothesis is that the tunable mechanical properties of laminates are inherent to the underlying layer-by-layer structure rather than the composite nature and can thereby be captured using 3D
printing of a single material. In order to evaluate the hypothesis, this work tests the mechanical properties of a 3D-printed dog-bone samples with an underlying bioinspired, layer-by-layer architecture fabricated from polylactic acid (PLA). Fused deposition modeling (FDM) is used to create the PLA samples, which focuses on determining the effect of pitch angle and infill percentage on the resulting mechanical properties. The pitch angles, here referring to the relative angle between alignments of “fibers” in adjacent layers, tested here range from 0° - 180° while the infill percentages examined are 30% and 50%. Tensile tests were performed on the samples up to the failure point to obtain values of the elastic modulus, ultimate tensile strength, and toughness. Experimental results have shown that there is a clear relationship between the mechanical properties and pitch angle as well as a clear dependence on pitch angle. Further, we demonstrate that these experimental trends are in good agreement with classical lamination theory and provide evidence that we can effectively create a structure that exhibits laminate-like mechanical behavior using additive manufacturing techniques of a single material.
NORTHERN ILLINOIS UNIVERSITY
DEKALB, ILLINOIS

MAY 2020

LAMINATE-LIKE BEHAVIOR OF AN ADDITIVELY MANUFACTURED POLYMER WITH UNDERLYING BIOINSPIRED ARCHITECTURE

BY

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A THESIS SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE

MASTER OF SCIENCE

DEPARTMENT OF MECHANICAL ENGINEERING

Thesis Director:
Robert Sinko
ACKNOWLEDGMENTS

For the completion of this project I would like to thank a few people who through their hard work and advice made the project happen. I would like to thank my advisor, Dr. Robert Sinko, who met with me every week for 2 years, gave me advice and ideas for every problem I encountered throughout the project, and gave me all the knowledge I needed for this project. In addition, I would like to thank Dr. Federico Sciammarella, who helped me with his knowledge and experience in the field of 3D printing in order to print all the parts that I needed for testing. I would also like to thank Todd Durham and Matt McCoy, who helped me print the parts in the Maker Space at the College of Engineering and Engineering Technology at Northern Illinois University. I would also like to thank Peter Mueller for helping me in the design process of the samples. I would like to thank Jeannie Peterson for her help with registering for classes and managing my degree progress report to make sure that I had taken all necessary classes. Finally, I would like to thank my family and friends who supported me throughout this time.
DEDICATION

To my mom, dad, grandma
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CHAPTER 1: INTRODUCTION

This chapter introduces several topics that serve as the primary motivation for this work. While each of them is described in the subsections below, a brief outline is provided in this first paragraph. In Section 1.1, natural systems are discussed as they serve as a source of inspiration for many scientists and engineers due to their superior performance compared to traditional engineering materials. In Section 1.2, bioinspired design is discussed as it relates to engineers who are developing new innovations using lessons learned from the underlying mechanics and chemistry of natural systems. Additionally, several examples of bioinspired design are provided in this section. In Section 1.3, the mantis shrimp is discussed in detail as it is one organism that provides a significant amount of the bioinspiration for this project and has also been investigated by several other scientists in a similar capacity. In Section 1.4, additive manufacturing is described with a specific focus on its applicability to this work. Finally, in Section 1.5, an introduction to composite laminates is provided.

1.1 Natural Systems

Engineers and scientists are increasingly turning towards nature and natural systems as an inspiration for new product design and development. The reason for this is that nature, through billions of years of evolution, has produced solutions to many complex real-life problems (Butler, 2005). However, the importance of natural systems to engineering was not always at the forefront of engineering design. In fact, engineering designs have historically had a huge impact on the environment with intervention in natural systems being a frequent consequence (National Academy of Engineering, 1996). These types of engineering analyses and designs were most
focused on controlling and/or working around nature rather than cooperating with it, benefiting from it, and, most recently, learning from it. Today, however, the engineering field has evolved, and most engineers now recognize that nature offers a wide variety of components and systems that, if understood and analyzed correctly can have a huge impact on engineering systems design and materials development.

One of the primary reasons engineers are so interested in natural materials is that they often exhibit mechanical properties that exceed the performance of traditional engineering materials. As shown in Figure 1, traditional engineering materials (e.g. metals, ceramics, etc.) often exhibit a tradeoff between fracture toughness and stiffness. Natural materials, on the other hand, do not exhibit this tradeoff. These materials, such as bone, dentin, and other proteins, employ design techniques, such as multiscale and multiphase architectures, that give rise to functionalities that man-made systems cannot achieve (Egan et al., 2015).

![Figure 1: Fracture toughness vs. elastic modulus for traditional engineering materials (left panel) and natural materials (right panel).](image)

1.2 Bioinspired Design

Based on the observation that natural materials often outperform traditional engineering materials, there has recently been increased interest in bioinspired materials design where design...
strategies from natural systems aim to be incorporated in the next generation of engineering materials. When considering bioinspired materials design, there are several design approaches including recombinant biology, hybrid approaches, and biomimetics. The recombinant approach involves taking naturally occurring biomolecules and rearranging them for an application that may vary significantly from those found in nature. An example of this is using resilin blends for high resilience rubber (Egan et al., 2015). The hybrid approach involves combining natural materials with engineering materials to incorporate mechanofunctionality directly into the engineering system. An example for this case would be blending cellulose nanocrystals (CNCs) extracted from wood with a synthetic polymer to create a high-stiffness polymer nanocomposite (Moon et al., 2011). These first two approaches, while not directly considered in this work, are effective strategies for incorporating natural design principles into new engineering materials and systems.

Biomimetics, the bioinspired design approach incorporated in this project, is the study of the structure and function of biological systems as models for the design and engineering of materials and machines (Hitchins, 2014). In this design approach, which is perhaps the most well-known of all bioinspired design methods, engineers aim to replicate, or copy, the underlying mechanics and structure observed in natural systems using conventional engineering materials. Bioinspired design approaches are often employed to either develop new products or provide improvement to existing products and has a large potential for influencing future technologies.

Nature has inspired a wide range of human accomplishments and has led to new innovations such as materials, tools, mechanisms, system, methods, etc (Bar- Cohen, 2005). There are many examples of biomimetic applications that have been successful. Some of these examples are relatively easy to mimic, while others are more complex. One of the simplest examples being implemented are the use of fins for swimming, which offer improved performance and efficiency
for the swimmer. An example of a more complex implementation would be the development of prosthetics that closely mimic real limbs and sensory enhancing microchips that are interfaced with the brain to assist in hearing and controlling instruments (Bar-Cohen, 2006). Another field that has been taking extensive advantage of biomimetics is dentistry. Using biomimetic approaches, dental professionals can develop implants and dental materials that are closer to the natural structure and function of teeth. For example, a bioengineered tooth was invented that, even though smaller in size than the normal tooth, correctly replicated tooth structure and the hardness of mineralized tissues. More broadly, the development of tooth regeneration technologies is an important first step in the establishment of engineered organ transplantation (Viswanath, Reddy, 2014).

