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The use of lattice structures in creating additively manufactured rib fracture implants

CHRISTINE GABRIELE
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Reviewed and approved* by the following:

Guhaprasanna Manogharan
Professor of Mechanical Engineering
Thesis Supervisor

Daniel Cortes
Professor of Mechanical Engineering
Honors Advisor

* Electronic approvals are on file.

ABSTRACT

Recent advances in technology have allowed for expansion in the inclusion of patient-specific medical solutions for injuries and diseases. Specifically, this paper aims to explore the possibilities for improving the patient experience with regard to creating more highly functional rib fracture implants. Using additive manufacturing, topologically optimized lattice structures can be printed specific to a patient's autonomy, allowing for reduction of typical implant-induced complications, specifically stress shielding due to uneven loading on the rib and neighboring implant.

In this paper, the effect on the strength and flexibility of rib fracture coupons based on variance in x-direction unit cell length and strut thickness and their resulting effect on porosity is explored. Five lattices were tested with differing properties. The results found indicated that increased porosity can improve mechanical properties of implants and better reflect the mechanical properties of a native human bones. The findings of the study were then compared with other similar studies and similarities and differences are analyzed. The studies found that the results of the experiment were verified based on similar load testing. As research on this topic evolves, more understanding of how the mechanical properties of lattices change based on varying geometries is evaluated.

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Chapter 1

Introduction

1.1 Problem Statement

Creating rib fracture implants from additively manufactured lattice-based titanium has the potential to better mirror the strength and flexibility of a native human rib than traditional implants. In this thesis, the experimental mechanical properties of these additively manufactured lattice structures are compared with simulated behavior and analyzed based the resulting values.

1.2 Motivation

Advances within the medical industry in the past century have improved the quality of patient life exponentially. New technologies, including additive manufacturing, have been introduced in many areas within the health sector, from 3-D printed organs to highly precise surgical tools. Patient-specific solutions to medical issues are a natural progression as the medical industry evolves. Thus, using additively manufactured fracture implants that can be varied based on patient anatomy is an area of advance that should be researched and considered carefully in the forthcoming years. Developing fracture implants that can be customized to fit each specific patient based on their individual anatomy has the potential to become the future of medical practices in multiple areas of interest.

Chapter 2

Literature Review

2.1 Discussion of Rib Fracture Injuries

Chest injuries are a commonality of many traumatic hospitalizations, with rib fractures often serving as the source of this trauma [1]. Around 25% of traumatic deaths occur as a result of chest trauma, and 10% of traumatic hospitalizations occur as a result of rib fractures [2]. Experiencing a rib fracture not only increases one's risk of mortality, but also the risk of other complications such as persistent lung problems and secondary pulmonic incompetence.

Additionally, rib fractures are more typical among older patients; the average age of injury occurs at about 47 years old [3]. Of patients over the age of 60 who died due to chest trauma, 55% sustained only rib fracture injuries as a cause of their death [3]. For patients over the age of 65, the mortality rate due to sustaining 2 or more rib fractures can increase by as much as 500% as compared to younger patients [4]. These numbers are indicative of the importance of improving the patient experience with regard to surgical stabilization of rib fractures (SSRF).

2.1.1 Rib Fracture Recovery

For trauma patients experiencing rib fractures, SSRF is imperative for total recovery. Benefits of SSRF include the reduction of risks such as permanent rib failure, pneumonia, lasting pulmonic disabilities, and even mortality [5]. SSRF can also decrease the length of patient hospital stays. Traditionally, SSRF consists of a chest scan to detect the area of injury, followed by a large surgical incision made near the patient’s injury.

In typical rib stabilization surgical procedures, a rib implant is shaped by the doctors to model the patient’s rib curvature, and then fixed to the rib with plates and screws [5]. This process is extremely invasive, and patients often experience lengthy recovery times due to the depth and size of the incision required for the surgery. The implant is pre-contoured before surgery, and the majority of the implants are pure or alloyed titanium. Titanium offers the fixation plate strength and flexibility. However, extensive bending of a titanium fracture may weaken and eventually cause failure of the implant [6].

Figure 1 illustrates the typical composition of a rib fracture implant. Circular pieces of metal are welded together, and a hole is left in the middle for screw insertion. This original implant is pre-contoured before surgery based on the patient’s anatomy, as detected during their computerized topography (CT) scan [7]. The plate is fixed to the rib with screws, while the areas above the fracture itself are left screwless. The implant is designed to remain in the patient’s body for the remainder of their life, but it is relatively atypical for patients to experience much discomfort a year or more past the date of the surgical procedure [8].

Figure 1. Image of a traditional rib fracture implant [5].

2.1.2 Areas for Improvement

Improvements for this process exist specifically regarding the modeling of the implant to the patient's rib structure. Traditional implants often do not sufficiently model the human rib's strength and flexibility [6]. As formerly mentioned, while implants are capable of somewhat encompassing properties of the human bone, these qualities do not mirror the simultaneous strength and flexibility of the human rib. These implants are subject to load failure if bent too often or contoured too severely. Suggestions for improvements to traditional implants include the use of additively manufactured (AM) titanium lattice structures to create rib implants that model the patient's rib structure before surgery [9].

2.2 Discussion of Lattice Structures

Lattice structures are 3-dimensional topologically ordered structures that can only be produced through the use of additive manufacturing [10]. These structures consist of repeating strut element patterns that connect at the nodes of the design [11]. A visual representation of some typical strut element patterns in lattice structures ca be viewed in Figure 2. Due to their unique makeup, lattice structures have high porosities while remaining very strong and flexible. These features are very popular in many industrial fields because they allow for structures to maintain their strength and present as lightweight. Lattice structures are also cost-effective, as they require less material for their composition than a typical solid structure [10].

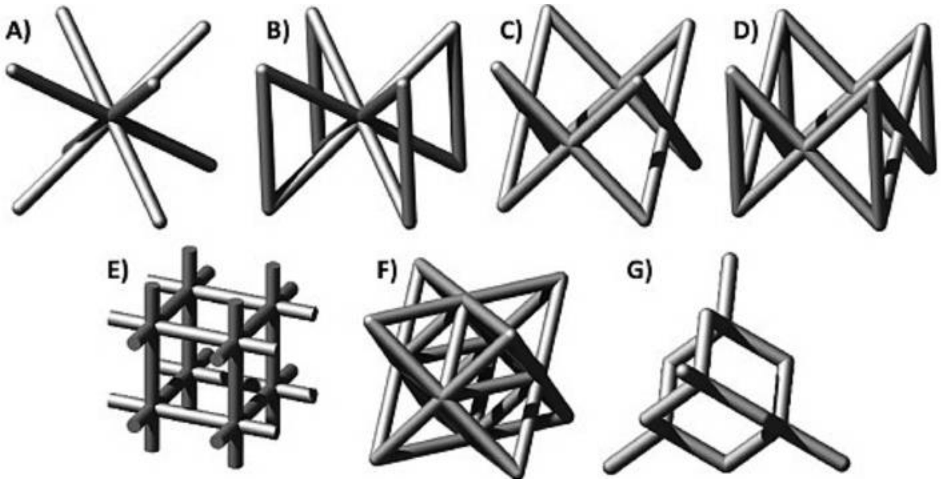


Figure 2. Examples of different types of struts that make up lattice structures [10]. A full lattice structure consists of repeating struts connected at the lattice nodes.

