2019

Raytheon -- Strength Optimized Designs Using Additive Manufacturing

Donovan Blanpied
University of Rhode Island

Reed Nelson
University of Rhode Island

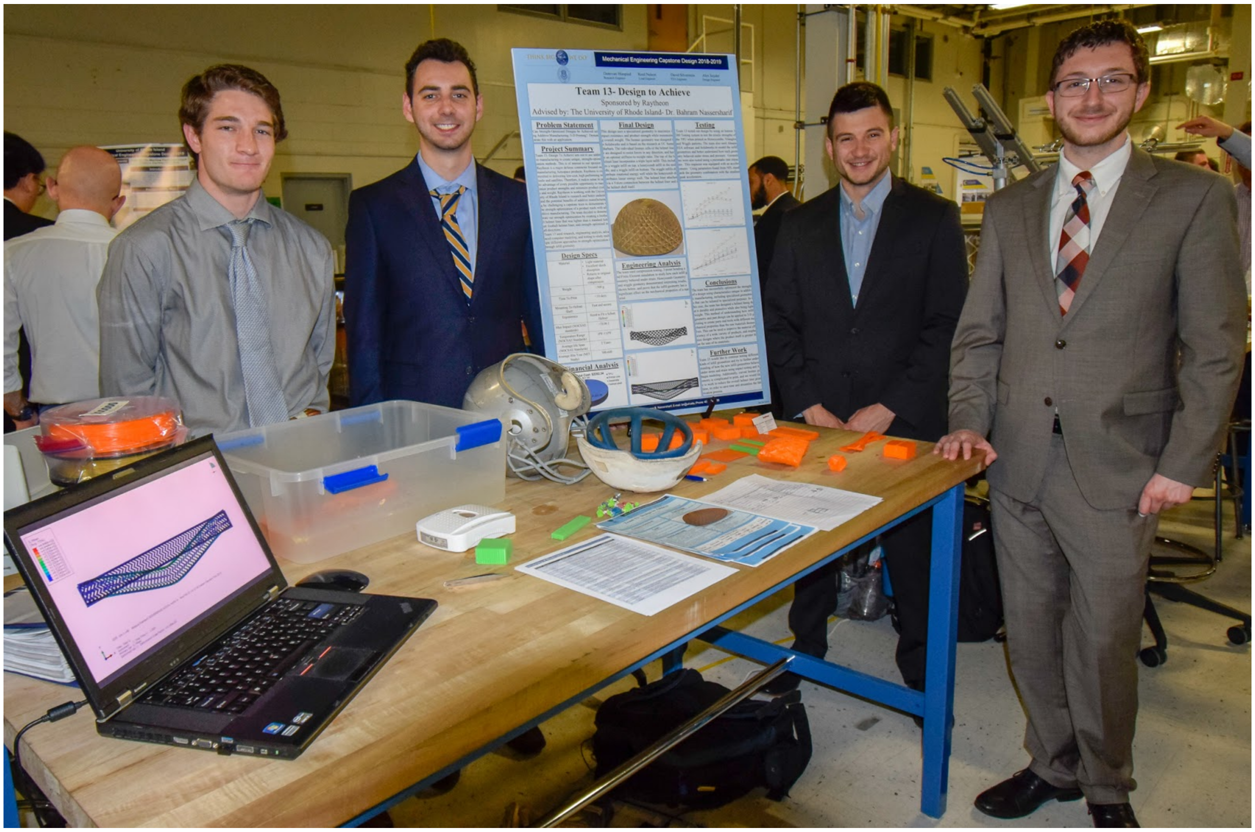
David Silverstein
University of Rhode Island

Alex Snyder
University of Rhode Island

Recommended Citation

Blanpied, Donovan; Nelson, Reed; Silverstein, David; and Snyder, Alex, "Raytheon -- Strength Optimized Designs Using Additive Manufacturing" (2019). *Mechanical Engineering Capstone Design Projects.* Paper 62.
https://digitalcommons.uri.edu/mechanical-engineering-capstones/62

Strength Optimized Designs Using Additive Manufacturing



TEAM 13: DESIGN TO ACHIEVE
Donovan Blanpied: Design Engineer
Reed Nelson: Project Manager
David Silverstein: FEA Engineer
Alex Snyder: Research Engineer
Sponsor: Raytheon
Advisor: Dr. Nassersharif
05/06/19

Abstract

Designing a structure to demonstrate the strength of 3-D printed part is more complicated than it seems. The design goal was to construct a device that demonstrates how 3-D printing can create a strength optimized design. The design must incorporate maximum strength, while not sacrificing other major components such as weight of the product, cost of the product, print time of the product and how much material is being used. Extensive research and tests were conducted on infill patterns, football helmets, and TPU material (material used in football helmets).

There are multiple infill patterns that must be considered. The most important aspect of printing parts via FDM 3D printing is the infill pattern. This will directly affect the print time, material used, cost, and strength of the printed part. The second most important concept of the 3-D printed part is the infill structure. There are many infill structures, each having its own strengths and weaknesses when approaching higher strength, time to print, material used and weight. The team decided to focus on four commonly used infill structures (honeycomb, wiggle, triangular, and rectilinear). The team conducted a 3-point bending test and compression test, strictly following the ATSM standards to find out more about the strengths and weaknesses of each specific infill pattern (shown in this report). A design has been created and the application is a football Helmet. The design has 2 parts. The first part is a smaller, circular piece as the very top of the helmet. This piece contains a “triple layer infill sandwich.” The triple layer infill sandwich is composed of 3 different infills: wiggle infill (good for distributing rotational energy), honeycomb infill (good for distributing linear impact), wiggle infill again (good for distributing rotational energy). The second part of the helmet liner is a dome composed of an Isomax structure with a hole cut out at the top of the helmet.

The team originally came up with 120 different designs in an attempted to best solve the task at hand. The method from obtaining these ideas came from brainstorming and online research. To narrow the solutions, a table was made with different attributes and rankings with each attribute. The team went through each individual concept and ranked it accordingly. After we had our top ideas team 13 conducted specific testing to figure out which idea was best and team 13 came up with this specific helmet liner.

Table of contents

List of Acronyms

I. ANSI- American National Standards Institute
II. ASTM- American Society for Testing and Materials
III. FEA- Finite Element Analysis
IV. FDM- Fused Deposition Modeling
V. MIT- Massachusetts Institute of Technology
VI. NFL- National Football League
VII. NOCSAE- National Operating Committee on Standards for Athletic Equipment
VIII. PVA- Polyvinyl Alcohol
IX. QFD- Quality Function Deployment
X. TPU- Thermoplastic Polyurethane
XI. URI- University of Rhode Island

List of Tables

List of Figures

Introduction

In 1984 Charles Hull created Stereolithography. Stereolithography was the first from of additive manufacturing. It worked by creating a digital model, and then shining a UV light on a material known as photopolymer which instantly created a 3-D tangible model of the design. This new technology was a huge advancement because it allowed innovators to test their new designs without having to make a huge upfront investment in manufacturing. Since then 3-D printing and additive manufacturing has taken off. Now additive manufacturing can produce extremely detailed products, printing using a variety of materials including gold and silver, and even manufacturing houses that are extremely affordable. Additive manufacturing continues to push to boundaries of what humans' thought was possible.

Concussions in the NFL have become a major concern, and something needs to change. It has been shown that approximately 40% of football players are diagnosed with some sort of brain damage after playing. This is simply not acceptable, and the NFL understands this and is using its resources to find a solution. There has been progress with the rules however the biggest issue is the helmets themselves which is what team 13 is trying to solve.

This report is focused on optimizing the strength of a 3-D printed part. The issue that Raytheon presented was "Can strength optimized designs be achieved using additive manufacturing?" The problem statement states: Create a strength optimized design using FDM and demonstrate it with an application. Raytheon is a defense company so making a product that is extremely lightweight while providing maximum strength can benefit them. The application of a high strength to weight ratio has limitless applications, in Raytheon's case: satellites, missile defense systems and even missiles. Raytheon also suggested using the honeycomb infill structure, and possible applications such as heat pipes, wave guides, and heat sinks. The team originally decided to use a heat sink as an application to demonstrate the optimization of thermal strength however, the team decided to use a helmet to emphasize a strength to weight optimized design. The team must complete this problem statement while also trying to limit weight, material used, print time, and cost. The solution to the problem statement is stacking multiple infill geometries in a helmet liner and using a custom infill called Isomax structure in a circular fashion. This will be done to use the benefits of each of these multiple infill geometries to demonstrate a strength optimized design. The team has conducted thorough research on additive manufacturing, helmets, infill (primarily infill patterns) and Isomax geometry. In addition, 3-point bending tests and compression tests have been conducted on multiple test subjects with multiple infill geometries. The findings of this research and tests will be demonstrated in the rest of this report.

Patent Searches

The patent search was a preliminary step for performing the literature searches. These searches included reviewing the patents for the products, processes, and concepts based on the guidelines provided for us above. The patent searches were conducted by every team member however the patent searches related to the current proof of concept will be covered. The primary terms that the group used to conduct those searches are: impact, heat, safety, printing, additive, strength, and plastics. The related terms that the group referred to are: aesthetic, testing, and materials, structure, ductile, absorb, cushion, impermeable, insulate, resistant, manufacturing, patterns, and optimize. When using uspto.gov to conduct the patent searches the group came up the following class numbers after searching both primary and related terms: A42B, F28F, F16P, B41F, and B33Y. These class numbers corresponded to the following definitions respectively:

- Hats; Head Coverings

- Details of Heat-Exchange and Heat-Transfer Apparatus, of General Applications

- Safety Devices in General

- Printing Machines or Presses

- Additive Manufacturing, i.e. Manufacturing of Three-Dimensional [3-D] Objects by Additive Deposition, Additive Agglomeration or Additive Layering, e.g. by 3-D Printing, Stereolithography or Selective Laser Sintering

At the beginning however, before revising the research strategy, the group struggled finding key words that were effective in finding topics related to additive manufacturing. Although after brainstorming some key words came to mind and turned out to be very helpful. The group also realize that some of the synonyms of the past key words were more useful. After that the group focused on class A42B for Hats; Head Coverings and chose sub classes A42B 3/12 for Cushion Devices, and A42B 3/06 for Impact Absorbing Shell, e.g. of crash helmets. The first search of "A42B 3/12" gave 110 patents, which was much more than the recommended amount 50 or less. As a result, the revised quick search of "A42B 3/12" and "A42B 3/06" together produced only 47 patents. After looking at the reference patents within that quick search the group did in fact find one that is relevant to our proof of concept. The "Sport Helmet" patent [9,756,892] was the one that inspired the group to continue the literature searches on the impact helmet liners. This was because the inner padding in helmet has a core of polymeric cellular material. This is particularly interesting because in the past the group researched biologically inspired structural materials for 3D printing. Coincidentally the group took what they learned from the patent and looked up polymeric cellular materials on Google. The first link happened to be a research paper on Mechanical Properties of 3D Printed Polymeric Cellular Materials. As a result, the group learned that 3D Printed Polymeric Cellular Materials have a higher stiffness and strength compared to primitive Polymeric Cellular Materials. This was interesting because the group utilized what they learned from the patent to guide them in their future literature searches. However, there were some patents that were not relevant to the proof of concept. Those patents consisted of any one that does not specifically cover manufacturing via 3D printing or designs that involve strength optimized materials. This exercise in finding patents relevant to the current proof of concept proved to be very helpful. It has broadened the group's scope as far as what kinds of devices they could make utilizing strength properties. Since the project proposed to the group is more open-ended than most of the class, this process of brainstorming, classification, review, broadening, and then reclassifying was repeated normally for a longer duration of time. As a result, the group has continually used this as a tool to eventually find a specific path to take with the proof of concept.

Evaluation of the Competition

Helmet liners that are traditionally used in the modern helmet consist of a cup like system that holds air pockets. These air pockets are sealed and surrounded with foam. This system has obvious flaws. The flaws are evident because of the high occurrence of head injuries in the NFL. Never has additive manufacturing been used to structure a football helmet liner. Not only is group 13's product competitive with the current helmet designs, it uses manufacturing techniques that have never been applied to this industry before.

The way in which internal structures can be created using additive manufacturing provides opportunities to create geometries such as the Isomax used in this project. These geometries can provide strength and energy absorption in ways not possible from traditional manufacturing techniques. Also, the precision of additive manufacturing produces parts with almost no waste. This not only is environmentally positive, it also is more financially advantageous for manufacturers.

The largest flaw in this design is printing time. Because of the large printing time (480 hours) the Isomax geometry is slower to produce than the conventional helmet. The large printing time also drives up the cost of this helmet above the current helmet used by the NFL.

Specifications Definition

For this portion of the project, the group made the decision to focus on the product of a football helmet liner. The liner of a football helmet provides a complex problem in impact resistance, or, energy absorption. If a liner of a helmet is good at absorbing the energy of an impact, the person wearing that helmet will experience as little of the impact as possible.