While biomimetics has clearly played a role in several industries, more recent developments have focused on improving the performance (mechanical, thermal, etc.) of engineering materials using lessons learned from biology. The aerospace industry is an example of one industry in which this application is implemented. Using a wind tunnel, researchers have found that the flipper of the humpback whale is a more efficient wing design than the current model used in the industry of airplanes. The reason for this is because the presence of the tubercles can cause a delay in the angle of attack which simultaneously maximizes lift and decreases drag in the aircraft (Fish et al., 2011). Another example in this field includes the use of the rough skin of the shark as inspiration in developing a striated foil coating for the wings of the aircraft which resulted in less friction and better fuel efficiency (Habib, 2018). The automotive industry has also adapted natural systems in order to increase performance in terms of fuel efficiency. An example of this is provided by Mercedes-Benz which is developing a new high fuel efficiency concept vehicle inspired by the
body shape of a boxfish. This car offers about 20% lower fuel consumption compared to the previous models (Buehler, 2015).

Examples of bioinspired products and systems are not limited to futuristic conceptual design either as many of the products and systems that are found in the market or in everyday life are inspired by natural systems. One example that is commercially available is gecko tape. Gecko tape is a product that has been inspired by the ability of lizards to climb up walls and walk on ceilings. This tape exploits van der Waals forces by mimicking the tiny hair like structures called setae that cover geckos’ feet. Another example is the kingfisher train in Japan that can achieve speeds up to 300 km/h and is inspired by the kingfisher, a species of tropical bird with a long bill. The train is designed in such a way that it has a long beak-like shape at the front of the train that results in reduced electricity consumption and increased speed (Alexander, 2018). Finally, solar cells are now being inspired by butterfly wings. Butterfly wings have cells that can collect light at any angle and by incorporating this structure into solar cells, the efficiency can be increased by a factor of two (Alexander, 2018). These are only a few specific examples of the wide range of engineering applications that draw inspiration from natural systems. It is almost certain that an increase in the use and implementation of bioinspired design in engineering and technology is will occur over the next few years. Biomimetics, as evidenced by previous examples, among several others, is helping technology reduce human impact on the environment and enhance overall quality of life (Butler, 2005).

1.3 Mantis Shrimp

In this study, biomimetic design is employed to replicate the underlying architecture of the mantis shrimp’s dactyl club. Mantis shrimp, also known as stomatopods, have a unique body
structure and several other interesting characteristics that have made these species intriguing to researchers. The mantis shrimp, pictured in Figure 2, is a small and aggressive creature found mostly in tropical and subtropical waters of the Indian and Pacific Ocean. Even though it is a beautiful animal and has a wide variety of colors, mantis shrimp is a deadly animal which has the ability to attack its preys with its sharp claws. Some experimentally observed characteristics of the mantis shrimp include the ability to crack holes in a glass container, fast punches that release heated bubble and a flashlight, as well as complex eyes that can detect cancer cells (Safford, 2014).

Figure 2: Image of a mantis shrimp (left panel). Illustration (center panel) and microscopic image (right panel) of its underlying layer-by-layer structure (Grunenfelder et al., 2014).

From a materials design perspective, the characteristic of this organism that is the most interesting is the repeated high impact loading of the dactyl club without failure. As mentioned previously, the internal body structure of the mantis shrimp is unique and is composed of layers of aligned fibers that each are oriented in different directions with respect to one another as shown in Figure 2. The first layer of the mantis shrimp is composed of mineralized hydroxyapatite which is in a highly crystalline form. The next layer is composed of the same material but in a softer form and made up of layers of unidirectional fibers stacked on top of each other. Each layer is rotated
slightly with respect to the previous layer such that the fibers form a helical shape as pictured in Figure 2. The last part of this structure is a series of chitinous fibers that holds the dactyl club and prevents the expanding of the club on impact (Scharping, 2018). Through evolutionary processes, biological composites have been optimized to fulfill specific functions. An example for this optimization is the mineralized dactyl club. As mentioned, the endocuticle region of this creature is made up of a helicoidal arrangement of mineralized fiber layers. This structure helps in impact resistance and energy absorbance. From the experimental and computational analysis, it is shown that a helicoidal structure design reduces damage propagation during an impact event and results in an increase in toughness (Grunenfelder et al., 2014).

Due to this behavior, several researchers have been inspired to come up with real life inventions that replicate the underlying structure of this creature. One example, which is inspired by the mantis shrimp’s saddle, is a biological spring combining both stiffness and flexibility. The movement when the mantis shrimp strikes the pray is driven by a power amplification system that releases a high amount of elastic energy (Miserez, Amini, 2015). The main component involved in this process is the saddle structure which allows the elastic energy to be stored prior to the attack. From the experimental analysis it was determined that the saddle is a bilayer structure with sharp changes in chemical composition and mechanical properties between layers. The outer layer is heavily mineralized and able to sustain compressive stresses, while the inner layer contains chitin and proteins and provides tensile resistance (Miserez, Amini, 2015). Due to the impressive characteristics of this natural structure, researchers have previously attempted to replicate it using engineering materials. Specifically, carbon fiber epoxy composites with a similar structure were shown to have increased impact resistance compared to materials typically used in aerospace engineering (Grunenfelder et al., 2014).
Although others have utilized this organism as inspiration for materials development in the past, this work aims to continue and further those efforts. As evidenced by current research in the field, the underlying helicoidal architecture of the mantis shrimp dactyl club is incredibly important to the high impact resistance and mechanical properties of the club itself. For this reason, it is of interest to determine if imparting this underlying structure – that is, a layer-by-layer construction of aligned fibers with a certain pitch angle between layers - to a mechanical component can be used to improve mechanical performance. Specifically, it is of interest to determine if an additively manufactured polymer component with this underlying architecture exhibits improved mechanical performance to a part with no internal structure.

1.4 Additive Manufacturing

In order to replicate the internal structure of the mantis shrimp dactyl club using a traditional engineering material, an appropriate manufacturing method is needed. Traditional subtractive manufacturing methods would not be appropriate for this work as it would not be feasible to develop the internal structure while maintaining the overall mechanical integrity of the part. A process such as injection molding could be used, however, the mold needed for this part would be incredibly complex and incredibly difficult to remove. From a traditional manufacturing approach, the best way to replicate the helicoidal structure would be to fabricate each layer independently and perform a joining operation to develop the final part – similar to the manufacturing process used for a laminate composite (see Section 1.5). To avoid the shortcomings of the methods discussed above, it was determined that additive manufacturing was an ideal alternative.