Human bones- especially human ribs- are simultaneously strong and flexible, a quality that is hard to replicate using non-living materials. The ability of lattice structures to recreate these qualities, then, is extremely useful in the creation of biomedical implants. Titanium is a commonly used biomaterial in human bone implants because of its strength, ductility, resistance to rusting, and fracture toughness [12], [13]. However, titanium is extremely rigid, meaning that it cannot properly replicate the flexibility of a typical human bone alone. Using lattice structures in titanium bone implants allows for a change in the limiting mechanical stiffness properties of titanium; the positive properties of titanium implants are retained while increasing the implant’s flexibility.

In a study conducted by scientists at the Melbourne school of engineering, it was determined that creating bone implants using titanium lattice structures had highly commendable results. In this study, the scientists found that the compressive strength of the implant was as high as 55 MPa, while the modulus of elasticity remained as a lower value 1.05 GPa [12]. These numbers are indicative of the possibilities for improvement in rib fracture implants through the use of titanium lattice structures.

2.2.1 The Body-Centered Cubic Unit Cell

The use of metals in orthopedic implants has been traditionally successful due to the desirable mechanical properties that they possess [14]. However, specification towards the uniqueness of each patient's bone structure is a necessary development within the surgical fracture fixation process that cannot be implemented using conventional mass-produced implants. A solution to this problem is the use of additively manufactured bone implants that can be printed based on each individual patient's orthopedic anatomy. Other benefits of the use of AM in these implants includes increased levels of porosity through the use of lattice structures. Increased porosity through lattice structures allows for a lightweight resulting product that retains beneficial metal mechanical properties. The benefits of using additive manufacturing to create lattice structures in bone implants are widely commended, but literature regarding experimental results from these procedures is relatively limited compared to the discussed potential of the technology [15].

When creating a lattice structure, many cell types can be used, including but not limited to cubic, gyroidal, and hexagonal [16]. The type of lattice chosen caused a variation in properties such as ductility, malleability, and deformability, which can affect the local strength and load failure of the resulting structure.

The body-centered cubic (BCC) unit cell is one of the more widely used lattice designs due to its simplicity and self-supporting structure [17]. The BCC unit cell includes no horizontal members, optimizing strut-based topology, which is more suitable for accurately predicting mechanical properties. It has been shown experimentally and computationally in previous studies that the BCC structure has the lowest stiffness of most commonly studied unit cell types due to the lack of struts aligned with the loading direction, suggesting the potential for fixation applications requiring increased flexibility [18]. Therefore, the lattices designed and analyzed in the contents of the following paper consist of a repeating BCC unit cell across the length of a metal coupon.

2.2.2 Closed Versus Open-Cell Geometries

Research conducted by Vigliotti et al. concluded that, in general, BCC lattices had higher levels of yield strength and bucking strength when compared with both cubic and FCC lattices [19]. In this research, the BCC lattice was classified as a stretching-dominated lattice due to its closed geometry, meaning that when presented with a macroscopic load, the lattice will stretch. In contrast, bending-dominated lattices flex under loading conditions, which correlates with lower stiffness levels and describe the behavior of open-cell BCC lattices. The classification of bending or stretching dominated behavior can be calculated using the equation below [20].

$$M = s - 3n + 6$$

where the values M, s, and n listed represent the Maxwell number, the number of struts, and the number of nodes within the unit cell respectively. Maxwell numbers less than zero represent bending-dominated behavior, while the opposite is true of a Maxwell number greater than zero. The Maxwell number of an open-cell BCC lattice is -13, which results from *s* and *n* values of 8 and 9, respectively [21]. However, the research conducted by Vigliotti et al. used different from *s* and *n* values according to the study being done in consideration with a closed-cell lattice, where the added walls elicit stretching-dominated responses that exhibit increased stiffness and increased strength. The overall conclusion from this research in consideration with closed versus open-cell lattices are that BCC unit cells show higher levels of strength overall when compared to other lattices, and that focusing on open-cell BCC lattices rather than closed-cell lattices has potential to reduce their stiffness and still include their increased strength, a desirable quality for implants [19].

2.3 Additive Manufacturing

Additive manufacturing offers the ability to produce components with internal porosity achieved via lattice structures without changing the external geometry. Thus, it is possible for additively manufactured parts to have mechanical properties that vary as a function of length via gradient lattice structures [22]. This enables the generation of lattice structures for bone implant applications which demonstrate properties comparable to trabecular bone. Additionally, the highly fine-tunable nature of AM lends itself to patient-specific design applications such as rib fixation, considering rib shape varies between patients depending on gender, age, and bone quality [2].

2.3.1 Binder Jetting

Binder jetting is a common additive manufacturing technique that utilizes liquid binders in order to create a final product [23]. In the binder jet printing process, powdered materials such as metals, sand, ceramics, or polymers, are deposited onto a build platform. Subsequently, an inkjet nozzle passes over the build platform while selectively dispensing the binding liquid over the powdered material. This procedure creates a two-dimensional pattern for the given layer. Once a layer has been completed, the build platform descends. The entire process repeats itself until a final three-dimensional product is formed layer-by-layer [24]. The final product is typically referred to as the ‘green part’, and the powdered materials that are not part of the final product are typically recycled to be used in the binder jetting process again [25].

Depending on the material used, binder jetting typically requires some post-processing. A material such as sand will often require little to no after-treatments. Metals and ceramics, on the other hand, require curing and sintering after the binder jetting process in order to restore the final product to an acceptable density level. Additionally, final parts can be permeated with other materials in order to achieve a desired material composition [24].

Powder composition is an important consideration in binder jetting. Fine powders possess the ability to flow in a liquid-like formation, which contributes to the success of the BJ additive manufacturing process. However, the composition of powders is much less predictable as the particles are not homogenous and often have varying levels of surface roughness. The characteristics of the powders used, therefore, must be considered when the final product goes through post-processing [26].