The National Football League, or, NFL has strict regulations for their equipment. Since concussions and head injuries have been an area of attention recently, the NFL has focused a lot of effort on improving helmet designs and specifically helmet liners. For this project, the NFL was taken as a customer. The regulations that the NFL requires out of its helmets were taken as the specifications that were designed to.

The NFL does not do their own manufacturing and testing of their own equipment. Instead they hire out their testing to an independent company, the National Operating Committee of Standards for Athletic Equipment. This company, NOCSAE[5] takes sporting equipment made by commercial manufacturers and certifies them for sporting leagues. From youth, to professional levels of sports leagues all use NOCSAE to certify their equipment.

This team used the NOCSAE standards, as well as, other sources to compile a list of specifications to design to. Below is a table of all the specifications the team found necessary to fulfill to reach the team's goal of having a stronger, lighter product.

Table (1): Design Specifications

Material	• Light material • Excellent shock absorption • Returns to original shape after compression
Weight	<500 g
Time to Print	<10 days
Mounting to Helmet Shell	Fast and secure
Ergonomics	Sized to Fit a Schutt Helmet
Max Impact (NOCSAE standards)	>70.06 J
Temperature Range (NOCSAE Standards)	0°F-110°F
Average life Span (NOCSAE Standards)	2 Years
Average Hits Year (MIT Study)	300-600

Other sources such as MIT were used to fulfill requirements not fulfilled by the NOCSAE standards.

Conceptual Design

List of Concepts Generated

Donovan Blanpied's Concepts

1. Lattice Structure: This concept is a web-like framework that would be an infill pattern. This would optimize strength and reduce weight by only providing support when needed. The geometry would be like trusses to distribute load.

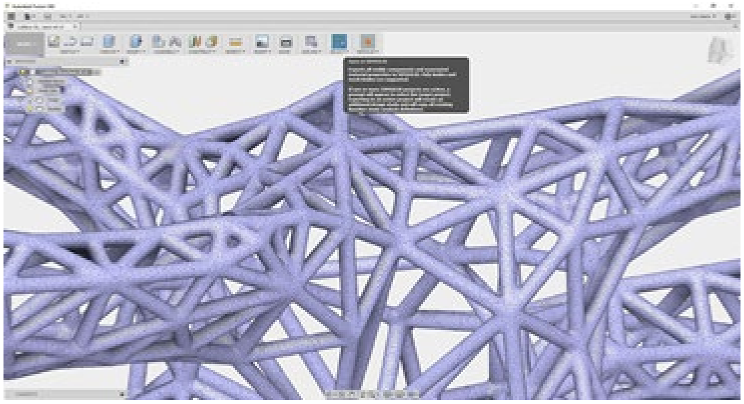


Figure (1): Lattice Structure

2. Octet Structure: Like the lattice structure the octet would be an infill pattern that would optimize strength. The octet also takes advantage of geometrical strength. However, it would require much more material but, has the advantage of being more versatile.

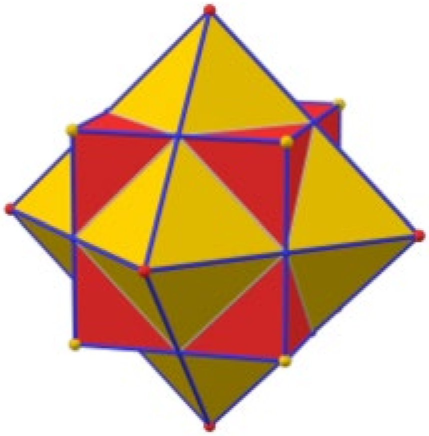


Figure (2): Octet Structure

3. Variable displacement bar (strain): This concept would use different infills to achieve variable strain. Under the same load, different infill patterns have different strain rates. This bar would use that concept to have variable displacement under the same load.

4. Variable displacement bar (thermal): This concept would be much like the strain bar; however, it would expand, or contract at different rates depending on the infill pattern.

5. Custom fitted heat pipe: This concept would be a heat pipe that would be able to fit into any formation. Using 3-D printing to tailor the heat pipe to any situation. This concept would also have a complex geometry on the interior of the pipe to act more efficiently. 3-D printing can manufacture much more complex interior geometries, these could prove to be advantageous to movement of heat.

6. Flexible heat pipe: A heat pipe made from flexible material, being able to be operational in moving parts. A 3-D printer could print flexible yet conductive material to be operational in moving parts such as machinery.

7. Cushion layer design: A combination of infill geometries that would optimize energy absorption. Certain infill geometries are better than others at absorbing impact. A combination of these geometries would be used to optimize impact resistance.

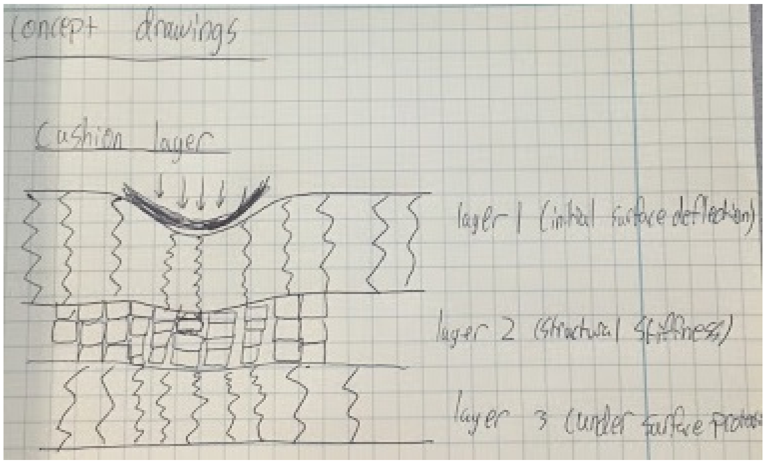


Figure (3): Cushion layer

8. Web like structure with optimized strength: This structure would be supported by a combination of webs to have minimal material used with maximum strength. The webs would act by distributing loads across the whole surface.

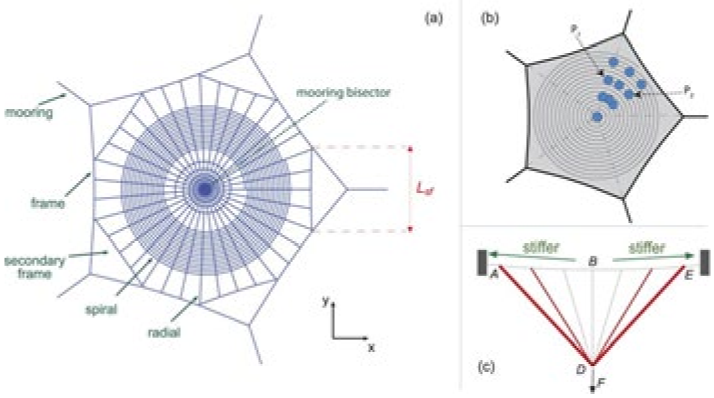
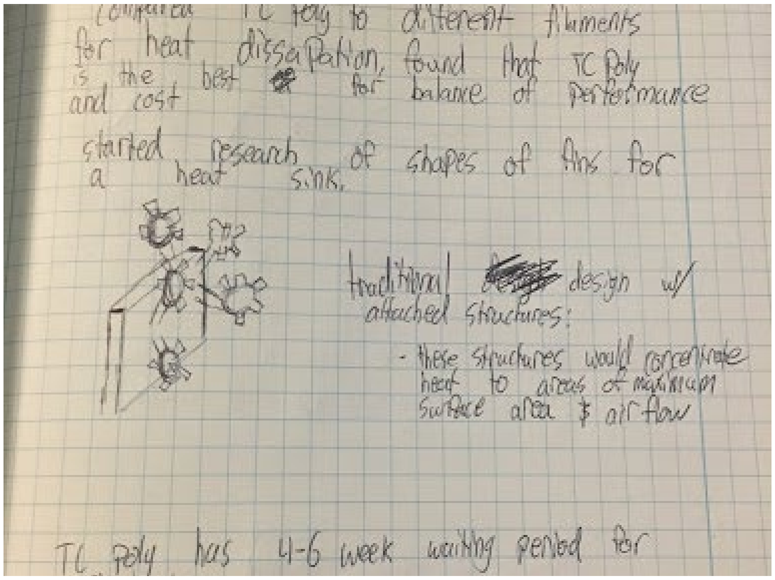


Figure (4): Web Structure

9. Honeycomb filled heat sink: Heat sink made of honeycomb geometry to have maximum airflow in x and y directions.

10. Lattice structures attached to fins on heat sink: A heat sink with fins that have added structures to improve surface area. These structures would concentrate heat to areas of maximum surface area and airflow. This would optimize heat dissipation.



compared TC poly to different filaments
for heat dissapation, found that TC Poly
is the best for balance of performance
and cost

started research of shapes of fins for
a heat sink.

traditional design w/
attached structures:
- these structures would concentrate
heat to areas of maximum
surface area & air flow

TC poly has 4-6 week waiting period for

Figure (5): Lattice structures on heat sink

11. Oscillating wave like heat fins: Heat fins made of oscillating wave geometry to maximize passive airflow and surface area. This would allow airflow in all 3 dimensions.

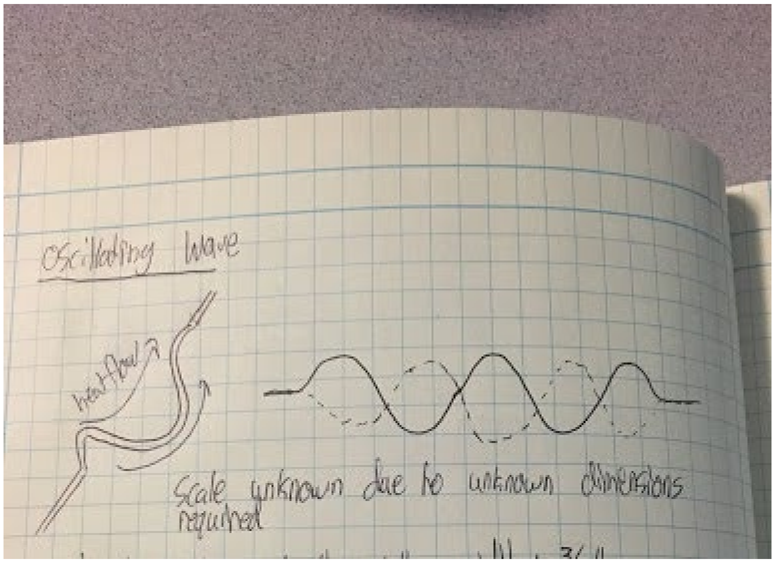


Figure (6): Oscillating wave heat fin

12. Oscillating angle heat fin: Like the wave plate, this heat sink would allow airflow in all 3 dimensions. The angle plate could also be changed to concentrate heat dissipation. This design has the advantage of a simpler geometry that would be

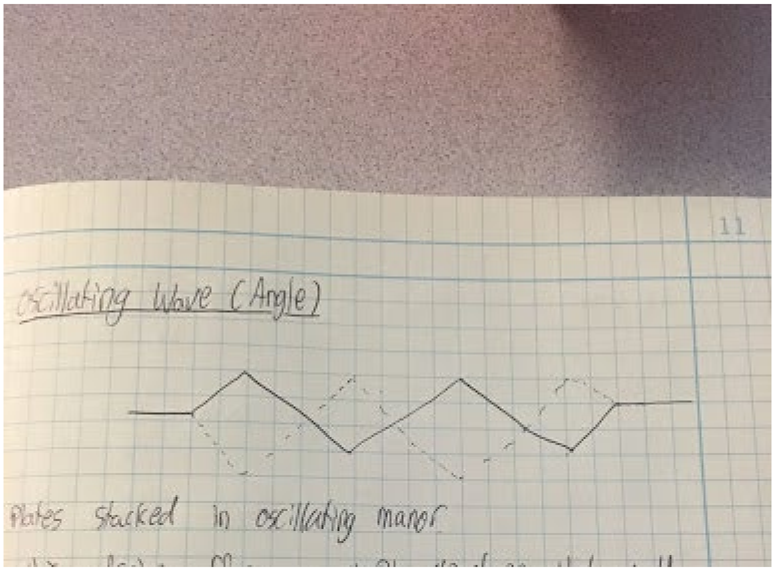


Figure (7): Angle wave heat fin

13. Variable base thickness: Heat sink with variable base thickness. The base of this heat sink would be thicker in parts that require heat dissipation. The thicker base would focus heat to be distributed by the fins.

14. Variable fin spacing: Heat sink with varied spaces between fins based on heat concentrations from source. Like the variable base thickness, the fins would be concentrated in areas in need of higher heat dissipation.

15. Heat sink Hybrid: A hybrid structure of oscillating waves made from honeycombs maximizing passive airflow in both x and y directions

16. Heat sink Hybrid: A heat sink combining variable base thickness with variable fin spacing

17. Heat sink Hybrid: A heat sink that would combine all elements of geometry and variable thickness.

18. Spherical structure: Spherical structure to be able to roll and withstand impact and distributed loads.

19. Spherical system: A system of spheres able to roll and withstand loads, this system of distributed spheres could adapt dynamically to where support is needed.