Additive manufacturing, often referred to as 3D printing, is the process of making a three-dimensional solid object directly from a solid model of the part of interest. In this process, the
material is deposited in a layer-by-layer method to produce a three-dimensional object. To date, 3D printing has primarily been used in engineering to create engineering prototypes. Nowadays, however, advances in additive manufacturing have enabled 3D printers to print objects that are comparable performance-wise with traditionally manufactured ones. 3D printing makes possible the building of a complex geometry while also having greater benefits than traditional manufacturing such as lower cost and production time. Another benefit of additive manufacturing is the amount of waste material. In additive manufacturing the material waste is far smaller than in traditional manufacturing. Speaking from a more global and economic perspective, 3D printing also has the ability and potential to enable mass customization of goods on a large scale (Schubert, 2014). As an example, ADIDAS is one of the biggest manufacturers of shoes and now uses 3D printing to produce midsoles for these products (Sher, 2019). By taking advantage of 3D printing, people can accomplish things that never seemed achievable with traditional manufacturing methods. Yet, this mass production is not easily accomplished for all types of products and manufacturing systems that exist, but additive manufacturing is expected to grow and pass traditional manufacturing in the future.

While it may seem simple in concept, 3D printing technology requires several parameters to be specified prior to printing such as project scale, selection of printing materials, and quality and strength of printed parts (Gorsse, 2017) and there are a high number of factors that affect the printability and the behavior of printed parts including the specific material, printing methods, time and temperature (Hou & Tian, 2017). Speaking to printing methods, there are several common 3D printing methods including Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), etc. FDM is one of the most widely used 3D printing method and the method that will be utilized in fabricating samples for mechanical testing in this research paper.
In this process, a plastic or wax material is extruded through a nozzle that traces the part's cross-sectional geometry layer by layer. In order to keep the plastic above the melting point so that it runs through the nozzle to print the layer, the nozzle contains resistive heaters. The plastic hardens after flowing from the nozzle and bonds to the previously deposited layer. Once a layer is built, the platform lowers, and the extrusion nozzle deposits another layer (Novakova-Marcincinova, 2012). The FDM process is illustrated in Figure 3. Materials that are most often used in FDM are ABS, polycarbonate, polyethylene, etc. In general, FDM seems to be an economical and efficient three-dimensional (3D) printing method for high-temperature polymer materials (Deng et al., 2018).

![Figure 3: Illustration of the fused deposition modelling (FDM) process (Novakova-Marcincinova, 2012).](image)

In this research project, polylactic acid (PLA) was chosen as the polymer to fabricate samples from FDM. PLA is a biodegradable thermoplastic polyester that is produced by biotechnological processes from renewable resources. Although other sources of biomass can be used, corn has the advantage of providing the required high-purity lactic acid (Plackett, Vazquez, 2004). Poly (lactic
acetic acid) (PLA) is produced from the monomer of lactic acid (LA). PLA can be produced by two well-known processes – direct polycondensation (DP) and ring-opening polymerization (ROP). The LA for the process is obtained from the fermentation of sugar. LA is converted to lactide and eventually to PLA as shown in Figure 4 (Sin & Tueen, 2019).

![Diagram of PLA production process and chemical structure](image)

**Figure 4: PLA production process and chemical structure.**

Because of its excellent biocompatibility and tunable physiochemical properties, polylactic acid is used in a wide variety of applications. PLA has various advantages when compared to other biopolymers: direct production of the lactide monomer from lactic acid, significant energy savings, the ability to recycle the polymer directly back to lactic acid, reduction of landfill volume, improvement of the agricultural economy, and high mechanical strength and low toxicity (Dorgan et al., 2000; Jamshidian et al., 2010). There are a wide variety of industries where PLA polymers are used including packaging, the medical industry, aerospace applications, and automobiles, thereby making it an ideal candidate to be used in this work. Most recently, polylactic acid has
seen wide adoption in biomedical applications due to the excellent biocompatibility and tunable properties.

1.5 Composite Laminates

The initial focus of this study was to develop an additively manufactured polymer part with a prescribed internal structure inspired by the mantis shrimp. The initial hypothesis was that imparting this structure would change, and more specifically enhance, the mechanical performance of the part compared to one without any prescribed internal structure. However, the preliminary results, which will be discussed later on in Chapter 3, showed that while the properties changed with changing internal structure, no enhancement was observed – thereby warranting a shift in focus for the project. Recognizing the importance of tunability of mechanical properties, the focus was shifted to laminates – a class of composite materials that exhibit similar tunability.

A laminated composite, or simply a laminate, is a composite that is constructed by stacking several unidirectional composite layers together (Gotsis et al., 1998). Each of the layers is known as a lamina and is traditionally a plane layer of unidirectional fibers embedded in a matrix. Each lamina itself is a composite material, which by definition is a material that is created by combing two or more disparate materials together on the macroscopic scale to form a useful new material (Jones, 2014). If composite materials are properly designed, they can exhibit better properties than the properties of each of the constituent materials taken separately. Some of the properties that can be improved include strength, stiffness, wear resistance, weight, thermal conductivity, and hygroscopic response (Bunsell, 1988).

Composite materials have mechanical characteristics that are different from those of more conventional engineering materials. Most common engineering materials are both homogeneous
and isotropic. A homogeneous body has uniform properties throughout, which means the properties are independent of position in the body. An isotropic material has properties that are the same in every direction at a point in the material, which means the properties are independent of orientation at that point (Jones, 2014). Composite materials are often both nonhomogeneous and anisotropic, meaning properties are nonuniform over the body and different in every direction (Jones, 2014). These are important characteristics as they allow the composites material to be adaptable to a wide range of loading conditions and also allows for the material to have a high strength to weight ratio.

As mentioned previously, a laminate is composed of two or more unidirectional laminae stacked together at different orientations. In this case the laminae can be of various thickness as well as consisting of different materials. This orientation of a lamina is determined by the angle between the reference x-axis and the major principal axis (i.e. fiber direction) of the ply (Daniel & Ishai, 2006). The structural hierarchy inherent in stacking multiple lamina together to form a laminate is illustrated in Figure 5. Composite laminates are usually composed of unidirectional glass/epoxy, carbon/epoxy and aramid/epoxy layers stacked together in a sequence with the fibers exhibiting superior mechanical stiffness and strength compared to the matrix.
According to classical lamination theory, by simply changing the stacking sequence and orientations of layers while using the same constituent materials, mechanical stiffness and strength can be changed by orders of magnitude. While the high degree of tunability is desirable, often the manufacturing methods for these laminates are cumbersome and time consuming as they involve fabricating layers individually and then fixing each of the layers together in a particular sequence. Instead, it would be desirable to assess if an additive manufacturing method could be used to develop these materials. Prior, there has been some work on developing laminates using the additive manufacturing industry. For example, additive manufacturing of polymer fiber composites has transformed this industry making it an enormous industry of highly customized parts with improved mechanical properties compared to un-reinforced polymers (Lin & Parandoush, 2017). Using the FDM method specifically for creating fiber reinforcement in a polymer matrix, the mechanical properties have shown a great improvement. For example, the short glass fiber ABS show an increase by 135% in tensile strength compared to conventional compression molding (Sekar et al., 2019).