In the additive manufacturing industry, binder jetting is notable for its inexpensive and relatively prompt material production. Additionally, large-scale structures can be created as long as a larger build platform is present. Binder jetting does not employ heat during the build process, which eliminates the buildup of residual stresses. As the need for additively manufactured parts increases, binder jetting proves to be a widely utilized AM process due to its versatility and relatively low-cost printing process [24].

2.3.2 Directed Energy Deposition

Often referred to as metal deposition, directed energy deposition (DED) is an additive manufacturing technique that utilizes a source of energy, such as a laser, electronic beam, or plasma arc, to melt powdered or wired materials and deposit them onto a build platform layer-by-layer [23]. Typical materials used in this process can include polymers and ceramics, but it is most popularly used with metals. The energy source is focused on a nozzle containing the build material in wired or powdered form, which is in turn heated and deposited in a deliberate position on a build platform. Most often in this process, the nozzle is mobile and build to pivot in many directions while the build platform remains in place. In some instances, multiple nozzles can be utilized in order to incorporate build materials of different compositions [27].

Directed energy deposition is most often used to repair materials in correlation with other manufacturing techniques, including Computer Numerical Control (CNC) machining. Because DED does not require a flat build plate or platform, the process can be utilized on curved or non-linear surfaces, offering an advantage for adding to or repairing materials. DED is commendable for being highly precise in small areas, as the computer-controlled nozzle can navigate accurately with small space for error [28].

The decision of what type of material to use for DED- powdered or wired- depends on the desired outcome for the material properties of the product. Some material that is not fully melted in the build process can become lost in DED. Second to powder bed fusion, directed energy deposition is one of the most commonly used additive manufacturing techniques due to the tradeoff it offers between accuracy and rapid production [29]. It is most commonly used for repair and rapid prototyping, but its popularity continues to evolve with changing technologies.

2.3.3 Material Extrusion

Material extrusion serves as one of the cheapest and most readily accessible forms of additive manufacturing present on the market today [30]. In the material extrusion process, a material is inserted into a heated nozzle and deposited onto a build platform. Typically, the nozzle is permitted to move in the horizontal direction while the platform moves vertically, allowing for the layer-by-layer additive process to commence [23]. Material extrusion most typically utilizes thermoplastics and composite materials, making it desirable for small-scale prototype prints and other simple plastic products [31].

Due to the relatively inexpensive material extrusion process, this additive manufacturing technique has become accessible to hobbyists and households, increasing the accessibility of 3D-printing to an average consumer [30]. Material extrusion is desirable for plastic products. This additive manufacturing technique is limited to a circular nozzle shape based on the constant pressure that must be applied to the material going through the nozzle. Not particularly accurate or rapid when compared to other additive manufacturing techniques, material extrusion is most desired for its inexpensive and simple build process [31].

2.3.4 Powder Bed Fusion

Powder bed fusion (PBF) is one of the most widely used additive manufacturing methods within advanced engineering [32]. Similar to directed energy deposition, powder bed fusion utilizes an energy source such as a laser (L-PBF) or electron beam (E-PBF) to melt a powdered material, typically (but not limited to) metal, on a build platform. In the powder bed fusion process, a layer of powder is deposited onto the build platform and is selectively melted by an energy source. The build platform then descends, and another layer of powder is spread out as the process repeats itself until the final product is completed [23].

Powder bed fusion is a popular additive manufacturing technique because it offers higher-quality surface finish when compared with other commonly used AM processes [32]. In PBF, the density of the final part achieved can be comparable to the solid metal used due to the lack of sacrificial bonders used in the process. Additionally, powder that is not melted in the build process often serves as support structures for consecutive build layers, limiting the need for additional support structures [33].

The overall surface finish of a product produced through powder bed fusion is of higher quality than one made through DED; however, powder bed fusion is a relatively expensive form of additive manufacturing and thus is not accessible to all AM needs [29]. Powder bed fusion will typically desire post-processing to ensure all excess powder is removed. In the case of metal materials made through PBF, heat treatment is typically used to diminish undesired internal stresses that may have formed throughout the build process [32].

2.4 Other Research

2.4.1 The Bone Biocompatibility of Titanium

First defined by research conducted by Professor Per-Ingvar Brånemark, osseointegration describes the process of metal fixture to bone in which only bone tissue grows around the implant, better securing the native bone tissue to the implant and thus minimizing post-surgical complications [34]. In order to reduce the possibility of other non-bone tissue interfering with the recovery process, the choosing the most biocompatible material for osseointegration is desirable.

In the past fifty years, metals have been replaced with polymers and ceramics in medical devices due to the high levels of biocompatibility and biofunctionality, a quality that metals do not contain [35]. However, in the case of bone implants, the end goal is to reduce stress shielding, which is better achieved through the use of metals. Stress shielding occurs when a metal implant, which is both stronger and stiffer than the native human bone, bears more load than the bone itself. In accordance with Wolff's Law, the bone will adapt to this decrease in load bearing and therefore increase its porosity or decrease its density, ultimately resulting in a weaker bone [36]. Titanium and titanium alloys are considered the most biocompatible metals when discussing bone implants due to their retainment of the strength of a metal combined with relatively low stiffness.

Titanium and its alloys are additionally averse to corrosion over time, which is desirable especially in implants designed to remain in the human body for the remainder of the patient's life, which is the typical use of an implant [37]. Additionally, the specific strength offered by titanium and other metals is closer to the strength of human bones than that of ceramics and polymers. Additionally, titanium is less metallic than other implants, meaning its effect on magnetic resonance imaging (MRI) is lower than other metals and thus more desirable for patient use [38].

2.5 Past Thesis Work

The research explored is this thesis delves off of accompanying research done by a team at the Pennsylvania State University and the University of Pennsylvania [39]. This team designed and 3D printed five sawbones models using powder bed fusion technology. These models were designed in the program nToplogy as unit-length gradient lattices that varied in strut thickness, unit cell length, and porosity by percentage. These varying properties can be observed in Table 1.

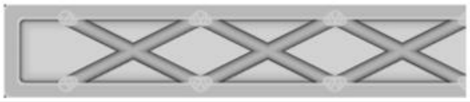
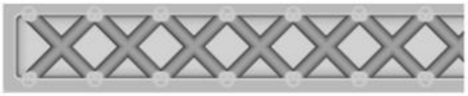
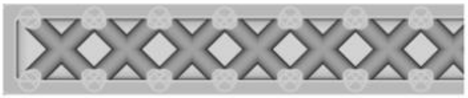
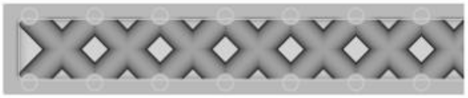
Label	Lattice cross section	Strut thickness (mm)	x-direction unit cell length (mm)	Porosity (%)
$S_{225}L_3$		0.225	3	86
$S_{225}L_2$		0.225	2	84
$S_{225}L_1$		0.225	1	78
$S_{325}L_1$		0.325	1	58
$S_{425}L_1$		0.425	1	36

Table 1. List of lattices [39].