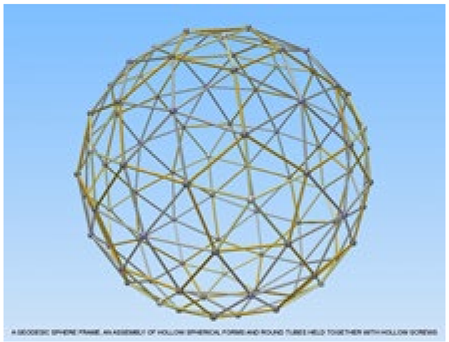


Figure (8): Spherical Structure

20. Flexible pressure vessel: A flexible pipe like structure to hold high internal pressures while remaining flexible.

21. Lightweight heat pipe: A heat pipe that would perform to industry standards but have a much lighter weight based on optimized geometry

22. Nano structures: Added Nano structures with structural geometry to optimize strength

David Silverstein's Concepts

1.Honeycomb Heat Sink Fin- [Fig: 10] A heat sink fin made using FDM to create a free-standing wall with a honeycomb structure constructed of:

- 1a. Copper
- 1b. Aluminum
- 1c. Thermoplastic
- 1d. Copper-coated thermoplastic
- 1e. Aluminum-coated thermoplastic
- 1f. Copper-coated Aluminum

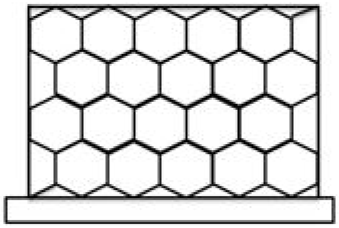


Figure (9): Honeycomb structure

2. Variable base honeycomb structure heat sink- [Fig: 11] A copper heat sink made using AM and techniques pioneered by Robert Smith, P.E. of Qualified Rapid Prototyping [6]. Specifically, decreasing the thickness of the base and fins according to Gaussian dis-attribution at the boundaries of the base and fins. the fins will be constructed from honeycomb structures to improve surface area and reduce weight. Constructed of:

- 2a. Copper
- 2b. Aluminum
- 2c. Thermoplastic
- 2d. Copper-coated thermoplastic
- 2e. Aluminum-coated thermoplastic
- 2f. Copper-coated aluminum

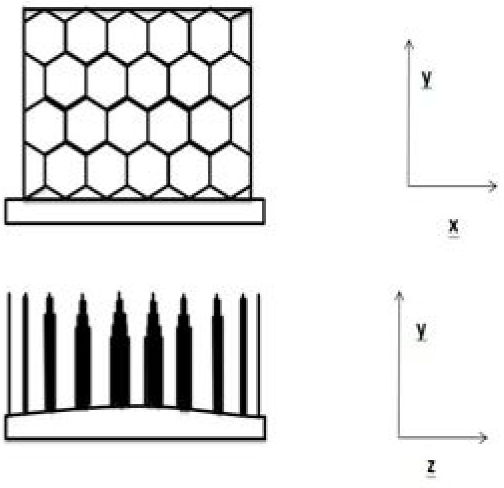


Figure (10): Variable base heat sink

3.Art-Deco Christmas trees- [Fig:12-Fig:15] A copper heat sink fin with a central heat pipe that decreases in thickness as it approaches the boundary according to Gaussian district-button, with regularly spaced circular disk fins that also decrease in radius according to Gaussian distribution. Constructed of:

- 3a. Copper
- 3b. Aluminum
- 3c. Thermoplastic
- 3d. Copper-coated thermoplastic
- 3e. Aluminum-coated thermoplastic
- 3f. Copper-coated aluminum

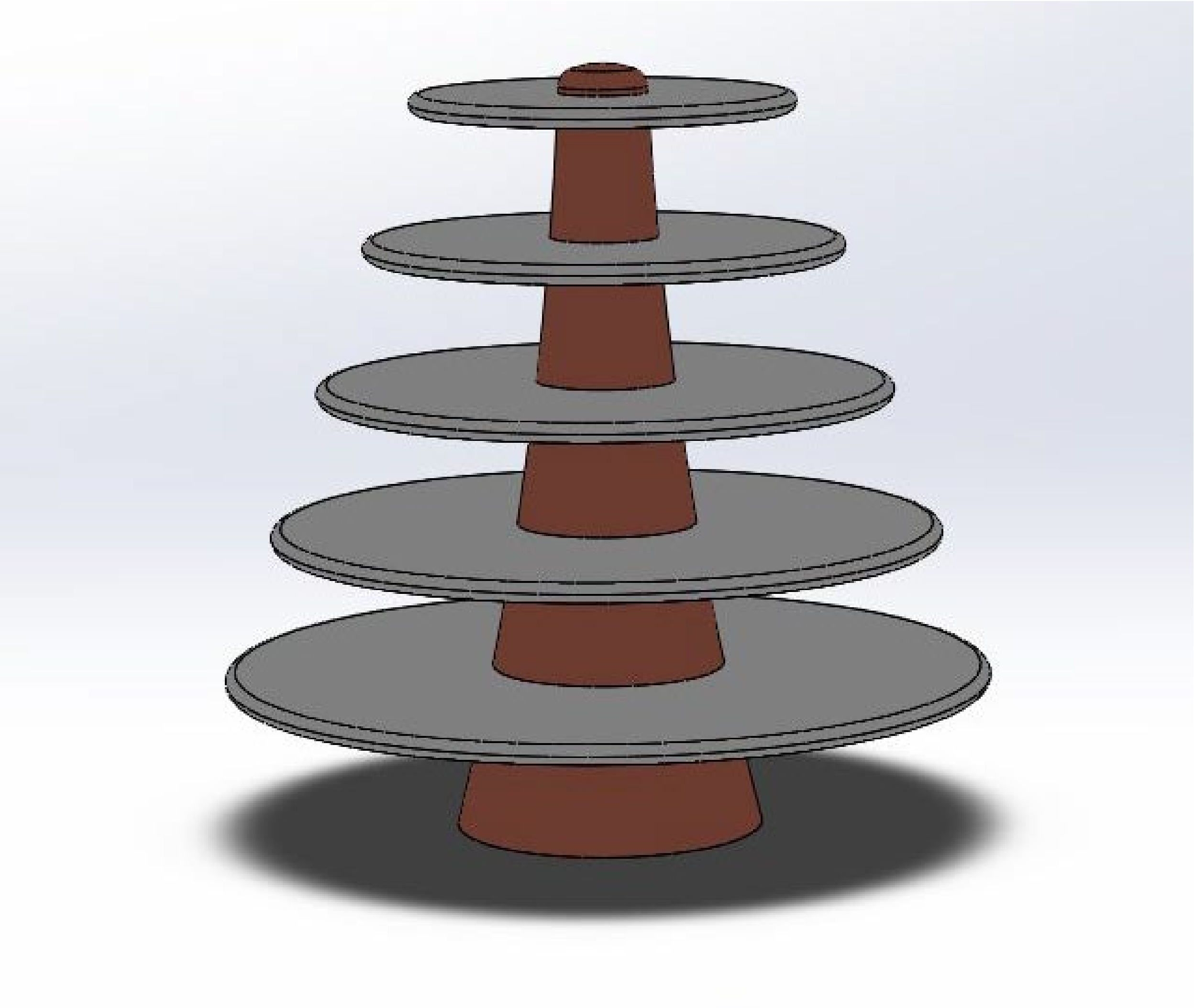


Figure (11): Art-Deco Christmas Tree

4.Animal-ear heat sink fin- [Fig:16] A circular fin consisting primarily of a large, extremely thin layer of material, with a fractal heat pipe that gets smaller and patters out to the edges like a vein delivering blood to a desert animal's ear. constructed of:

- 4a. Copper
- 4b. Aluminum
- 4c. Thermoplastic
- 4d. Copper-coated thermoplastic
- 4e. Aluminum-coated thermoplastic
- 4f. Copper-coated aluminum

Figure (12): Animal ear design

5.Spike Plate Heat Sink- [Fig:17] Several cylindrical spikes of varying length according to Gaussian distribution and spread across the base plate in Gaussian distribution. Constructed of:

- 5a. Copper
- 5b. Aluminum
- 5c. Thermoplastic

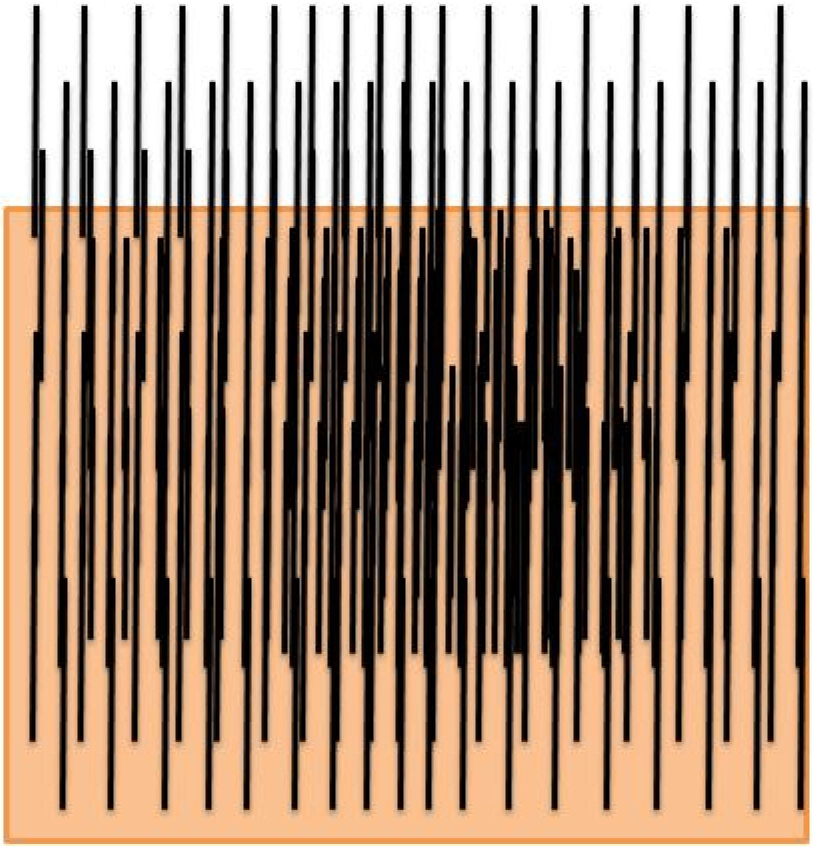


Figure (13): Spike heat sink

6.Branching Heat Sink- [Fig:18] A heat sink with a complex branching geometry of fins designed to decrease in the overall number of fins as the heat sink gets further from the source of heat. Constructed of:

- 6a. Copper
- 6b. Aluminum
- 6c. Thermoplastic
- 6d. Copper-coated thermoplastic
- 6e. Aluminum-coated thermoplastic• 6f. Copper-coated aluminum

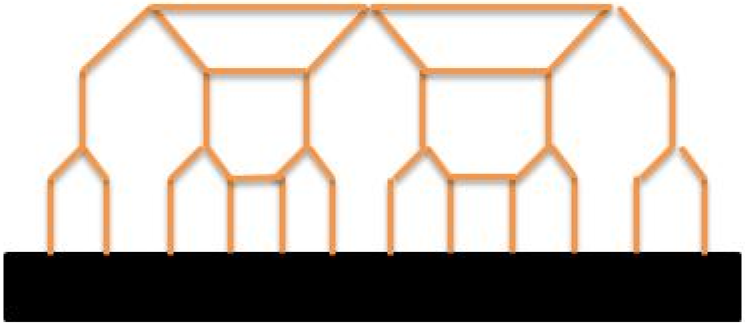


Figure (14): Branching Heat Sink

Alex Snyder Concepts

Figure 14 shows the two helmet liner design concepts. Design concept 1 is a honey comb on the outer layer to provide maximum strength in all directions. This layer is followed by a vertical wiggle infill pattern to dissipate the irrational energy. The following layer (closest to the skull) is another honeycomb layer. The reason for placing the honeycomb layer here as well is to insure this layer absorbs as much force as possible, before it reaches the skull. Looking at concept 2 it can be scene that the makeup of this helmet liner is a wiggle infill, followed by a honeycomb layer, followed by another vehicle wiggle pattern. The reason for the outermost wiggle pattern is to address the torsional force that is not directly a 180-degree impact. The next layer is the backbone of this design which is the honeycomb layer. This layer provides strength in all directions. The final layer (closest to the skull is another vertical wiggle infill pattern. The purpose of this is to have an infill layer closest to the skull that is very soft, providing comfort. Figure 15 shows the heat sink designs created earlier in the semester. The plate fin design number 1 is created using a honey comb or wiggle pattern to provide strength. With the way these fins are oriented, this design is best used if the heat being dissipated is in the same direction as the fins. When looking at the round tip design, it can be shown that his infill pattern will be printed using a square or triangular infill pattern. The Reason the tips have a spherical end to the fin is to provide maximum heat dissipation in all directions, making this a good heat sink for general applications.