Figure 5: Representation of a lamina and the stacking of multiple lamina at various orientations to form a laminate (Luersen & Lopez, 2013).
1.6 Objective of Study

As stated previously, the initial goal of this project was to determine if incorporating underlying mechanical structure, inspired by the mantis shrimp’s dactyl club, into an additively manufactured polymer part could be used to enhance its’ mechanical performance. While incorporating this structure into a component, was successful, the improvement in mechanical properties was not successful. At this point, the scope was refined to assess how incorporating this bioinspired structure could be used to impart laminate-like behavior (i.e. tunable mechanical properties with changing internal structure) to a homopolymer component using 3D-printing technologies.

With this refined scope in mind, the primary objective of this research project is to design and test a PLA dog-bone component with an internal helicoidal structure inspired by the mantis shrimp. Specifically, this work aims to develop a layer-by-layer material fabricated using FDM where PLA “fibers” are printed at different pitch angles in each layer. In a sense, this work fabricates a pseudo-laminate where PLA serves as the reinforcing, filler phase in the absence of any specific matrix phase other than air. Once the samples are fabricated, tensile tests were performed to measure the elastic modulus, fracture strength, and toughness of the samples to determine how pitch angle and infill percentage can be used to change the mechanical properties. Beyond analyzing the experimental results, another objective for this research project is determine whether the component with underlying bioinspired architecture can be treated as a laminate material according to traditional lamination theory. A comparison between experimental data and this analytical analysis will be made in order to be able to determine whether a “laminate-like” material can be achieved using a single material and the bioinspired layer-by-layer design.
CHAPTER 2: EXPERIMENTAL METHODS

2.1 Experimental Sample Design

In order to assess the effect of prescribed internal structure on the mechanical performance of an additively manufactured polymer, it was necessary to select an appropriate part geometry. For simplicity of design and ease of testing, the ASTM D638 dog-bone sample was used as a standard for dimensions and design. According to this specification, samples were designed to have a length 167 mm, a width 23 mm and a height 6 mm as pictured in Figure 6. The parts were designed in SolidWorks and were printed in a 3D printer using fused deposition modelling. In order to speed up the manufacturing process and due to the size constraints of the print bed, three samples were printed at once as illustrated in Figure 6. The total amount of time needed for the printing of the 12 total samples was 5.5 hours. The nozzle temperature used in the printing process was 210°C.
While determining the overall shape and size of the samples was fairly straightforward, the main difficulty in developing the model involved creating the internal structure. Initially, an attempt was made to develop the sample without any support structures and just PLA fibers. However, the internal structure, especially for the 30% infill structure, proved difficult to hold together during the printing process, and as a solution to this problem, it was determined that walls on all sides of the sample would make the structure more stable and the results in the experimental procedure more accurate. To design the internal structure, each layer was explicitly modeled and made to consist of aligned solid sections separated by air gaps as illustrated in Figure 7. The relative thickness of the solid portions and size of the air gap was modified in order to change the overall infill percentage of the sample while preserving the external dimensions as specified by the ASTM D638 standard dimensions. Infill percentage is a measure of the solid internal volume fraction of an additively manufactured sample. While infill percentage can often be controlled as a parameter on the 3D printer, here it is controlled explicitly through the internal structure of the
solid model that includes air gaps between the PLA portions. In this work, samples with an infill of 30% and 50% by volume are compared. In order to change the infill percentage, the width of the solid portions is held the same but the spacing between each of them is changed.

"Figure 7: Individual layer view for a 50% (left panel) and 30% (right panel) infill percentage showing the aligned solid PLA sections and associated air gaps."

As pictured in Figure 8, each of the internal layers are then stacked together to form the overall sample. Each of the dog bones follow a standard design method with the top and bottom layers being solid PLA material with 100% infill while the rest of the layers follow a +α degree pattern for each of the inner layers. The reason why the dog bone has the top and bottom layer is for support during the printing process as the print bed itself cannot support the fragile nature of the inner layers. Figure 8, which shows a printed dog bone without the top layer as well as the SolidWorks model, demonstrates good agreement between the solid model and the resulting printed part.
Figure 8: Internal structure of the samples showing the layer-by-layer structure for the printed parts (left panel) and SOLIDWORKS model (right panel).

Each sample consists of a total of 10 layers and are referenced by the pitch angle $\alpha$ between layers. For example, the $\alpha = 30^\circ$ sample consists of the top layer being a 100% infill linear layer, the second layer being oriented at $30^\circ$ to the loading direction (along the length of the dog-bone), followed by a 60\(^\circ\) layer, 90\(^\circ\) layer, 120\(^\circ\) layer, and so on with a final bottom layer being exactly the same as the top layer. The samples for this research project have pitch angles of $\alpha = 30^\circ$, 45\(^\circ\), 60\(^\circ\), 90\(^\circ\), and 0\(^\circ\) with the 0\(^\circ\) sample serving as the baseline sample. The stacking order of layers for each different sample is provided in Table 1.

Table 1: Layer orientations for dog-bone samples.