The team conducted four-point bending testing on each coupon to failure and analyzed the resulting mechanical properties of the varying lattices in an attempt to determine the effect of strut thickness and unit cell length on the stiffness and strength of the coupon. The team placed a 1.1 kN/14 Nm load/torque on the cell at a displacement rate of 1.3mm/min. The four-point testing was chosen due to the typical bending stresses undergone by traditional rib implants. The process used can be visually observed in Figure X.

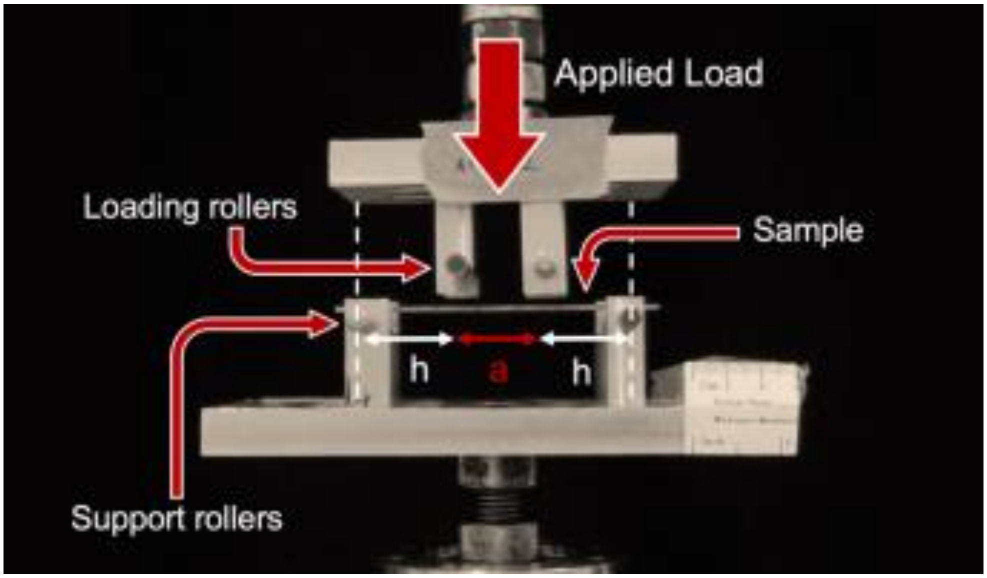


Figure 3. Four-point bending conducted on latticed coupons. “a” represents a center span distance of 25 mm while “h” represents a loading span distance of 25 mm.

Through testing 40 different coupons, the team discovered that variations in strut thickness of the lattice had a higher impact on the material properties of the lattice than variations in unit cell length. This result was on par with the team’s hypothesis, which suggested that the aspect that had a larger impact on the porosity of the coupon would thus have a larger impact on its mechanical properties.

The results showed that as strut thickness increased from 0.225mm to 0.425mm and cell length decreased from 3mm to 1mm, mean bending stiffness, strength, proof load, and toughness increased by measurable factors. The increase in strut thickness specifically caused an increase from 2946.6 ± 194.8 N*mm to 3338.4 ± 190.3 N*mm and from d from 235.7 ± 15.6 N to 267.1 ± 15.2 N in bending strength and proof load, respectively. It was determined that changes in properties resulting from differing unit cell lengths were negligible.

The team also analyzed the differences in properties for heat-treated and non-heat-treated samples, which showed that heat treated samples experienced a significant increase in men bending stiffness, mean proof load, mean bending strength, max load, and toughness.

The research discussed in this thesis examines the team's hypothesis that strut thickness has a larger impact on the mechanical properties of the tested coupon than changes in unit cell length. In this thesis, the experimental results obtained are compared with simulated results using the topology optimization technology nTopology.

Chapter 2

Materials and Methodology

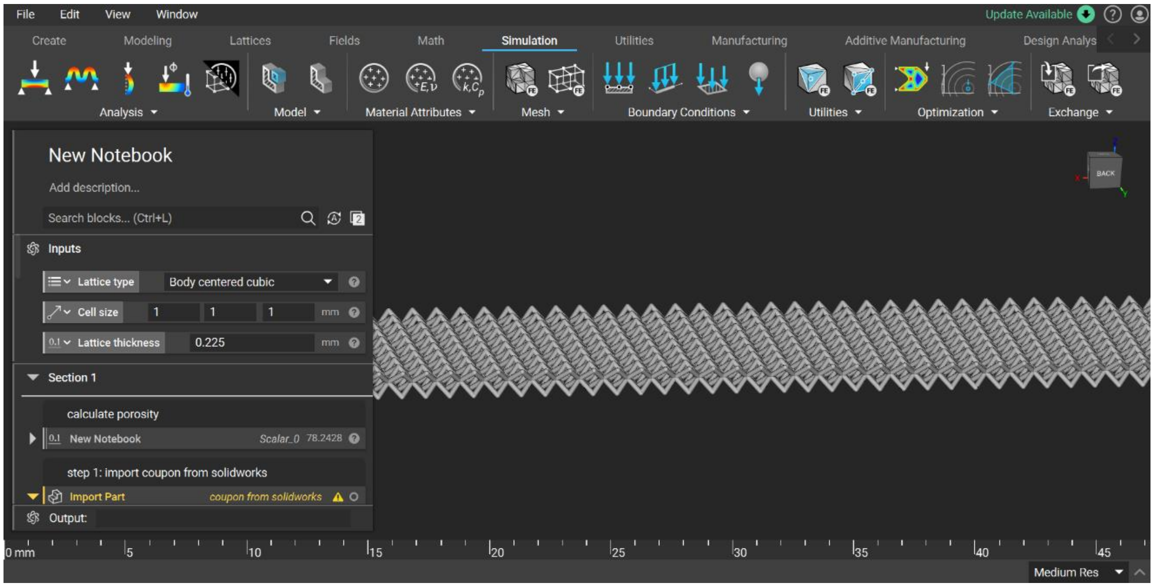
3.1 The use of nTopology

The coupons designed and tested in the previous research were created in the topology optimization software called nTopology. nTopology is an advanced engineering software that allows for complex simulations and modeling based on a technology that employs both computer and graphics processing units (CPU and GPU, respectively) [40]. Typically commended for its ability to predict and design topologically optimized parts and structures, this technology was utilized specifically because of the lattices employed in the design.