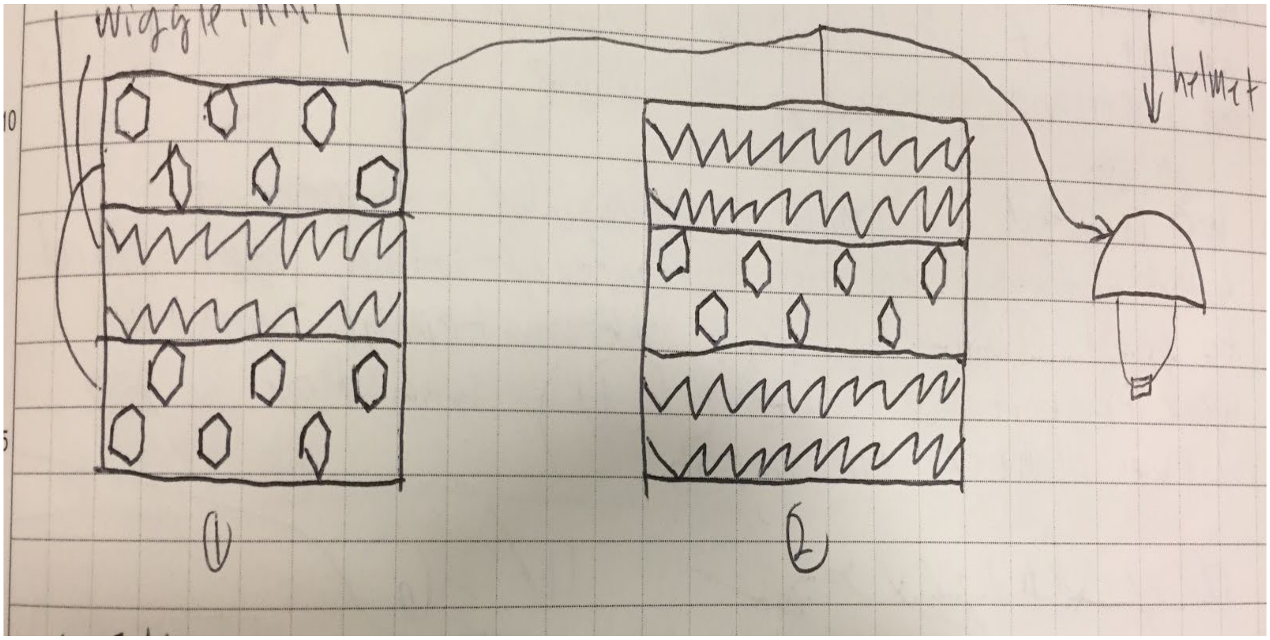


Figure (15): Honeycomb/sandwich

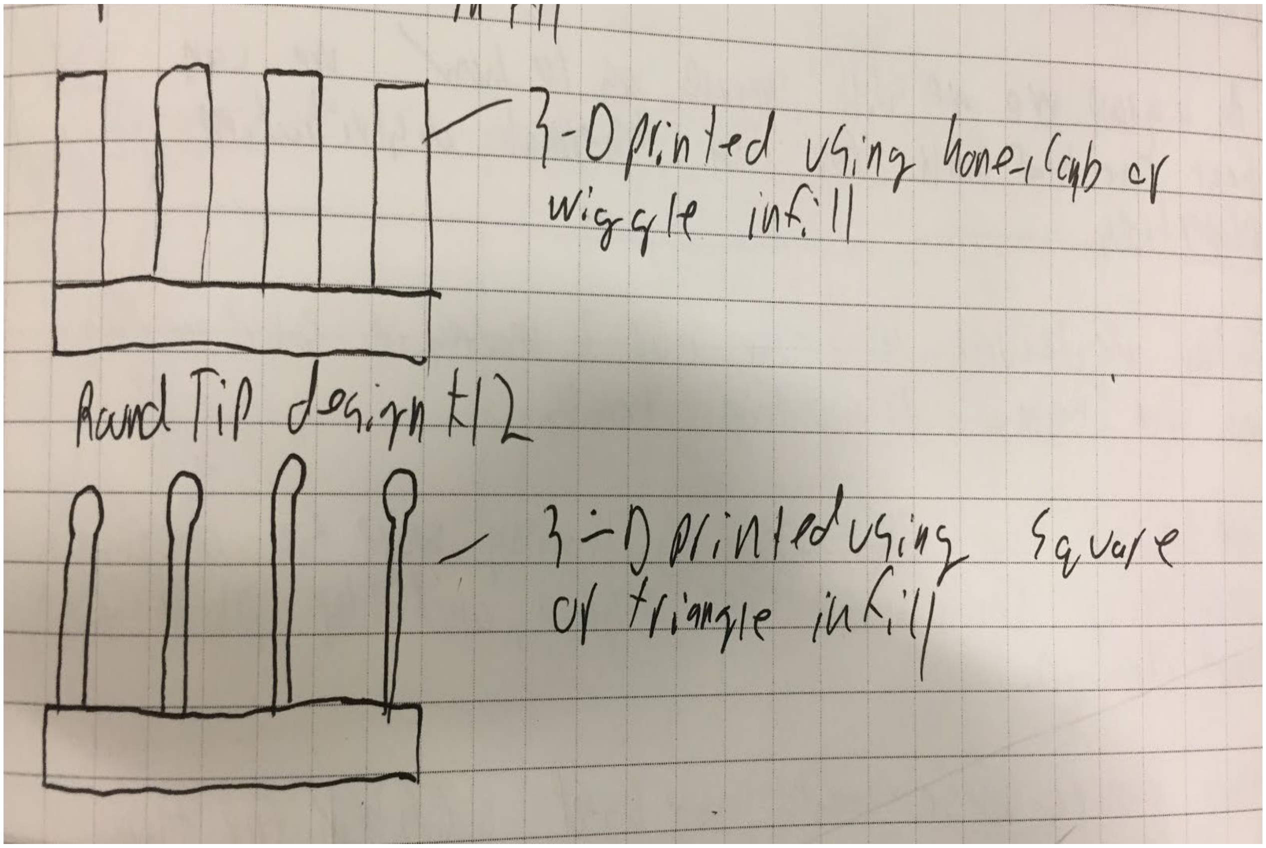


Figure (16): Heat Sink Design

QFD

A Quality Function Deployment assessment, or QFD was used by group 13. The QFD focuses on the customer needs and what elements the group needs to focus on to meet those needs. The QFD also highlights what elements of construction of the project interfere with each other. Lastly, the analysis takes into consideration other competitive products already on the market.

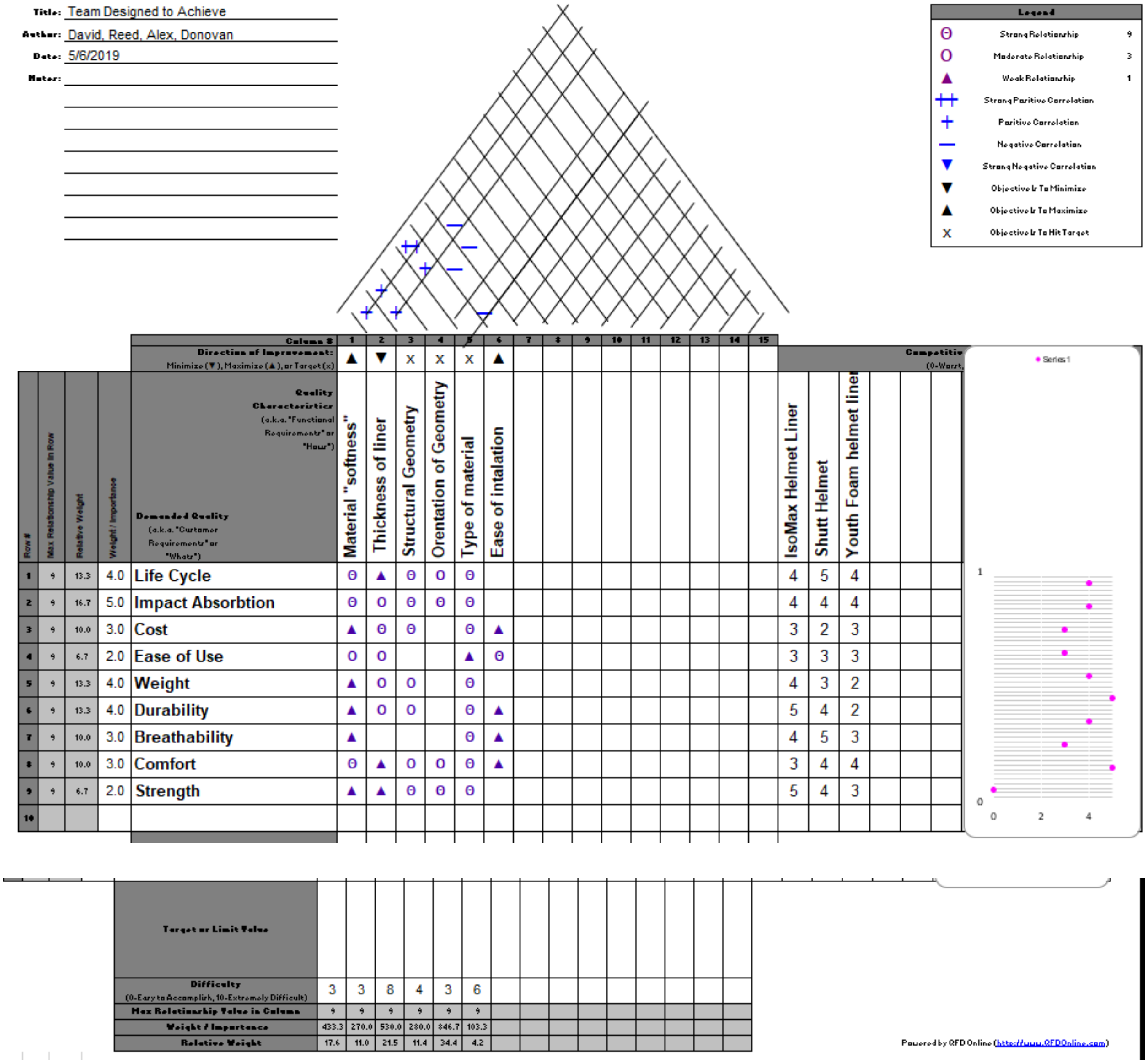
Demanded Quality

The Demanded Quality, or customer needs explained what the product needed to accomplish. Since the product that was chosen to highlight structural geometry was a football helmet liner, the group looked to the National Football League as guidance. First, a very important characteristic of a football helmet is that it will be operational for the required time. This was labeled “Life Cycle”. For group 13’s helmet liner to be competitive with the football helmets in use, it needs to be able to last just as long as the current designs. Impact absorption is the main purpose of a helmet liner. This was the highest weighted customer requirement. The cost of the helmet liner is something that could be extremely reduced through 3-D printing. If group 13’s design is to be better than the current design, it will have to be cheaper. The ease of use of a helmet is pretty much the same if the overall design is not changed. The new design of a helmet must be just as easy to use as the older designs. The weight of the helmet must be competitive with other products as well. Weight is extremely important in sports equipment, and players will almost always choose a lighter piece of equipment. The helmet liner also must be durable. If the structure is not reliable over multiple hits, then it is not functional. Breathability and comfort go hand in hand. These were chosen as Customer Requirements because players will gravitate towards the more comfortable helmet.

Quality Characteristics

Quality Characteristics, or how, explain how the group is to accomplish the customer quality. Material softness focuses on how soft the material used to print is to the touch. The material group 13 used is TPU. TPU comes in many different varieties, some of which are harder than others. The thickness of the liner has a direct impact on how the liner operates. If the liner is too thick, the player’s head will not fit inside of the helmet, if the liner is too thin, it will not provide enough protection. To optimize impact absorption, the helmet liner must be somewhere in the middle. Structural geometry is the focus of this project. As seen in the testing results, different structural geometries have different characteristics. To optimize our design, the proper structural geometry needed to be chosen. For similar reasons, the orientation of that geometry also affects the performance of the material. The type of material would change the performance as well. If the group chose a rigid and brittle material, that material would break under impact and not be sustainable under multiple hits. The TPU that group 13 used achieves this. Lastly, ease of installation, the helmet liner needs to be able to be installed into the helmet shell without much trouble.

Below, the visual QFD analysis is shown.