<table>
<thead>
<tr>
<th>Layers</th>
<th>Pitch Angle (30)</th>
<th>Pitch Angle (45)</th>
<th>Pitch Angle (60)</th>
<th>Pitch Angle (90)</th>
<th>Pitch Angle (0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100% support</td>
<td>100% support</td>
<td>100% support</td>
<td>100% support</td>
<td>100% support</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>45</td>
<td>60</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>90</td>
<td>-30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>90</td>
<td>-45</td>
<td>0</td>
<td>-90</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>-30</td>
<td>0</td>
<td>60</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>-60</td>
<td>45</td>
<td>-30</td>
<td>90</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>-90</td>
<td>90</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>-45</td>
<td>60</td>
<td>-90</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>60</td>
<td>0</td>
<td>-30</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>100% support</td>
<td>100% support</td>
<td>100% support</td>
<td>100% support</td>
<td>100% support</td>
</tr>
</tbody>
</table>
2.2 Experimental Equipment

This research project utilizes two tensile testers, pictured in Figure 9, to obtain the stress-strain data for the 3D printed samples and measure the mechanical properties. The tensile testers that were used for these experiments were the MTS 810 and Easy Test EZ50. The MTS 810 Material Testing System has testing capabilities for low and high force static and dynamic testing. This tester can test materials ranging in strength from plastics to aluminum, composites and steel. It can accommodate standard and large size specimen and grips. In this tester a wide variety of testing can be performed such as tensile testing, high cycle fatigue, fracture mechanics and durability testing. The EZ50 offers an extensive range of features which is ideal for performing testing applications. This machine is appropriate for tensile and compression testing of different specimen that are made of different materials. The reason why two different tensile testers were used is due to the fact that the MTS 810 broke down and was too costly to repair prior to completion of this project. However, it is believed that the EZ50 offers comparable results because the strain rate is maintained at the same for both testers to ensure that the results are consistent.
2.3 Experimental Procedure

As stated above, the 3D printed samples were tested in MTS 810 tester and Easy Test EZ50 to measure the mechanical properties under tensile load. The sample was fixed in the grips of the tensile tester as shown in Figure 10 below. The tensile tester was calibrated in such a way that the data gathered from the testing would be given in terms of force measured in Newtons and displacement in millimeter (mm) until the fracture of the part. This displacement of the sample during the test was an average displacement measured by monitoring the position of the grips during the test. For each material architecture, twelve samples were tested in order to measure and quantify any experimental variability.
Figure 10: Image of one of the 30% infill samples loaded in the EZ50 tensile tester.

After the testing was performed, a force versus displacement graph could be constructed based on the data that was output from the testing machine. In order to calculate the mechanical properties of the parts that were being tested, the set of data had to be converted to stress and strain. The normal tensile stress, $\sigma$, was calculated by dividing the measured normal force applied to the sample, $N$, divided by the cross-sectional area, $A$, according to Eq. (1).
\[ \sigma = \frac{N}{A} \]  

(1)

The force is obtained directly from the output of the testing machine. The cross-sectional area over which the force was applied was obtained from the SolidWorks model of the part due to the complexity of the cross-sectional area as shown in Figure 11. As can be seen from the figure, the cross-sectional area is not just a solid layer where it can be calculated as height times width. In this case, the layers form a different type of rectangle with spaces in the middle and it is necessary to take these under consideration when calculating cross-sectional area.

![Figure 11: Cross-sectional area of the dog bone.](image)

Normal strain is a measure of the change in length of a sample normalized by the original length. Equation (2) shows the strain calculation formula where change in length, \( \Delta l \), again can be obtained from the data from the tensile tester and original length, \( l \), was found to be 167 mm based on the SOLIDWORKS model and D638 specification.

\[ \varepsilon = \frac{\Delta l}{l} \]  

(2)

After constructing the stress-strain curves from the experimental data, a number of mechanical properties were obtained. One of the most important mechanical properties of a material is
Young’s modulus, also known as the modulus of elasticity. It can be calculated using the relationship between stress and strain as shown in Equation (3) below. Young’s modulus describes the elastic properties of a material undergoing tension or compression. It is the ability of a material to withstand the changes in length when a force is being applied. Young’s modulus is only applicable for the elastic regime, when the load applied is small enough such that the part can return to its original dimension when the external force is being removed. Therefore, the elastic modulus, which is simply the ratio of stress to strain, is found by taking the initial slope the stress-strain curve as shown in Figure 12.

\[ E = \frac{\sigma}{\varepsilon} \]  

\text{(3)}

Figure 12: Example stress-strain plot obtained from a tensile test of the dog-bone samples showing the mechanical properties studied in this work.

Two other mechanical properties of interest that can be calculated for the sample are toughness and the modulus of resilience of the part. Toughness is the ability of the part to absorb energy and plastically deform without fracturing and can be calculated by taking the area under the stress-
strain curve up to the fracture point. Similarly, modulus of resiliency is the ability of the material to absorb energy up to the onset of plastic deformation. From a stress strain graph, the modulus of resiliency can be calculated by taking the area up to the yield point where elastic deformation occurs. Figure 12 illustrates these properties graphically as two different areas under the stress strain curve with the modulus of resilience being the area $A_1$ and the toughness being the combined area of $A_1 + A_2$.

Finally, the yield stress, ultimate stress, and strain at failure can all be obtained from the stress-strain curve as illustrated in Figure 12. The yield stress is the component of stress at the yield point or where the material loses its purely elastic behavior. Ultimate stress on the other hand is the maximum stress point a material can resist. All these values are important to understand the mechanical behavior of a part being tested.
CHAPTER 3: RESULTS AND CONCLUSIONS

In this chapter the results of both experimental and analytical analyses are presented and discussed. The stress-strain data for each of the samples is presented, as well as the calculated mechanical properties using the formulations provided in Chapter 2. Further, a discussion of lamination theory and how it can potentially be applied to this homopolymer structure is discussed. Finally, some potential future work is discussed, and a few ideas are given for continuing to expand the scope of this project.

3.1 Experimental Results for 50% and 30% Infill Samples

Experimental results from the tensile tests are provided in this section for the samples prepared with 50% infill and 30% infill. These properties are calculated from the data gathered during the experiments and the stress strain graphs are shown in Figure 13 and Figure 14 for 50% and 30% infill, respectively. It is important to note that these stress-strain plots represent the average stress-strain behavior for the 12 samples tested for each different pitch angle.
Figure 13: Average stress-strain plots for the 50% infill sample for pitch angles of $\alpha = 0^\circ$ (maroon curve), $\alpha = 30^\circ$ (blue curve), $\alpha = 45^\circ$ (green curve), $\alpha = 60^\circ$ (yellow curve), and $\alpha = 90^\circ$ (dark green curve).
Figure 14: Average stress-strain plots for the 30% infill sample for pitch angles of $\alpha = 0^\circ$ (maroon curve), $\alpha = 30^\circ$ (blue curve), $\alpha = 45^\circ$ (green curve), $\alpha = 60^\circ$ (yellow curve), and $\alpha = 90^\circ$ (dark green curve).