This thesis aims to test the lattices generated in nToplogy and compare the mechanical properties predicted by the simulation to the physical properties found in experimental testing of each latticed coupon. nTopology is a relatively new form of software in CAD design, and therefore simulation results based on its computer processing are not typically considered acceptable for the scholarly field. However, as this technology continues to evolve it has high potential for becoming one of the most commonly used and referenced design software, specifically in cases that employ latticed structures and limitless topology optimization.

3.2 The Generation of the Design Coupons

Each coupon used in the design process was created as a flat plate with dimensions of 100 x 10 x 1.5 mm with varying strut thicknesses and unit cell lengths. These dimensions were used due to the typical dimensions of a modern rib fracture fixation plate. The material used was Ti-6Al-4V, a typical implant material choice. A solid coupon was created and designed in the CAD software SolidWorks, then imported to nTopology. Once in nTopology, the desired lattice was added the coupon and varied based on the desired cell lengths and strut thicknesses. Five final lattices were generated with a thickness of one unit cell and can be viewed in Figures 5, 6, 7, and 8.



New Notebook

Add description...

Inputs

Lattice type: Body centered cubic

Cell size: 1 1 1 mm

Lattice thickness: 0.225 mm

Section 1

calculate porosity

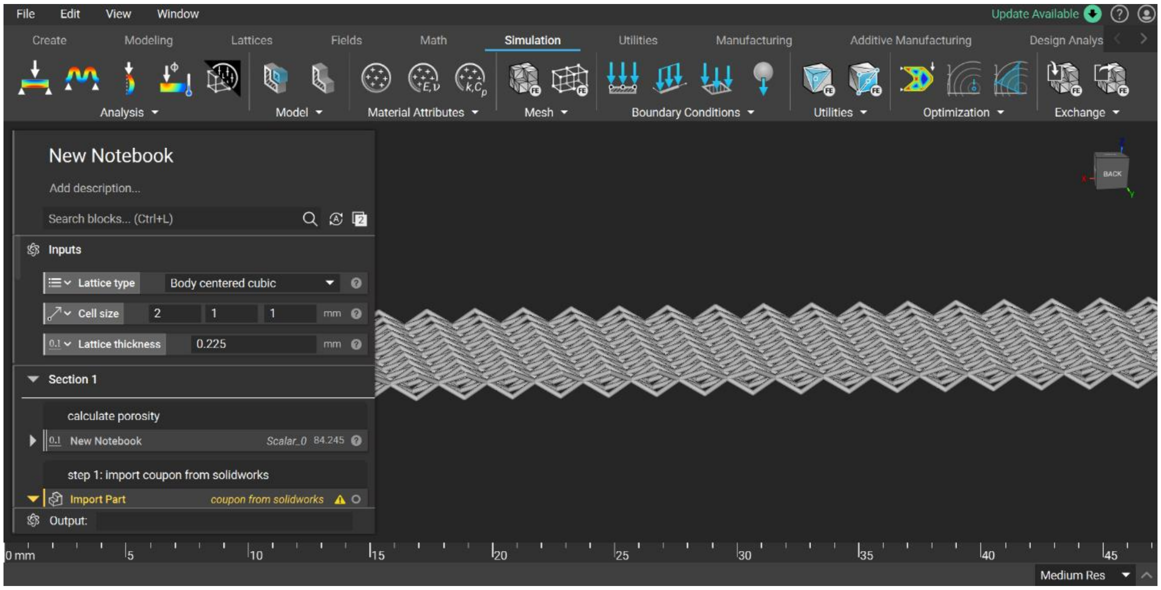
New Notebook Scalar_0 78.2428

step 1: import coupon from solidworks

Import Part coupon from solidworks

Output:

Figure 4. Lattice with x-direction unit cell length of 1 mm and strut thickness of 0.225 mm



New Notebook

Add description...

Inputs

Lattice type: Body centered cubic

Cell size: 2 1 1 mm

Lattice thickness: 0.225 mm

Section 1

calculate porosity

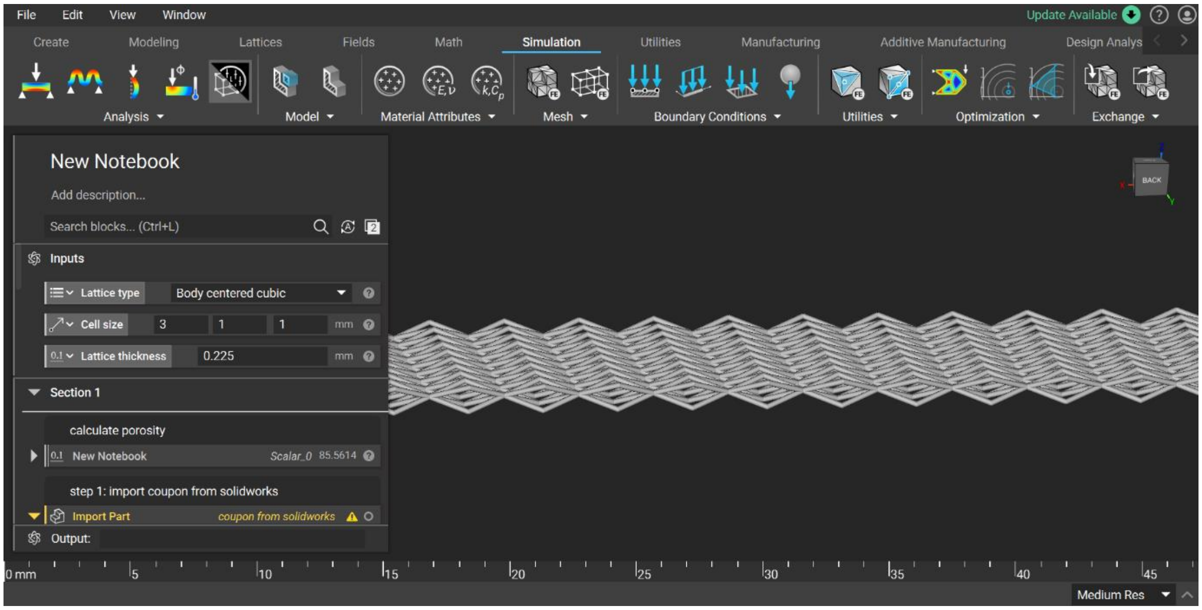
New Notebook Scalar_0 84.245

step 1: import coupon from solidworks

Import Part coupon from solidworks

Output:

Figure 5. Lattice with x-direction unit cell length of 2 mm and strut thickness of 0.225 mm



New Notebook

Add description...