Title: Team Designed to Achieve
Author: David, Reed, Alex, Donovan
Date: 5/6/2019
Notes:

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Competitiv (0-Worst,		
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)	▲	▼	x	x	x	▲												
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Material "softness"	Thickness of liner	Structural Geometry	Orentation of Geometry	Type of material	Ease of intalation										IsoMax Helmet Liner	Shutt Helmet	Youth Foam helmet liner
1	9	13.3	4.0	Life Cycle	Θ	▲	Θ	O	Θ											4	5	4
2	9	16.7	5.0	Impact Absorbtion	Θ	O	Θ	Θ	Θ											4	4	4
3	9	10.0	3.0	Cost	▲	Θ	Θ		Θ	▲										3	2	3
4	9	6.7	2.0	Ease of Use	O	O			▲	Θ										3	3	3
5	9	13.3	4.0	Weight	▲	O	O		Θ											4	3	2
6	9	13.3	4.0	Durability	▲	O	O		Θ	▲										5	4	2
7	9	10.0	3.0	Breathability	▲				Θ	▲										4	5	3
8	9	10.0	3.0	Comfort	Θ	▲	O	O	Θ	▲										3	4	4
9	9	6.7	2.0	Strength	▲	▲	Θ	Θ	Θ											5	4	3
10																						

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Target or Limit Value															
Difficulty (0-Easy to Accomplish, 10-Extremely Difficult)	3	3	8	4	3	6									
Max Relationship Value in Column	9	9	9	9	9	9									
Weight / Importance	433.3	270.0	530.0	280.0	846.7	103.3									
Relative Weight	17.6	11.0	21.5	11.4	34.4	4.2									

Powered by QFD Online (http://www.QFDOnline.com)

Figure (17): QFD table

Design for X

Safety/Durability

The main concern about football nowadays is whether the players are safe from repetitive blows to their heads and whether that leads to concussions or more serious head trauma. The current football helmets on the market are made to absorb several linear impacts however they are not designed to attenuate rotational impacts. The idea behind using lattice structures within the helmet liner was to optimize the stiffness in all directions while using the least amount of material to do so. Hence Isomax, the lattice structure proposed, was tested to have the highest stiffness to lightness ratio. This structure is composed of "forming the shapes of pyramids with three sides and a base, and octahedra, reinforced inside with a 'cross' of intersecting diagonal walls (UC Santa Barbara Engineering)." In brief the Isomax structure is designed to resist crushing and shearing forces without increasing the density of the cell walls. The name Isomax comes from the idea of the structure having isometric properties even though the FDM additive manufacturing process creates anisotropic parts. So once the base Isomax cell was created there were some additional steps for "flexing" the outer edges of the base cell, to create "circular patterns" which spanned up and around to create the final half dome section full of "flexed" Isomax cells. This helmet liner was printed with a semiflexible material called Polyflex TPU. TPU is currently used as a material in football helmet liners due to its high abrasion and chemical resistance as well a low temperature flexibility and durability. Overall this helmet liner was designed to be able to crush and reform so that it can be used repeatedly until it fails so that a replacement can be put in its place.

Manufacturability/Reliability

The other main concern for the ones playing football is the availability of the product, and that has to do with how long it takes to manufacture. Due to the complexity of the print there was a definite need for structure material. So, to decrease the amount of support, the half dome section of flexed Isomax cells was reduced to an eighth section. This section was then rotated so that the longest flat face mated with the build platform. This allowed for the least amount of curvature of the helmet liner to span outwards from the bed, therefore the least amount of structure material necessary for that model. However, this took roughly 55 hours to complete in the raise3D printers available at Schneider Electric, which would result in about 20 days of printing for the final product. Afterwards the half dome was reduced yet again to create the thinnest possible slice, a twenty-eighth section (there are 28 columns of flexed Isomax cells that span 360 degrees to create the half dome section). This section was rotated and placed flat on the bed in the same manner as the eighth section. Now it could be printed in 9 hours, corresponding to about 10.5 days of printing, after optimizing the print properties. This mostly had to do with reducing the structure material and increasing the printing speed. This was also performed using the Wanhao Duplicator 4 Dual available in the 3D Printing Laboratory available in the URI library. The reason behind switching to such printer is that the reliability was very high given that there are 3D printing technicians available to calibrate and perform maintenance to such printers. This reliability factor was also comforting knowing that a lot of the issues in the past with the Raise3D printers would not be present. Going back to the first semester, when the Makergear M2 and M3-ID were available, these were the best when it came to reliability because of the little number of hours on such printers. However, those were inaccessible in the second semester due to the need for the full time use to create parts for a soft robotic arm in Hongyan Yuan's research project.

Project Specific Details and Analysis

Market Analysis

Participation in playing football has been steadily decreasing over the past 10 years. This is because recent studies have found strong links between brain damage and head injuries due to the violent hits that occur during football games. This has led to a decrease in the amount of sales of football helmets and football helmet liners. Football is one of the most popular sports to watch in America which means the interest is still there. The only reason the football helmet market is being held back is because of the technology. If athletes were assured to have fewer lingering injuries after the game, the football helmet that could achieve this would be extremely successful in the market. Team 13 believes this can be accomplished with the 3-D printed TPU Isomax/triple layer infill helmet liner.

Market Segmentation

Due to the versatility of the TPU, the technology that team 13 has developed can be applied to any football helmet regardless of age level. This means the product will be able to target 100% of the football helmet liner market.

Target Market

There are currently 32 NFL teams and this number has not changed in years which does not provide many possible customers. As of 2018 there are currently 774 colleges and universities that provide a football program. Although this may seem like a good market to target this is not the case because not many new college football programs are being created. Approximately only 5 new programs are started per year. Where an increased number of football helmets being sold can increase the most with the right technology is the youth football market. The choice to play football at a young age is completely up to the parent regardless if the child is interested. Because the technology is not there right now, this market is not being used nearly as much as it should be. With the current design of the football helmet team 13 has designed a higher emphasis on safety has been achieved which should lead to letting parents let their kids participate in youth football. This will restore the youth football helmet market to what it once was.

Market Need

There are many factors that will make potential customer want to purchase a football helmet. The main factors are, comfort, price, safety, and looks however the number one factor is safety. Team 13's helmet liner is extremely safe. Team 13's helmet is not as visually aesthetic as the average football helmet and still costs more than the average football helmet (2282$ vs $1500). Where team 13's helmet surpasses its competition is in comfort and safety. The helmet liner its self weighs 462 grams. That is a little less than a pound, this is far lighter than any other football helmet on the liner and will results in higher comfort compared to other football helmet liners. The most important factor that the helmet liner incorporates is its high safety. The combination of the triple sandwich layer with the Isomax dome structure creates a helmet liner that pushes impact absorption to its extremes. In addition, the material being used (TPU) makes sure the helmet liner can bounce back to its original shape which is crucial to football players in case of reparative hits in a short time span. Other helmet concepts liners such as the ones from UCLA (lattice structure concept) use a different material that takes a brief time frame to reform is dangerous and could lead to an increased risk of major head injury.

Cost vs Price analysis

The cost for manufacturing team 13's helmet liner is currently $2282 however when mass producing this product the price will dramatically fall as the raw materials used to produce the product is $41.47 (helmet liner and Velcro) and the helmet shell itself is approximately $300. Most of the cost to produce the helmet is using the 3-D printer for such a long period of time however with mass production this price will fall. There is no information on the top selling youth football helmet, but the top selling NFL football helmet is currently $1500. With $1500 being the amount that customers are willing to pay that will mean the vendor will profit -$782 when selling a helmet. Although this may seem like there is no money to be made with this product, the tradeoff of price for safety should increase what customers are willing to pay for a top of the line helmet that ensures maximum safety.

Detailed Product Design

The concepts team 13 came up with were the triple layer infill and Isomax structure. To implement these into the final design team 13 faced a major problem. The problem was fitting these infills/structures. The solution to this was using the flex command and placing these structures on a specific degree of arc that made up the helmet liner.