The main property of interest in this work is the elastic of Young’s modulus of the samples, but several other mechanical properties including modulus of resilience, yield strength, strain at failure, and toughness are calculated according to the equations presented in Chapter 2. Figures 15 below shows the calculated mechanical properties as a function of pitch angle for each of the two infill percentages (30% and 50%) considered in this work. As stated previously, the main objective of this work, at least initially, was to determine whether incorporating internal structure within the parts would result in improved mechanical properties compared to a case with no internal structure. The initial expectations were that the mechanical properties would be enhanced when comparing the $\alpha = 0^\circ$ sample, which is being treated as the baseline sample, compared to those with non-zero pitch angles.
Figure 15: Experimental results for the calculated values of (a) elastic modulus, (b) failure strength, (c) modulus of resilience, (d) toughness, and (e) failure strain as a function of pitch angle for 50% (blue curves) and 30% (red curves) infill.
When viewing the results presented in Figure 15, it is readily apparent that there is not an improvement in mechanical properties when incorporating a non-zero pitch angle. The observed trends from these figures are as follows:

- For the elastic modulus (Figure 15A), the highest value is observed for the baseline sample with a subsequent decrease up to $\alpha = 45^\circ$ for both infill percentages. For higher pitch angles, it is observed that the modulus starts to increase again, but never reaches the value observed for the baseline sample.

- The failure stress (Figure 15B) exhibits a very similar trend to the elastic modulus where the $\alpha = 0^\circ$ sample is able to carry the highest stress. While the failure stress decreases significantly for the $\alpha = 30^\circ$ sample, there is a slight increase in strength as the pitch angle is increased from $\alpha = 30^\circ$ to $\alpha = 90^\circ$.

- The modulus of resiliency (Figure 15C), a measure of the energy stored in the material up to the yield point, has consistent trends with failure stress and elastic modulus with a peak at $\alpha = 0^\circ$ and lower values for all non-zero pitch angles.

- The toughness is calculated by taking the area under the whole curve of the stress-strain graph. It follows a consistent trend with a peak at $0^\circ$ as shown in Figure 15D.

- Finally, the failure strain (Figure 15E) exhibits a unique trend that show some benefit of incorporating a non-zero pitch angle. In this graph the $\alpha = 0^\circ$ sample experiences the lowest strain while the $\alpha = 45^\circ$ degree the highest strain for the 50% infill samples. For the 30% infill samples, there is a more irregular pattern, however it is clear that the maximum failure strain occurs for $\alpha = 45^\circ$ and the lowest failure strain is for the $\alpha = 0^\circ$ sample.
3.2 Summary of Experimental Results

Based on the data gathered from the tensile tests and subsequent analysis, it can be concluded that incorporating underlying structure did not necessarily improve mechanical properties of the components compared to the baseline case. Rather, all of the mechanical properties measured (with the exception of the strain at failure) exhibit an initial decrease in their values from the baseline value of $\alpha = 0^\circ$ followed by an increase as the pitch angle between layers is increased up to $\alpha = 90^\circ$. The strain at failure, on the other hand, actually exhibits a maximum value for a non-zero pitch angle – indicating that this quantity can be improved by incorporating some internal structure in a part. To this effect, it appears that the primary effect of incorporating this internal structure into the samples is increased ductility at the expense of mechanical stiffness and strength. Further, when comparing the result for different infill percentages, we see that there are similar trends regardless of the infill percentage. In fact, the most notable difference between the two different sample types is that the mechanical property values are lower for the 30% infill samples compared to the 50% infill. This is to be expected as there is physically less material to support the applied loading in the 30% infill samples compared to the 50% infill samples.

Overall, these trends were a bit discouraging from the initial hypothesis as incorporating a helicoidal structure did not improve the mechanical properties. However, these results do not necessarily contradict the observed behavior of the mantis shrimp dactyl club which uses a helicoidal structure to achieve impressive mechanical response. The reason for this has to do with the loading condition used in our experiments compared to the natural system. There are examples in which these helicoidal structures have achieved better results in impact resistance. This example
includes an helicoidal structure made of carbon fiber epoxy which results in higher impact resistance than the quasi-isotropic materials used as a standard in aerospace industry (Grunenfelder et al., 2014).

Despite no improvement in mechanical strength or stiffness resulting from changing pitch angle, it is apparent from the experimental data that changing the pitch angle can be used as a means of controlling the mechanical properties of the part. In other words, without changing the amount of material used, the mechanical properties can be tuned by changing the internal structure. To this effect, it was then hypothesized that the structure that was created behaves similar to a laminate whose properties can be tuned by changing the orientations and stacking order of individual lamina. In the following section, a discussion as to whether or not these samples exhibit “laminate-like” behavior is provided.

3.3 Classical Lamination Theory and Applicability to Experimental Results

Although the initial experimental results did not show the desired improvement in mechanical properties with changing pitch angle of the internal material structure, it is evident there is a clear dependence on pitch angle for the mechanical properties measured here. In an effort to explain the observed experimental results, it was hypothesized that the material studied in this work could be treated as a composite laminate. As stated in Chapter 1, a laminate is a material composed of two or more unidirectional laminae stacked together at various orientations. Traditionally, the lamina themselves are a composite composed of unidirectional fibers (i.e. the filler phase) embedded in another host, or matrix, material. In this work, however, each “lamina” is composed of only a
single material (PLA), but the overall material still employs a layer-by-layer architecture similar to that employed in the fabrication of laminates. Therefore, it remains to be seen if the observed mechanical behavior fits into classical lamination theory that will be described in the following paragraphs.

As stated in the experimental procedures section, the main property that is being calculated for the 3D printed samples with different internal structures is the Young’s modulus. The overall Young’s modulus of a laminate can be predicted using the mechanical properties of the constituent materials and the composite lay-up – that is, the stacking order of lamina. Lamination theory is a macromechanical analysis that begins by considering the properties of each individual layer. A single orthotropic lamina subjected to a state of plane stress can be fully characterized by four independent constants – the four reduced stiffnesses \( Q_{11} \), \( Q_{12} \), \( Q_{22} \), and \( Q_{66} \) (Hyer, 2009). It should be noted that a unidirectional lamina is inherently orthotropic as it possesses three planes of material symmetry. Each of these reduced stiffnesses components depends on the principal elastic moduli, principal Poisson’s ratios, and in-plane shear modulus as shown in Eqs. (4) – (7) below.

\[
Q_{11} = \frac{E_1}{1-\nu_{12}\nu_{21}} \approx \frac{E}{1-\nu^2} \quad (4)
\]

\[
Q_{12} = \frac{E\nu_{21}}{1-\nu_{12}\nu_{21}} \approx \frac{E\nu}{1-\nu^2} \quad (5)
\]

\[
Q_{22} = \frac{E_2}{1-\nu_{12}\nu_{21}} = \frac{E}{1-\nu^2} \quad (6)
\]

\[
Q_{66} = G_{12} \approx \frac{E}{2\nu(1+\nu)} \quad (7)
\]

In the equations above, \( E_1 \) and \( E_2 \) are the elastic moduli in the 1- and 2-directions, \( \nu_{12} \) and \( \nu_{21} \) are the major and minor Poisson’s ratios, respectively, while \( G_{12} \) is the shear modulus of the
material which is calculated by taking the initial slope of the shear stress-strain curve. In Poisson’s ratio, the first subscript defines the loading direction while the second subscript defines the transverse strain direction. For example, $\nu_{12}$ is used to calculate the amount of transverse strain developed in the 2-direction for an applied loading in the 1-direction. Further, the relationship between the major and minor Poisson’s ratios is $\nu_{21} = \nu_{12}(E_2/E_1)$. For a composite lamina, these properties may either be measured directly from experiment or estimated using an appropriate micromechanical theory.