Inputs

Lattice type: Body centered cubic

Cell size: 3 1 1 mm

Lattice thickness: 0.225 mm

Section 1

calculate porosity

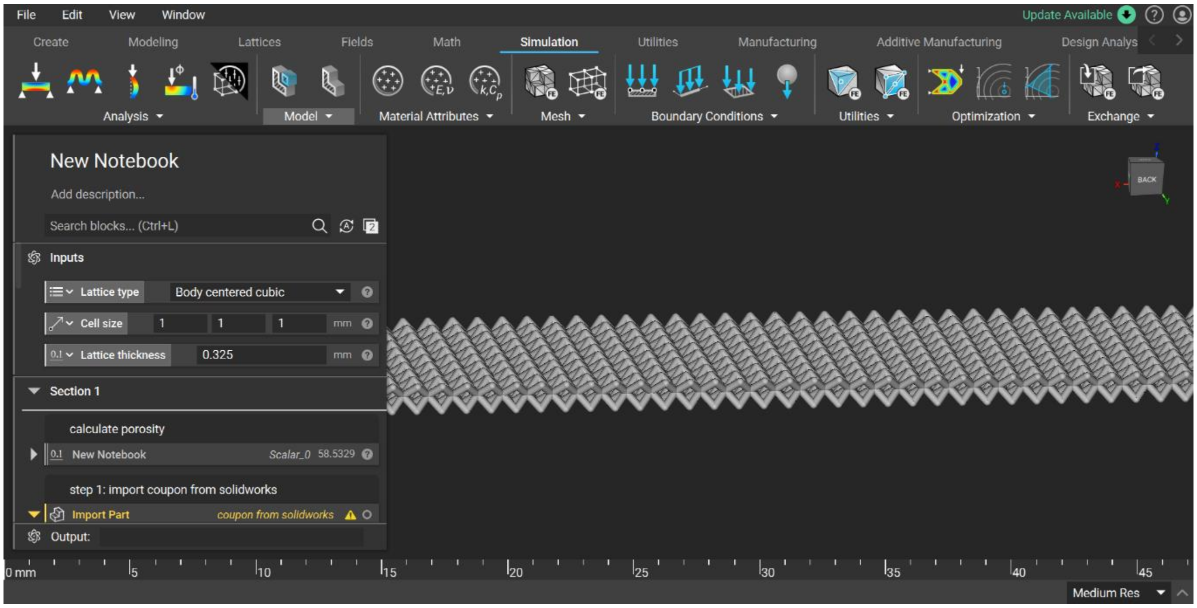
New Notebook Scalar_0 85.5614

step 1: import coupon from solidworks

Import Part coupon from solidworks

Output:

Figure 6. Lattice with x-direction unit cell length of 3 mm and strut thickness of 0.225 mm



New Notebook

Add description...

Inputs

Lattice type: Body centered cubic

Cell size: 1 1 1 mm

Lattice thickness: 0.325 mm

Section 1

calculate porosity

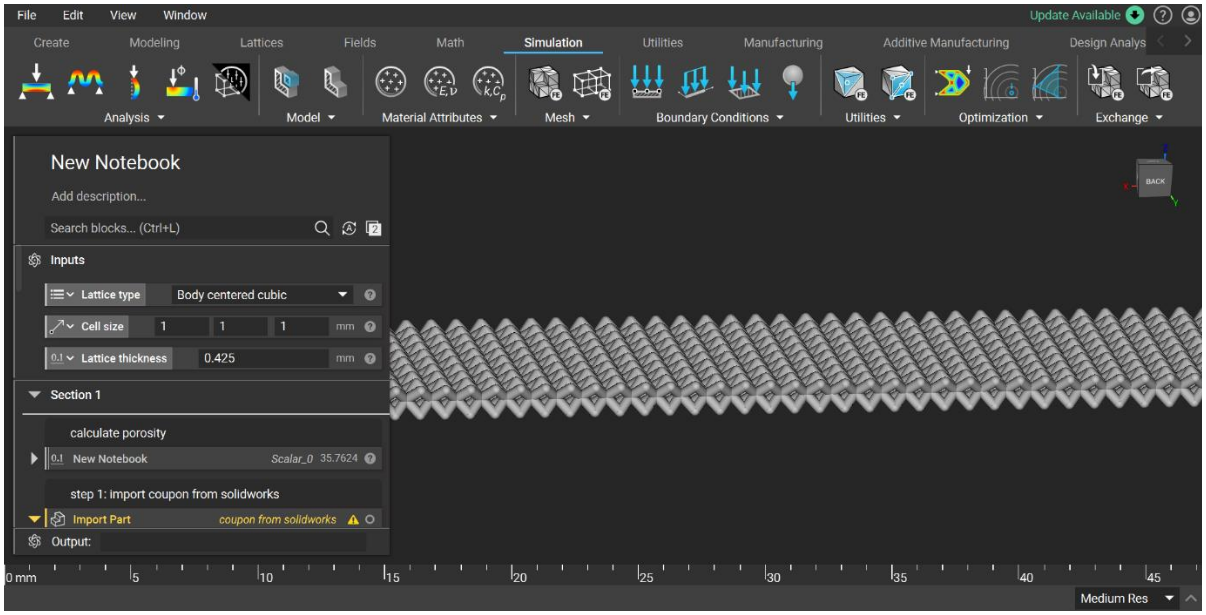
New Notebook Scalar_0 58.5329

step 1: import coupon from solidworks

Import Part coupon from solidworks

Output:

Figure 7. Lattice with x-direction unit cell length of 1 mm and strut thickness of 0.325 mm



New Notebook

Add description...

Inputs

Lattice type: Body centered cubic

Cell size: 1 1 1 mm

Lattice thickness: 0.425 mm

Section 1

calculate porosity

New Notebook Scalar_0 35.7624

step 1: import coupon from solidworks

Import Part coupon from solidworks

Output:

Figure 8. Lattice with x-direction unit cell length of 1 mm and strut thickness of 0.425 mm

With respect to the order in which they appear in the above figures, the coupons have porosities of 78%, 84%, 86%, 58%, and 36%. This porosity amount was calculated using the nTopology software, which is adept at finding a precise value of porosity for topology optimization. The amount of unit cells in the width of the coupon remained constant at 9 unit cells wide for each coupon. The length of unit cells varied based on differing x-direction unit cell length, with the coupons that were 1mm long in the x-direction by unit cell being composed of 99 unit cells, constituting a total of 891 unit cells in each entire coupon. In contrast, the coupon that was 2mm long in the x-direction by unit cells were 49 unit cells long, constituting a total of 441 unit cells in the coupon. Finally, the coupon that was 3mm long in the x-direction by unit cell was 33 unit cells long, constituting a total of 297 unit cells in the coupon. Variance in the number of unit cells and their size and thickness has an effect on the mechanical properties of the structure regardless of the material that it is composed of, which is observed based on the way the cells respond to outside stresses.