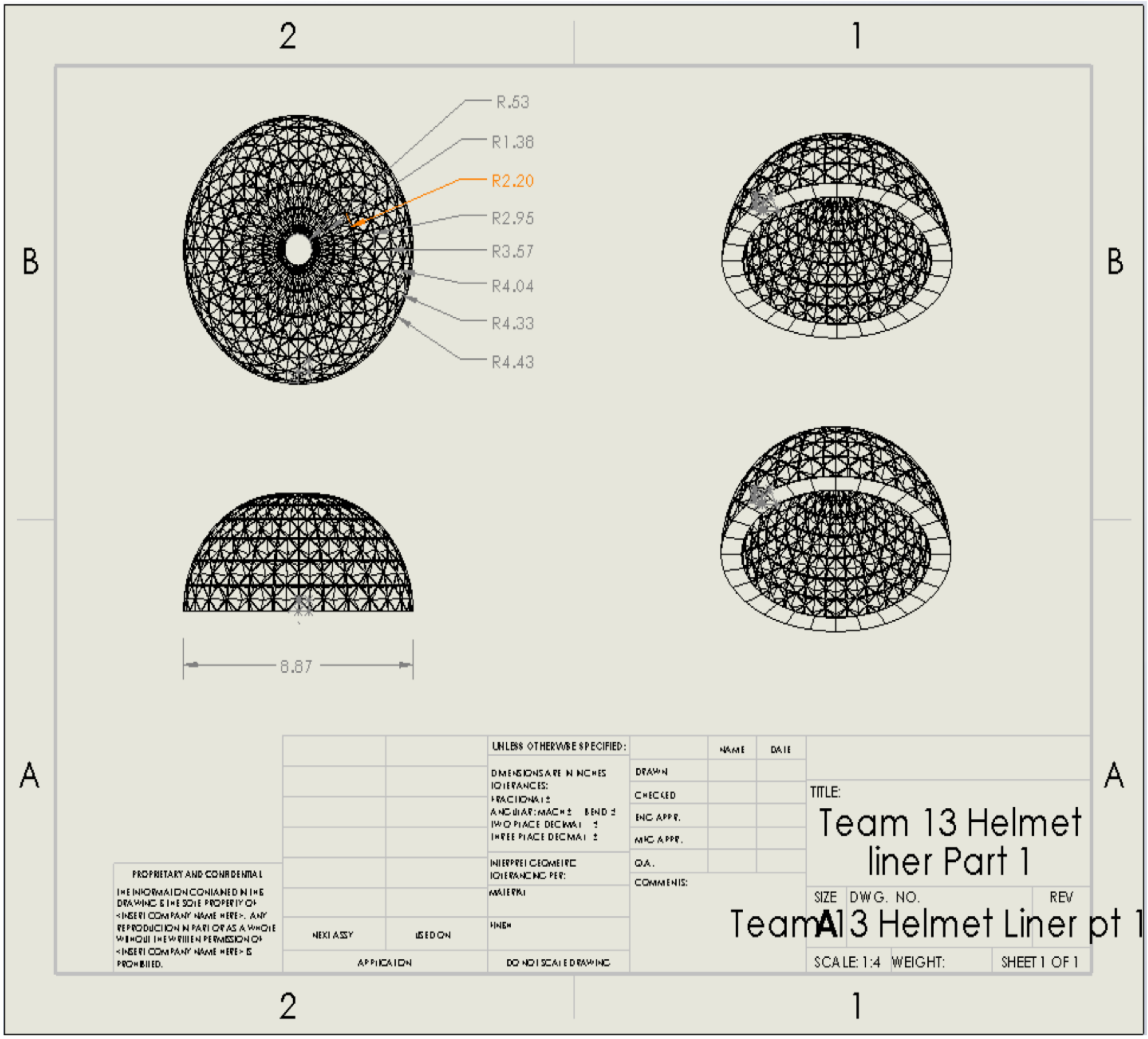


Figure (18): Technical documents for the Helmet Liner

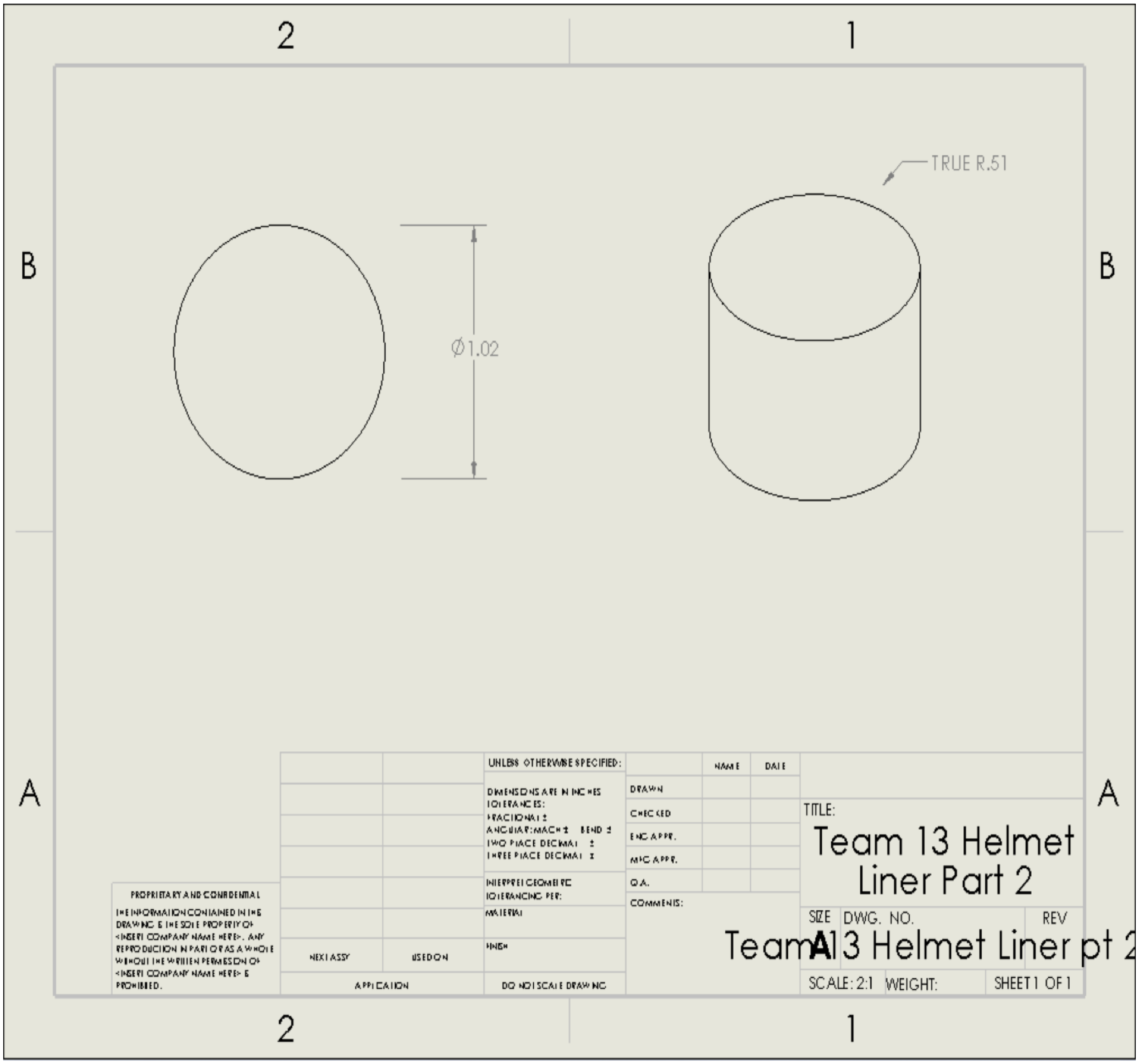


Figure (19): Helmet liner (triple layer infill)

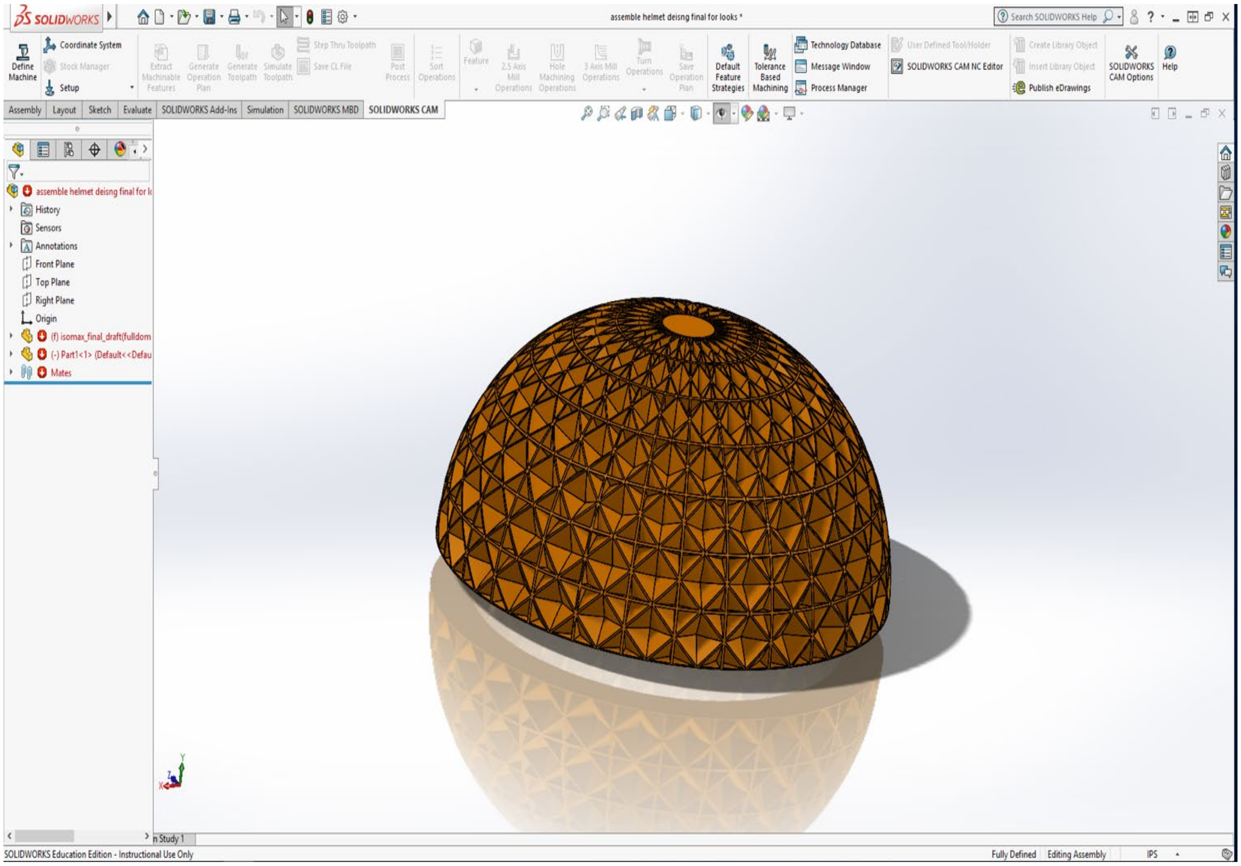


Figure (20): Assembly of complete liner in solidworks

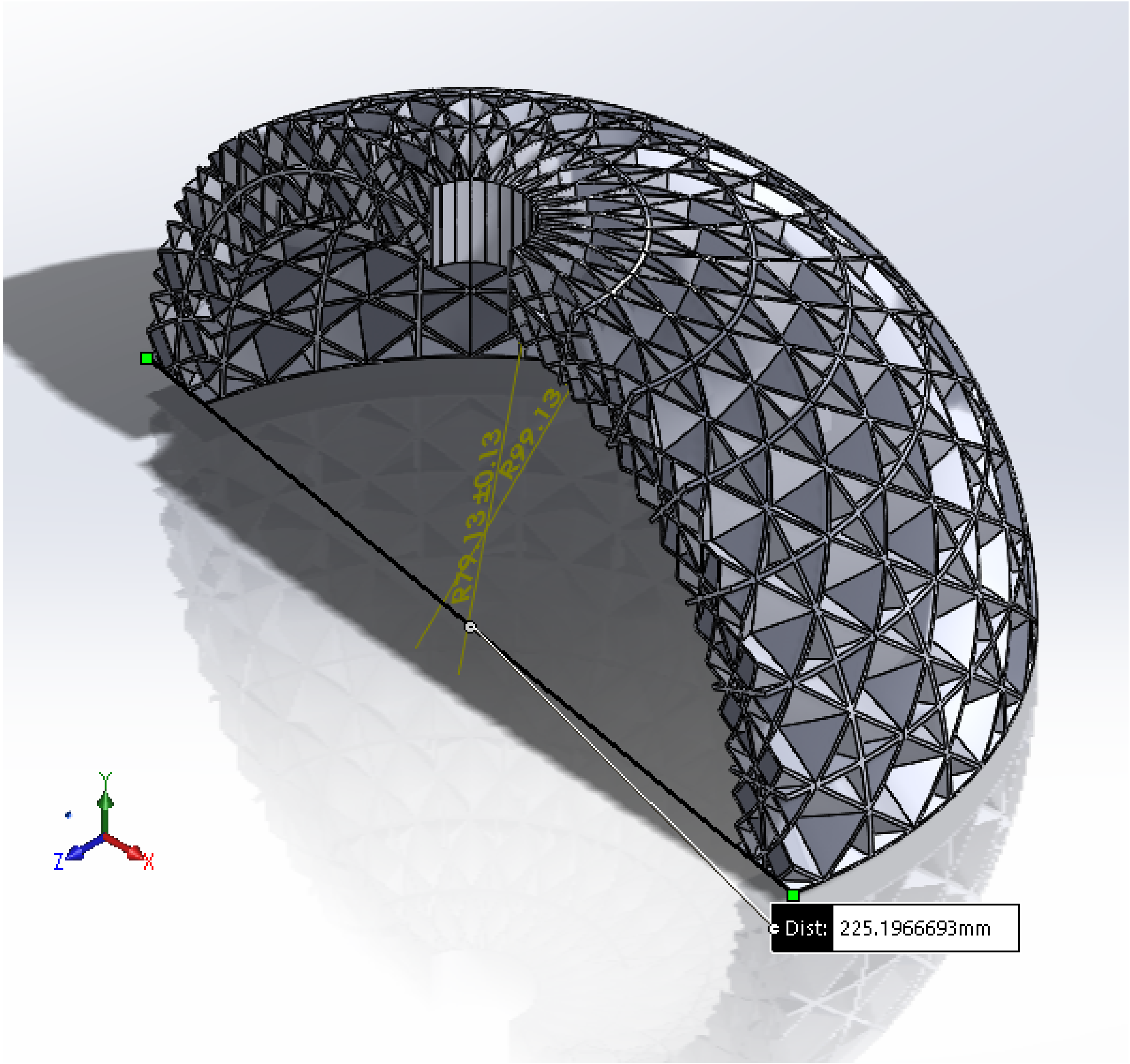
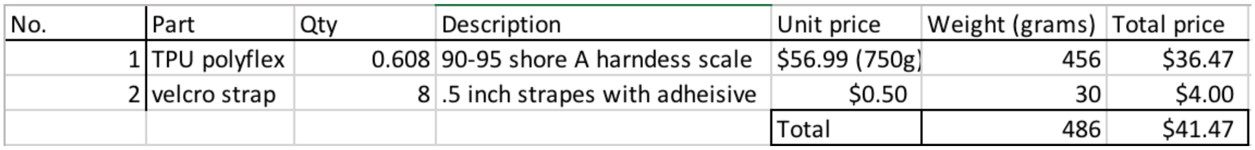


Figure (21): Cross sectional view of helmet assembly

BILL OF MATERIALS

Table (2): Bill of Materials



No.	Part	Qty	Description	Unit price	Weight (grams)	Total price
1	TPU polyflex	0.608	90-95 shore A harndess scale	$56.99 (750g)	456	$36.47
2	velcro strap	8	.5 inch strapes with adheisive	$0.50	30	$4.00
				Total	486	$41.47

Engineering Analysis

Material Analysis

The product is made from Polyflex TPU, a lightweight, semi-rigid thermoplastic that bends under stress, and returns to its original shape after deformation. Since the helmet is designed to take multiple hits with varied recovery period, it is very important that the helmet liner be able to absorb an impact and return to its original shape rapidly to absorb the subsequent impact.

Polyflex TPU is also sensitive to ambient humidity. This is most noticeable during the product process, where humidity levels of greater than 50% of the relative humidity can have an adverse effect on printing, leading to manufacturing errors and production delays. This can be offset by implementing a method of environmental control such as a dehumidifier. In the future, a second capstone team could revisit this project and test the helmet liner under various humidity levels, and test how the helmet liner behaves or feels if a player is using the helmet and perspiration is building up.

Polyflex TPU prints at temperatures between 210˚C and 230˚C and is solid below these temperatures. The helmet is designed to operate at temperatures between -18˚C and 45˚C and can be expected to operate reliably under these conditions.

Structural Analysis

The primary body of the helmet liner is printed with a 3-D geometry called Isomax. Isomax is a cell shape designed to have an optimal stiffness-to-weight ratio by the University of California-Santa Barbara [3]. Isomax is an excellent choice for this project because it approaches the theoretical limits of material strength, while remaining extremely lightweight since it consists mostly of empty air pockets. This allows the helmet liner to be only ~500 grams in total weight but remain a strong structure capable or absorbing impacts.

A small portion at the top of the helmet liner will be printed with a triple-layer geometry originally conceived for this project. Called "sandwich geometry", it features two outer layers of wiggle geometry, and an interior layer of honeycomb geometry. These geometries were chosen for their unique features that were made apparent during testing and FEA analysis. Specifically, honeycomb geometry was the second-stiffest geometry during three-point bending and compression testing and was strong in all directions. It was also much lighter than the stiffest geometry, and so was chosen to be the core of the sandwich geometry. Wiggle geometry was not very stiff but absorbed impacts and distributed the force of direct impacts in parallel directions to the body. This is most apparent in the Abaqus models.