In this work, however, it is desirable to modify the reduced stiffness formulations given in Eqs. (4) – (7) to account for the fact that only a single material is being used to formulate the individual layers within the dog-bone structure. In order to make this modification, however, one must assume that each of the individual layers behaves isotopically. In other words, it is assumed that, despite the fiber-like structure formed by the solid PLA portions in each layer, the properties of each layer are the same in all-directions. For an isotropic material, the reduced stiffnesses can be modified by noting that $E_1 = E_2 = E$, $\nu_{12} = \nu_{21} = \nu$, and $G_{12} = E/2(1 + \nu)$. For PLA, the material properties are taken to be $E = 3.5$ GPa, $\nu = 0.203$, and $G_{12} = 2.4$ GPa (Igmen, 2015).

The stiffness values provided in Eqs. (4) – (7) are applicable when the material is loaded along the principal axes. However, for a laminate, each lamina is loaded at a different angle relative to its own principal axes since each layer has a unique orientation. Therefore, the stiffness values in the loading direction, will vary from one layer to another due to the fibers being oriented differently with respect to the direction of loading. Consider the $\alpha = 45^\circ$ sample that is being used in this research project. Ignoring the top and bottom layer for now, the part has eight internal layers which
all have different pitch angles with respect to the loading direction. For this particular sample, there are 4 unique orientations to consider as illustrated below in Figure 16.

![Figure 16: Illustration of the different layers in the \( \alpha = 45^\circ \) sample relative to the loading direction.](image)

For example, in the \( \alpha = 45^\circ \) sample pictured in Figure 16, each layer is rotated 45° with respect to the previous layer. Here, each of the layers will have different stiffness values in the loading direction (x-direction) due to the fiber orientation. To transform the stiffnesses to the x-y coordinate system, Eqs. (8) – (10) can be used where \( m = \cos(\theta) \) and \( n = \sin(\theta) \) and \( Q_{11}, Q_{22}, Q_{12} \) and \( Q_{66} \) are the principal reduced stiffnesses described as in Eqs. (4) – (7).

\[
Q_{xx} = m^4Q_{11} + n^4Q_{22} + 2m^2n^2Q_{12} + 4m^2n^2Q_{66} \tag{8}
\]
\[ Q_{yy} = n^4 Q_{11} + m^4 Q_{22} + 2m^2n^2 Q_{12} + 4m^2n^2 Q_{66} \]  
(9)

\[ Q_{xy} = m^2n^2 Q_{11} + m^2n^2 Q_{22} + (m^2 + n^2)Q_{12} - 4m^2n^2 Q_{66} \]  
(10)

The stiffness values calculated from Eqs. (8) – (10) are for an individual lamina. According to lamination theory, the laminate stiffness matrix can then be found by calculating three types of laminate stiffnesses according to Eqs. (11) – (13)

\[ A_{ij} = \sum_{k=1}^{n} Q^k (z_k - z_{k-1}) \]  
(11)

\[ B_{ij} = \sum_{k=1}^{n} Q^k (z_k^2 - z_{k-1}^2) \]  
(12)

\[ D_{ij} = \sum_{k=1}^{n} Q^k (z_k^3 - z_{k-1}^3) \]  
(13)

where \( Q^k \) is the stiffness of layer \( k \), \( z_k \) is \ldots, and \( z_{k-1} \) is \ldots The \( A_{ij} \) terms are extensional stiffnesses relating in-plane load to in-plane strains. The \( B_{ij} \) terms are coupling stiffnesses, relating in-plane loads to moments and curvatures to in-plane strains. The \( D_{ij} \) terms are bending laminate stiffnesses relating moments to curvatures (Daniel & Ishai, 2006). For each of these terms, the indices \( i \) and \( j \) can take on values of \( x \), \( y \), and \( s \), resulting in nine components for each type of stiffness. By arranging these in matrix form, the stiffness matrices \([A]\), \([B]\) and \([D]\) are created and they are functions of the geometry, constituent material properties, and stacking sequence of each individual ply. The overall stiffness matrix for the laminate is a 6x6 matrix that is found by arranging the \([A]\), \([B]\) and \([D]\) matrices as shown in Eq. (14).
This stiffness matrix relates the load applied to the laminate to the strain and curvature developed in the laminate and can be used to find the engineering properties of the laminate. However, it is more convenient to deal with compliances when trying to calculate mechanical properties as it leads to more straight-forward analytical expressions. The laminate compliance matrix is found by taking the inverse of the laminate stiffness matrix as shown in Eq. (15):

\[
\begin{bmatrix}
N_x \\
N_y \\
N_s \\
M_x \\
M_y \\
M_s
\end{bmatrix} =
\begin{bmatrix}
A_{xx} A_{xy} A_{xs} B_{sx} B_{xy} B_{xs} \\
A_{yx} A_{yy} A_{ys} B_{yx} B_{yy} B_{ys} \\
A_{sx} A_{sy} A_{ss} B_{sx} B_{sy} B_{ss} \\
B_{xx} B_{xy} B_{xs} D_{xx} D_{xy} D_{xs} \\
B_{yx} B_{yy} B_{ys} D_{yx} D_{yy} D_{ys} \\
B_{sx} B_{sy} B_{ss} D_{sx} D_{sy} D_{ss}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_s \\
\kappa_x \\
\kappa_y \\
\kappa_s
\end{bmatrix} = [a] \begin{bmatrix}
N_x \\
N_y \\
N_s
\end{bmatrix}
\]

where \([a] = [A]^{-1}\).

Having all the components of the laminate compliance matrix, the only term needed for the calculation of Young’s modulus is only the first term of the \([a]\) matrix which will be \(a_{xx}\). Finally, Young’s modulus in the x-direction (i.e. the loading direction) is calculated by Eq (16).

\[
E_x = \frac{1}{\frac{1}{h} a_{xx}}
\]

Using the previously described lamination theory, an attempt was made to fit this analytical model to the experimental data to determine if laminate-like behavior could be imparted through underlying structure into a sample composed a single material. In attempting to fit the analytical model to the experimental data, the following assumptions were made...
1. The elastic modulus was assumed to be the same in the 1-direction and 2-direction. In other words, \( E_1 = E_2 = E \). The elastic modulus value used for PLA was \( E = 3.5 \text{ MPa} \).