Chapter 3

Results

Results and findings were researched based on support of the original test hypothesis and conclusion, which stated that larger changes in porosity had larger changes in material properties of the coupon. Since four-point bending testing was conducted by the Pennsylvania State University and UPenn team, a yield strength was not determined in this specific study and instead a bending strength was calculated. The team's research here indicated a negative trend between increasing porosity and bending stiffness with a slope of -0.1073 and a line-fitting accuracy value of R^2= 0.9524. The graph visually depicting the correlation found between stiffness and porosity for heat-treated coupons can be viewed in Figure 10.

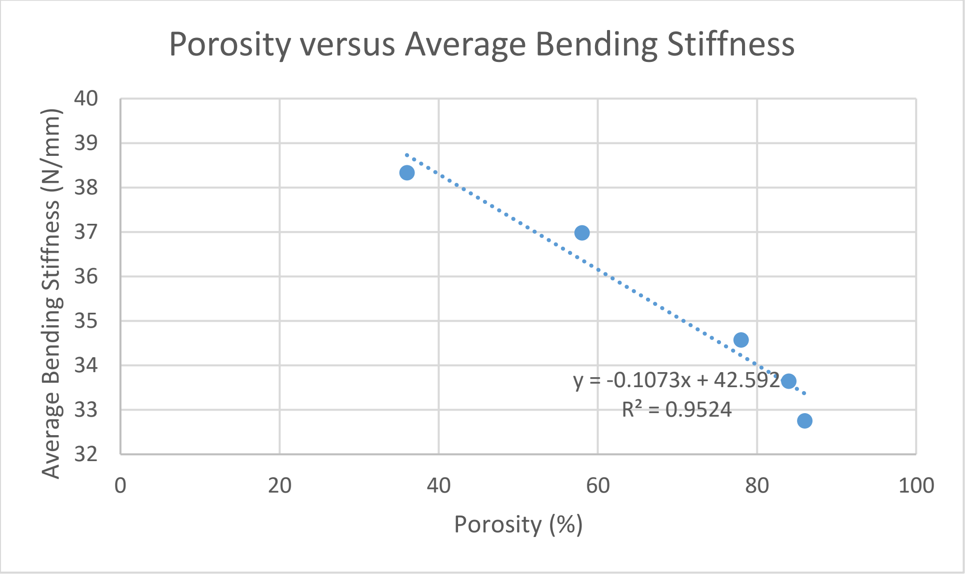


Figure 9. Porosity Versus Average Bending Stiffness

The team also found a linearly decreasing relationship between average bending strength and porosity, with a slope of -6.7877 and a line-fitting accuracy value of R^2= 0.6474, indicating a possible need for further results testing to confirm the accuracy of the linear relationship. The graph visually depicting the correlation found between bending strength and porosity for heat-treated coupons can be viewed in Figure 11.

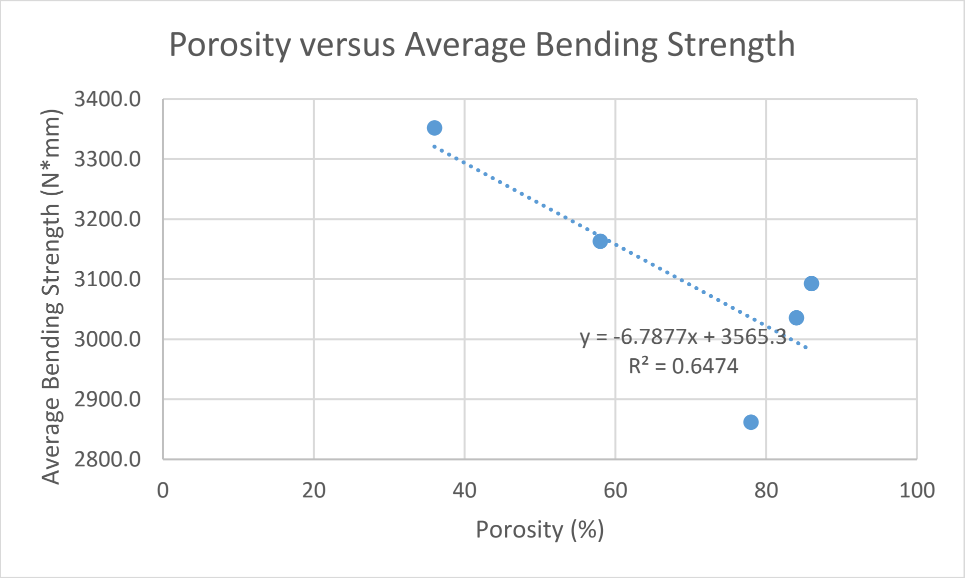


Figure 10. Porosity Versus Average Bending Strength

Chapter 4

Discussion

In research conducted by Molinari et al., multiple lattices of varying strut thicknesses and geometries were tested [41]. In every lattice tested, a trend of decreasing Young's modulus, yield strength, and stress with increasing porosity was observed. The porosities tested varied between 47.8% and 82.6%, values comparable with the range of 36% to 86% porosity as tested in the team's research, which showed the same general trend with regard to stiffness.

Specifically, the research conducted by Molinari et al. showed an enhanced rate of decrease in yield strength as opposed to stiffness in porosities higher than around 65%. When tailoring the lattice to reduce stiffness, the yield strength decreased steadily with porosity until around 60-65% porosity, where the slope for the decrease in yield strength nearly doubled.

Molinari et al. performed compressive testing on 10 lattice structures varying in properties and specifically observed the effect of porosity on material properties including stiffness, Young's modulus, yield strength, and stress. The study reported a range in modulus from 1 to 20 GPa, which is comparable to that of trabecular bone at around 18 GPa and to the intended range of moduli in the UPenn/Penn State University study of about 1-12 GPa [39]. The other study included exclusively BCC lattices, which regardless of porosity will have deviations in behavior under loads and stress. Additionally, compression testing was performed in the Molinari et al. study as opposed to the Judkins et al. study which focus on four-point bending. Both studies tested heat-treated lattices made from Ti-6Al-4V material through laser powder bed fusion additive manufacturing technology. Further research in comparing results between this two studies would primarily suggest conducting compression testing on the five BCC lattices from the latter study and comparing resulting values based on porosity differences.

Studies conducted in 2021 in Bejing by Jin et al. discuss the effect of heat-treating lattices made through powder bed fusion technologies with titanium alloys [42]. The results specifically analyzed changes in microstructure and mechanical properties based on heat treatment for BCC and FCC Ti-6Al-4V lattices, which allows for comparison between these findings and those discovered by Judkins et al. The results showed that heat treatment has the potential to eliminate inconsistences in horizontally built versus vertically built mechanical properties in all types of lattices.