Abaqus Models

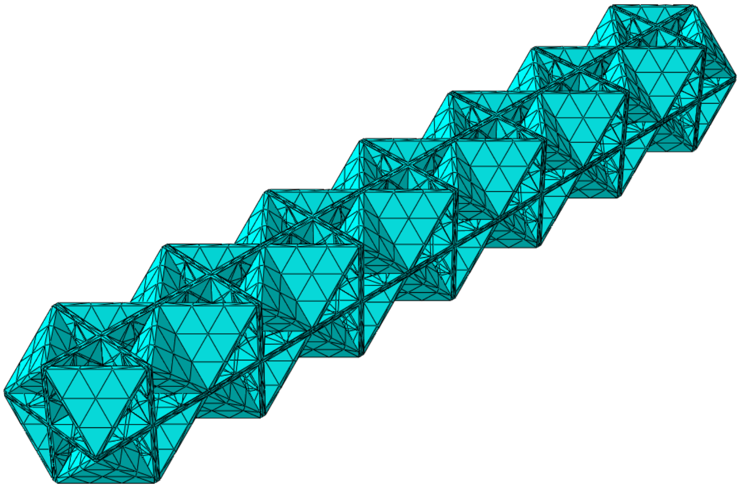


Figure (22): An attempted mesh of Isomax geometry undergoing 3-point bending

Attempts were made to analyze Isomax geometry in Abaqus. These attempts were unsuccessful due to the overall complexity of the Isomax geometry, and due to time constraints. Attempts to import Isomax geometries from Solidworks to Abaqus took over twelve hours to run and had numerous import errors that rendered them unreliable models for testing. With more time, more advanced simulations, or a more powerful computer FEA models could be simulated to better understand how Isomax geometries distribute strain as an assembly.

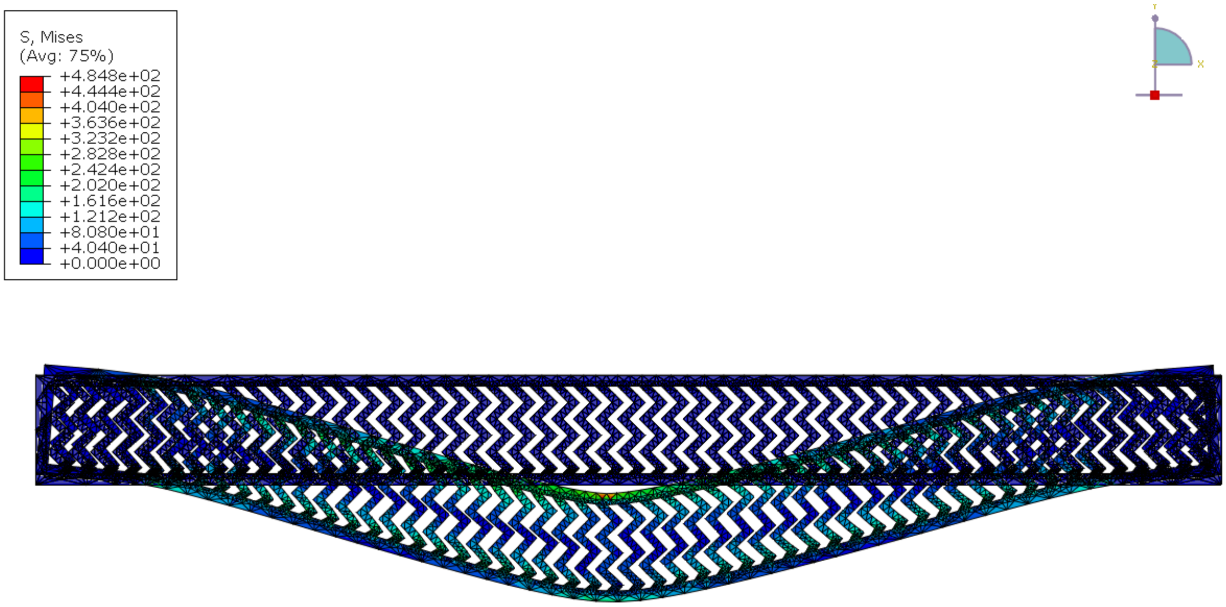


Figure (23): The wiggle geometry, based on printed samples, experiencing 3-point bending stress

In this model, a force was applied to the central point of the top layer and two vertically static boundary points were set at points 10 cm inward from either side of the bottom layer, shown as red shapes here. One thing that was apparent from both the Abaqus model and from experimental testing is that much of the force is not translated vertically through the model or absorbed by the geometry. During testing, it became apparent that this was because the wiggle geometry tends to redirect force horizontally. This may explain why so much of the stress remains at the top of the model. This may be because the shape of the wiggle geometry allows the struts to collapse into each other and fold together, redirecting the impact forces elsewhere. This could be a helpful feature for the outer edge of a football helmet and is why this geometry was chosen as the outer layers of the sandwich geometry.

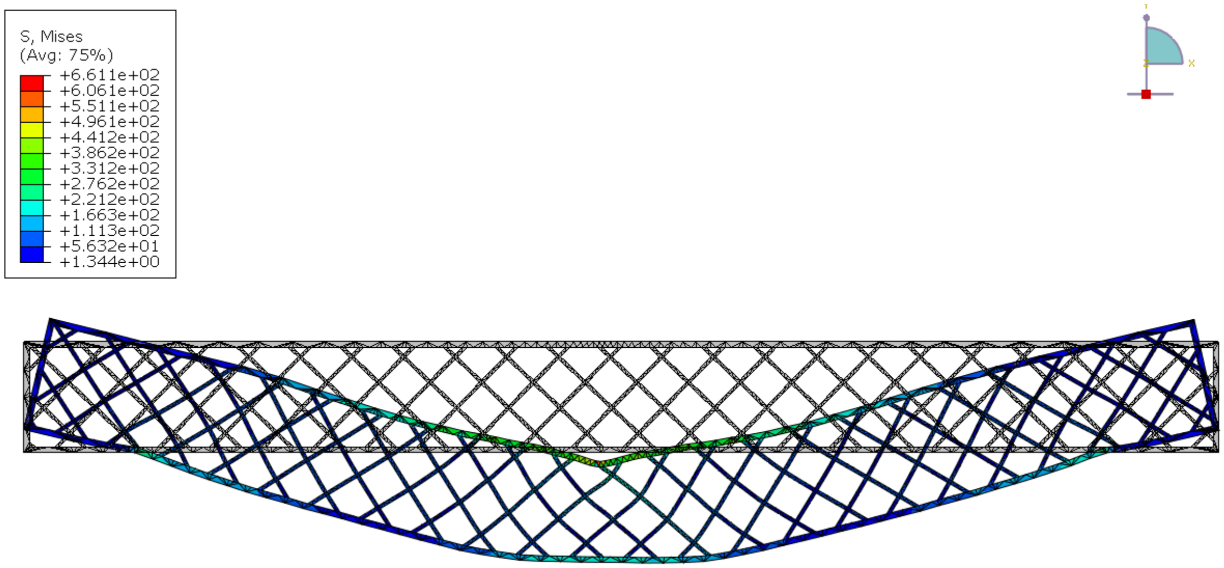


Figure (24): The rectilinear geometry, based on printed samples, experiencing 3-point bending stress

This model was done to compare rectilinear geometry with wiggle geometry. Rectilinear is similarly lightweight and flexible, but the Abaqus model helps clarify some points of concern. Specifically, the rectilinear model is more prone to buckling, as can be seen in the highlighted areas. Some deformation is acceptable and even encouraging if the deformation is elastic and serves to absorb and disperse impact forces. The buckling shown here in fig (x) is concerning because it shows a that this geometry might tear. That is why this geometry was not chosen for the helmet liner.

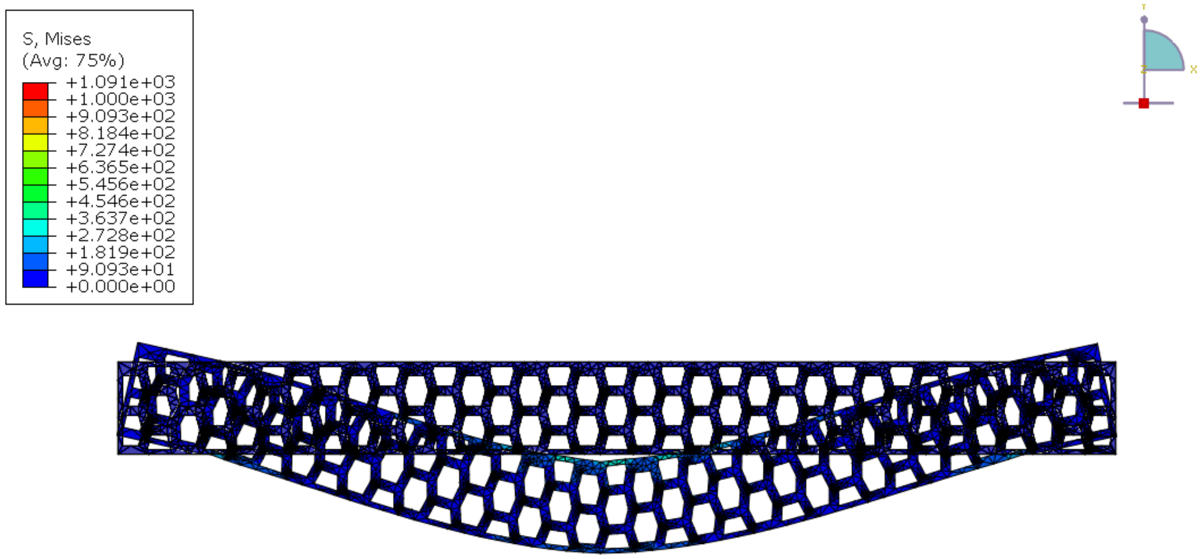


Figure (25): The honeycomb geometry, based on printed samples, experiencing 3-point bending stress

The first thing that is clear is that the simulated geometry can absorb most of the stress very efficiently. The initial force and boundary conditions are concentrated within the red circles and are where the stress is relatively high. The stress that this geometry experiences is higher than the stress experienced by the wiggle geometry, but far more concentrated. All simulations used the same boundary conditions, material properties and forces. The difference in stress distribution indicates that this geometry is far more rigid, requiring more stress concentration to deflect and does not easily buckle.

State of the art:

The Isomax geometry is relatively new, and according to analysis done by scientists at UC Santa Barbara, approaches the theoretical limits of material stiffness as defined by the Hashin-Shtrikman Bounds (Berger, 2017). The sandwich geometry is our own design but implements common infill geometries to create a new design. Further testing should be performed in accordance with NOCSAE standards and ANSI/ ISO 17065 International Guidelines. The helmets should be tested with triaxial accelerometers at the center of gravity and a realistic head form. The first set of tests involves dropping the assembly onto seven specific test points on the helmet, and three additional randomized points. The second set of tests needed to ensure that this product meets safety guidelines is to use an impactor to hit the assembly at speeds greater than or equal to 64 feet per second, and at six different test points, followed by one randomized test point. If the helmet passes all impacts and meets standards, it will be considered up-to-code.

Build/Manufacture

The procedure for building and manufacturing the Isomax cell filled helmet liner was straight forward after the models were perfected in Solidworks. The major problem when it came to printing at first was whether the models were sliced correctly. Slicing is the process of transforming the STL model into g-code. This g-code is read by the printer based upon the settings applied by the slicing software i.e. simplify3D, Ideamaker, slic3r, cura, etc. The slicing software used was simplify3D and Ideamaker. Simplify3D was used the most however because of the print preview option. This was very convenient because it allowed the users to look at the path at which the extruders would follow for each line. So simplify3D was the key for understanding where the voids were coming from in between the cell walls. This made the team realize that the models would never come out perfect unless they were edited in Solidworks. The issue was then located and the only step necessary in editing the model was to add a combine function. This is illustrated in the screenshots below, with the 1/8th symmetric section of the base Isomax cell.

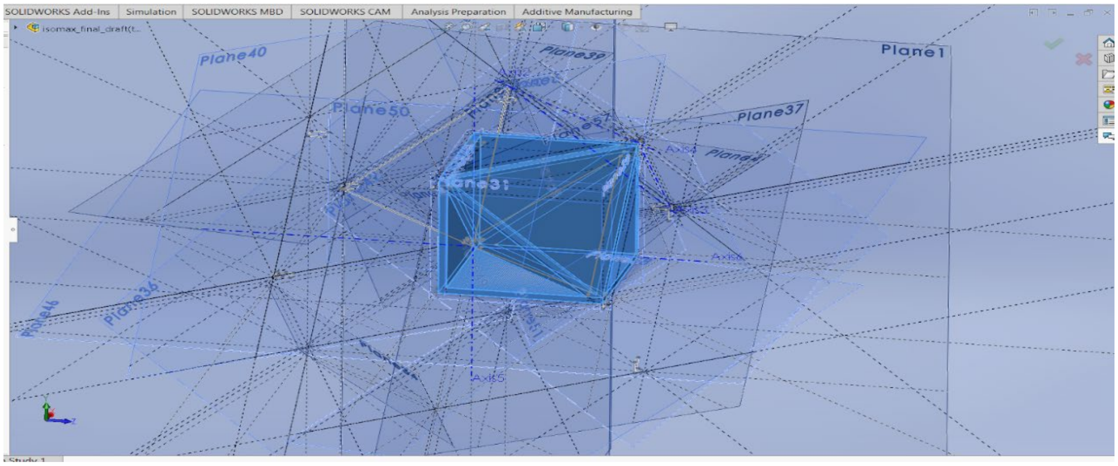


Figure (26): Section of Isomax geometry

Since this symmetric section was in two pieces instead of one before the combine function, there was a void in the cell wall as depicted in the sliced preview below.