2. The elastic modulus value is the same for all layers (Igem, 2015).

3. The major and minor Poisson’s ratio are assumed to be the same for this structure such that \( \nu_{12} = \nu_{21} = \nu \). The value used here is \( \nu = 0.203 \) (Igem 2015).

With these assumptions in mind, a comparison between the analytical model and experimental data is provide in Figures 17 and 18. Comparing the blue curve (experimental data) and green curve (analytical model), it is clear that there is a similar trend between the experimental data and the predicted values from lamination theory for both the 30% and 50% infill cases. However, the values do not agree in terms of their numerical magnitude.

![Figure 17: Comparison of elastic modulus predicted from classical lamination theory (yellow and red curves) to the experimental data (blue curve) for 50% infill samples.](image)
Figure 18: Comparison of elastic modulus predicted from classical lamination theory (yellow and red curves) to the experimental data (blue curve) for 30% infill samples.

After observing these trends, it was determined that an additional assumption was needed. Initially, the top and bottom layers were not treated any differently than the internal layers. However, it is clear from the printed parts and the solid, that the top and bottom layers are inherently different and most likely stronger/stiffer than the internal layers due to their being completely solid (i.e. 100% infill). Therefore, in order to refine our analytical model, the second assumption is changed to be that the principal mechanical properties are be different in the first and last layer compared to the middle layers. To account for this difference the following correction was made:

- The top and bottom layers are treated as isotropic layers with $E_1 = E_2 = E = 3.5$ MPa
• The middle layers are still assumed to have $E_1 = E_2$, but are assumed to have a reduced elastic modulus compared to the top and bottom. The elastic is reduced based on the infill percentage of those layers in accordance with the rule of mixtures for composites.

Using these assumptions, the middle layers for the 50% infill sample are given a value of $E_{50} = 1.75$ MPa and the middle layers for the 30% infill sample are given a value of $E_{30} = 1.05$ MPa. Looking back at Figure XX and comparing the blue curve (experimental data) and orange curve (refined analytical model), it is clear that there is much better agreement between the experiment and theory. This provides significant preliminary evidence that the sample with a prescribed internal structure exhibits laminate-like behavior, and further, that these properties can be predicted according to lamination theory with a few minor assumptions regarding the principal engineering constants.

3.4 Conclusions

In this work, dog-bone samples were designed with a prescribed internal structure inspired by the mantis shrimp. This internal structure, created using a layer-by-layer approach with each layer rotated by a certain angle compared to the layer below it, was initially hypothesized as a mechanism to improve the mechanical properties of the component. After performing standard tensile tests on the sample, it became apparent that the mechanical properties did not improve when incorporating the helicoidal structure. Aside from resulting in increased ductility of the material, changing the relative pitch angle between layers served to decrease both the strength and toughness of the material for in-plane loading of the layer-by-layer structure. These relative trends held for multiple infill percentages (30% and 50%) and indicate that this helicoidal architecture is not effective for improving in-plane mechanical properties.
However, based on these initial experimental observations, it is apparent that changing the pitch angle between adjacent layers is an effective mechanism for changing the overall mechanical properties of the composite. Mechanical properties, such as elastic modulus, ultimate strength, and toughness, have been shown to be changed by up to a factor of two to three just by changing the relative organization of material within the polymer component. This is an incredibly useful finding as it demonstrates that prescribing internal structure to an additively manufactured component is an effective way of tuning the overall mechanical behavior. Without any internal structure, the mechanical properties of the component can only be changed by changing the constituent material or printing parameters. Instead, this work shows that intentionality in the internal structure – something that had previously been simply a consequence of the additive manufacturing tool pathing – can be used an effective means to tune the mechanical properties of a part without changing the type or amount of material. Although outside the scope of this work, it is hypothesized that prescribed internal structure could also be utilized in this capacity to tune the effective thermal or electrical properties of the additively manufactured components.

Going a step further, this work also demonstrates that for this particular helicoidal architecture, classical lamination theory can be adapted to predict the resulting mechanical performance of the component. When comparing the experimentally measured mechanical properties to the predicted values from lamination theory, it is clear that there is a good agreement in the overall trends and numerical values between the two approaches. Further, the results from this work demonstrate the potential for using additive manufacturing and a single material to create a structure that exhibits laminate-like behavior. While the traditional approach to laminate manufacturing and utilization of two materials still has some advantages over using a single
material, the results shown here are a promising first step towards increased adoption of matrix-free laminates.

3.5 Future Work

Although this work has provided valuable insight into matrix-free laminates and additive manufacturing, there are still several open research questions and opportunities to continue this work. First and foremost, it will be important to determine whether or not this fabrication method and prescribed internal structure can be captured using other materials. Other polymers, such as nylon or polyethylene terephthalate (PETG), which have different properties compared to PLA, would be interesting to consider and already have been shown to be capable of manufactured using 3D printing techniques. Metals have more recently been used as materials in additive manufacturing and would also be a good candidate to create components with internal structure. However, it remains an open question as to how feasible it would be to create such an intricate structure using metals.

Another potential area of future work would involve considering alternative loading mechanisms for the previously considered layer-by-layer structure. The samples in this work only considered in-plane tensile loading for the structure, but as previously discussed, it is believed that the true benefit of this underlying structure may only be relieved through alternative loading mechanisms. Some types of loading that could be considered are in-plane compression, out-of-plane tension and compression and impact loading. These different types of mechanical tests could be used to assess the overall mechanical performance of this structure and potentially provide evidence that the structure can be used to improve mechanical performance for different types of
loading. For these different types of mechanical tests, a similar parametric study approach could be taken where the effect of pitch angle and infill percentage on mechanical properties are assessed.

The results of this work have shown that the in-plane elastic modulus can be predicted using a modified version of classical lamination theory. However, there is significant opportunity to further validate this laminate-like behavior and demonstrate even better agreement between this theory and the experimental results. To further validate the applicability of classical lamination theory to these samples, several samples with arbitrary layer orientations can be fabricated, tested, and then assessed to determine if their measure mechanical properties, match those predicted by the theory. Additional agreement between the theory and a wider range of samples will only serve to enhance the conclusions from this work.

Finally, it would be important to consider the effect of other types of internal structure designs and determine how they can be used to determine mechanical properties. In this work, the internal structure was restricted to aligned solid sections of material that replicated natural fibers in the mantis shrimp dactyl club or synthetic fibers in laminates. However, there are many other well-known geometric patterns such as waves, swirls, lattices, etc. that could offer potential improves to mechanical performance. Establishing a framework for how each specific internal structure, or equivalently the 3D printing pattern, influences mechanical behavior would be incredibly important to engineers in developing future designs.
REFERENCES