The best heat treatment temperature of the BCC lattice was determined to be 920 degrees Celsius to avoid extensive grain growth that results from higher temperatures and eliminate remaining differences in homogeneity of grain size that results from lower temperatures. Of the different heat treatment methods tested, it was determined that BCC lattices specifically benefit with regard to increased modulus and energy absorption in conduction with small decreases in ultimate tensile strength when compared to FCC lattices in higher temperatures, where a lower decrease in ultimate tensile strength is observed but with lower increases in those desirable mechanical properties. Heat treatment was determined to better eliminate undesired porosities and other defects within the structures, thus allowing for better mechanical properties and more predictable behavior.

The findings in the Judkins et al. study additionally shed light on the effect of heat treatment on BCC lattices made through powder bed fusion, and showed that heat treatment caused, on average and disregarding error, a 5.06% increase in bending stiffness, a 46.46% increase in proof load, a 46.45% increase in mean bending strength, a 5.66% increase in maximum load, and a 6.58% increase in toughness [39]. This study, however, observed heat treatment at much lower temperatures of about 590 degrees Celsius as opposed to the minimum observed heat treatment of 750 degrees Celsius in the Beijing study. In comparison to the Beijing study, both observed more consistent material properties under heat-treated materials. Based on stiffness calculations, both studies observed higher energy absorption under heat treatment.

The testing done in the Beijing study was compression testing under a strain rate of 0.001 s^{-1}, as opposed to the four-point testing done in the UPenn/Penn State University study. Thus, the Jin et al. study sheds more light on material properties not observed in the latter study, including ultimate tensile strength, strain, and elastic modulus. The study also focused solely on heat treatment rather than variance in lattice properties and consisted of a square lattice with many stacked unit cells rather than a flat coupon one unit cell thick. Finally, the difference in heat treatment temperatures could denote the studies incomparable altogether. While the comparisons made show some similarities, further testing must be done to make more accurate comparisons between two relatively different studies.

In comparison with the four-point bending testing, researchers from the University of Cassino and Southern Lazio observed the effect of three-point bending on lattice structures with varying spans [43]. The material used was Ti-6Al-4V, with FCC and octahedral lattices tested. Span distance tested included 200, 120, and 45 mm span lengths, with the intention of the research focused on aeronautical applications. The most comparable span distance was 45 mm to that of the 25 mm span distance tested in the UPenn/Penn State University research [39]. No evidence of heat treatment on the lattices was declared. While little is reported on the resulting mechanical properties of the testing, the results indicated span distance has an effect on the energy required to illicit failure on the specimen, which is relevant regarding where pins should be place on a rib fracture implant to best balance stiffness and strength.

Overall, this research points to the need for more bending testing to be applied on lattices of varying geometries. The loads applied to the specimens were not displacement loads and the 45mm span distance withstood a load of about 3,000N, making any comparison of this research to that of the Judkins et al. findings too different to compare. The understanding of how bending strength and other material properties evaluated in bending testing react under varying loads provides a gap in research that should be further explored as lattice designs are further studied.

While exact comparisons between research published is never possible, findings throughout multiple sources shed light on how lattice structures perform under varying loading, geometrical, and heat treatment conditions. Findings by Qui et al. showed that strut size, which has a measurable effect on mechanical properties of a lattice, can vary based on the laser speed and power used in the material creation process [44]. Fang et al. found that in lattices designed to minimize stiffness, the location of failure modes were the most important indicator of the performance of the lattice [45]. Dumas et al. found deviations of up to 50% between simulated and tested yield strength and stresses in tested lattices, indicating a need for further mechanical testing of how lattice structures behave in reality under changing loading conditions [46].

Chapter 5

Conclusion

The results found that porosity and heat treatment affected the mechanical properties of the tested lattice with varying results. Decreasing porosity decreased stiffness and bending strength, the former of which was confirmed in studies by Molinari et al. Heat treatment increased the consistency of the mechanical properties of the lattice, also reflected in studies by Jin et al. Further studies must be conducted to confirm the relationship found between the mechanical properties of the lattice with varying strut thickness and cell size.

The opportunity for further research is extensive. Conduction of simulated four-point bending testing on lattices could be compared to the experimental results in order to determine how factors such as heat treatment and error within printing may affect the structure. Additionally, compression testing could be performed on the lattices used in the UPenn/Penn State University studies for further comparison to other research that utilizes this type of testing. In that vein of work, more studies that include four and three-point bending of lattices could shed more light on how these lattices perform under simultaneous loads, something typical of a bone fracture implant. These studies could also help gather more data on properties such as bending strength and loading conditions. Testing could be performed with screws to further understand how their added geometry may affect the mechanical properties of the lattices.

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ACADEMIC VITA

Christine Gabriele

EDUCATION

The Pennsylvania State University | Schreyer Honors College **University Park, PA**
College of Engineering | Bachelor of Science in Mechanical Engineering *Class of 2022*
College of Liberal Arts | Minor in Economics

PROFESSIONAL EXPERIENCE

Systems for Hybrid-Additive Process Engineering (SHAPE) Lab **State College, PA**
Rib Fracture Fixation Implants Research Team Member *December 2020-Present*

- Actively working towards developing patient-specific rib fracture implants created through the use of 3D - printed titanium lattice structures
- Tested the hypothesis that lattices created with higher levels of porosity would better reflect a human rib's flexibility and strength than typical implants using 4 models created in Topology

Cobbs Creek Healthcare
Newtown Square, PA
Junior Data Analyst
May 2021– August 2021

- Converted pharmaceutical consumer data into analytical insights for clients using programs such as Dataiku, Tableau, Excel, and SQL
- Worked directly with clients to construct map-based consumer target areas in order to enhance business outreach
- Developed interpersonal and presentation skills by creating slide decks of project objectives to be presented to the client

LEADERSHIP EXPERIENCE

Penn State Dance Mara (THON) **University Park, PA**
Development: Local Engagement Captain *May 2020-May 2021*

- Served as the main point of contact between the Borough of State College and the largest student-run philanthropy in the world, THON
- Coordinated the placement and collection for over 15 donation boxes downtown, raising a total of $3,112.78 in 7 months
- Served as one of the first freshman committee captains and oversaw the leadership development of 18 freshman over the course of 5 weeks to prepare them to become future leaders of THON

Engineering Writing **State College, PA**
Research and Teacher's Assistant *August 2021 – Present*

- Helped develop a micro-credentialing badge for students involved in professional research writing
- Enhanced student learning by editing resumes and professional writing samples for engineering students

HONORS AND INTERESTS

Honors: Dean's List all semesters, Schreyer Honors College Scholarship Recipient
Interests: skiing, snowboarding, soccer, piano, guitar, politics, autobiographies, mental health practices, medicine
Proficiencies: MatLab, SolidWorks