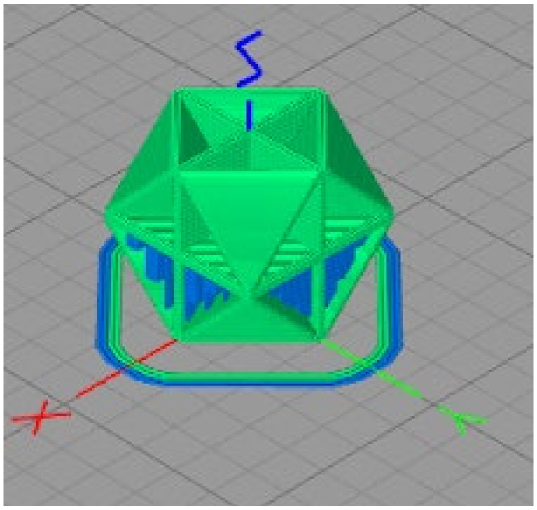
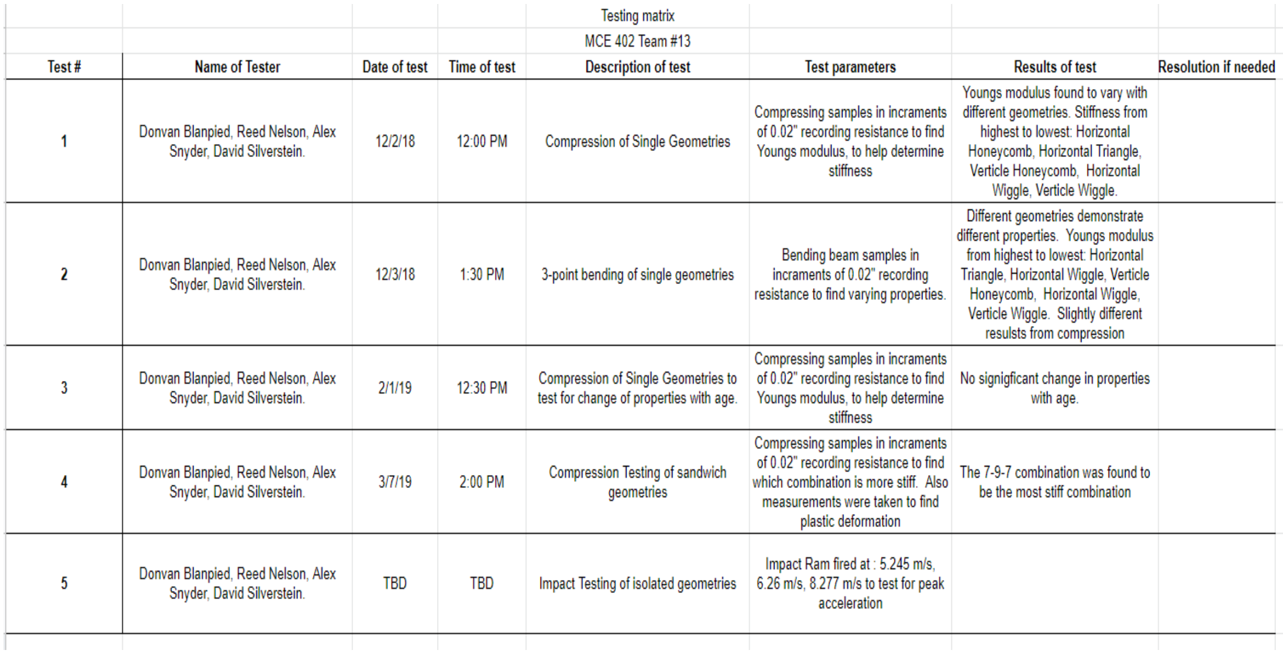


Figure (27): 3-D model of Isomax

However, after that change was made in Solidworks the model was finally sliced correctly. Once the models were sliced correctly the hardest part was over. The printer properties were then optimized by first starting off with the recommended Polyflex TPU and PVA print settings, and then making slight changes based upon how well the extruders were depositing the filaments. For example, the most important changes as oppose to printing speed and temperatures, was to turn off retraction completely for the Polyflex TPU and adding an ooze shield. This was important because retraction was causing jamming and therefore the first layer of TPU was great but afterwards it was not able to laminate. However, there were some other issues that also caused jamming or under extrusion. The first one that came about was the filaments absorbing moisture from the ambient air surrounding it. This is because both Polyflex TPU and PVA are hygroscopic. So as a counter, these filaments were stored in an airtight container with a desiccant dehumidifier as well as some desiccant packages. This provided a means for regulating the moisture, but sometimes even a pre-drying process was necessary depending on how long those materials were exposed. The recommended drying procedure was to keep the filaments in the oven for 4 to 6 hours at 70 degrees Celsius. If this was not performed when necessary, the most obvious indicator was that the extruders would have steam flowing out with the filament. The other thing noticed was bubbles in the strands. However, printing in an enclosed printer like the raise3D N2 dual and dual plus could prevent the need for pre-drying. The raise3D printers were not completely air tight because some of the doors didn’t stay flush and there were no gaskets along the seams. Although having the desiccant dehumidifier and packages spread within the enclosure helped for those long prints of about 55 hours. There were also problems getting the TPU to extrude at the beginning of this project. This solely had to do with the fact that Polyflex TPU is semiflexible and for that reason it would get spun around the gear and not even reach the hot end. That issue was fixed by decreasing the loading speed for TPU and by relieving any drag on the filament. Drag on the filament was usually caused by kinks in the guide tube or by filament residue getting stuck in the polycarbonate guide track. Overall there were several other issues with the raise3D printers. For example, a bent extruding rod caused an offset in the x-y plane between both extruders as well an offset in the z level. There were several attempts to calibrate the extruder offsets, but the bent rod was causing under extrusion for the TPU due to its added drag. Therefore, even though these printers regulated the environment well, the vast amount of other issues made it not worth using them. That is why the executive decision was made to switch over to the library printers for the remainder of the semester. Since dual extrusion was a necessity for printing complex lattice structures, the only one available was the Wanhao Duplicator 4 Dual. This was nice to use but it did not have a complete enclosure like the raise3D printers. So as a counter it would be recommended to buy an airtight enclosure that the printer could fit in, so that the desiccants could properly regulate the humidity for long prints. The final step for manufacturing these models was a post process. This involved dunking the models in water to allow the PVA support structure to degrade. Anything that did not immediately get absorbed could be taken out with tweezers. Finally, after the model is clean, there is a post-drying process that is performed exactly like the pre-drying. Afterwards the models would be laminated with sheets of Velcro on both outer and inner curves, so that it can be easily fixed and removed from the helmet when necessary.

Testing

Over this past year, group 13 performed tests to isolate the performance of different structural geometries. The basic performance and material properties of the different geometries needed to be assessed to accurately optimize our design. Below is the testing matrix explaining all the testing that was done.



Testing matrix

MCE 402 Team #13

Test #	Name of Tester	Date of test	Time of test	Description of test	Test parameters	Results of test	Resolution if needed
1	Donvan Blanpied, Reed Nelson, Alex Snyder, David Silverstein.	12/2/18	12:00 PM	Compression of Single Geometries	Compressing samples in incraments of 0.02" recording resistance to find Youngs modulus, to help determine stiffness	Youngs modulus found to vary with different geometries. Stiffness from highest to lowest: Horizontal Honeycomb, Horizontal Triangle, Verticle Honeycomb, Horizontal Wiggle, Verticle Wiggle.	
2	Donvan Blanpied, Reed Nelson, Alex Snyder, David Silverstein.	12/3/18	1:30 PM	3-point bending of single geometries	Bending beam samples in incraments of 0.02" recording resistance to find varying properties.	Different geometries demonstrate different properties. Youngs modulus from highest to lowest: Horizontal Triangle, Horizontal Wiggle, Verticle Honeycomb, Horizontal Wiggle, Verticle Wiggle. Slightly different resulsts from compression	
3	Donvan Blanpied, Reed Nelson, Alex Snyder, David Silverstein.	2/1/19	12:30 PM	Compression of Single Geometries to test for change of properties with age.	Compressing samples in incraments of 0.02" recording resistance to find Youngs modulus, to help determine stiffness	No signigficant change in properties with age.	
4	Donvan Blanpied, Reed Nelson, Alex Snyder, David Silverstein.	3/7/19	2:00 PM	Compression Testing of sandwich geometries	Compressing samples in incraments of 0.02" recording resistance to find which combination is more stiff. Also measurements were taken to find plastic deformation	The 7-9-7 combination was found to be the most stiff combination	
5	Donvan Blanpied, Reed Nelson, Alex Snyder, David Silverstein.	TBD	TBD	Impact Testing of isolated geometries	Impact Ram fired at : 5.245 m/s, 6.26 m/s, 8.277 m/s to test for peak acceleration		

Figure (28): Testing Matrix

Performance Testing

When the group decided to target impact resistance, the next step in the process was to figure out how to measure that numerically. Young's Modulus came to mind. In short, Young's Modulus is a way to measure how stiff a material is. Group 13 decided to focus on testing how Young's Modulus and impact strength were related. To do this, 4 different infill patterns were printed in two different orientations. The wiggle, recliner (grid), honeycomb, and triangular infill patterns were selected to be tested. These patterns were chosen because they are the most common of infill patterns used in 3-D printing. The infill patterns were also printed in horizontal and vertical orientations. Below, an example of the two orientations is demonstrated with the honeycomb infill pattern.

To do this, two basic tests were performed. A three-point bending test, and a compression test were performed with the Instron testing machine, as seen below.

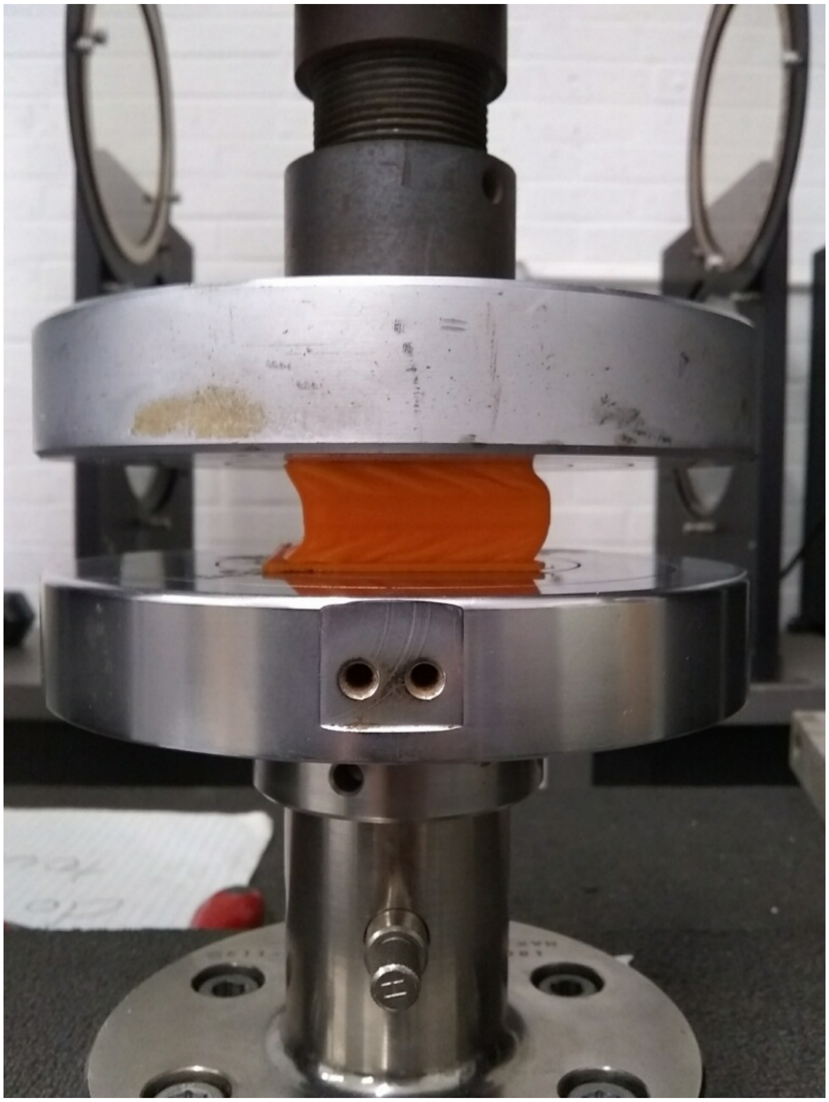


Figure (29): Image of sandwich structure in compression

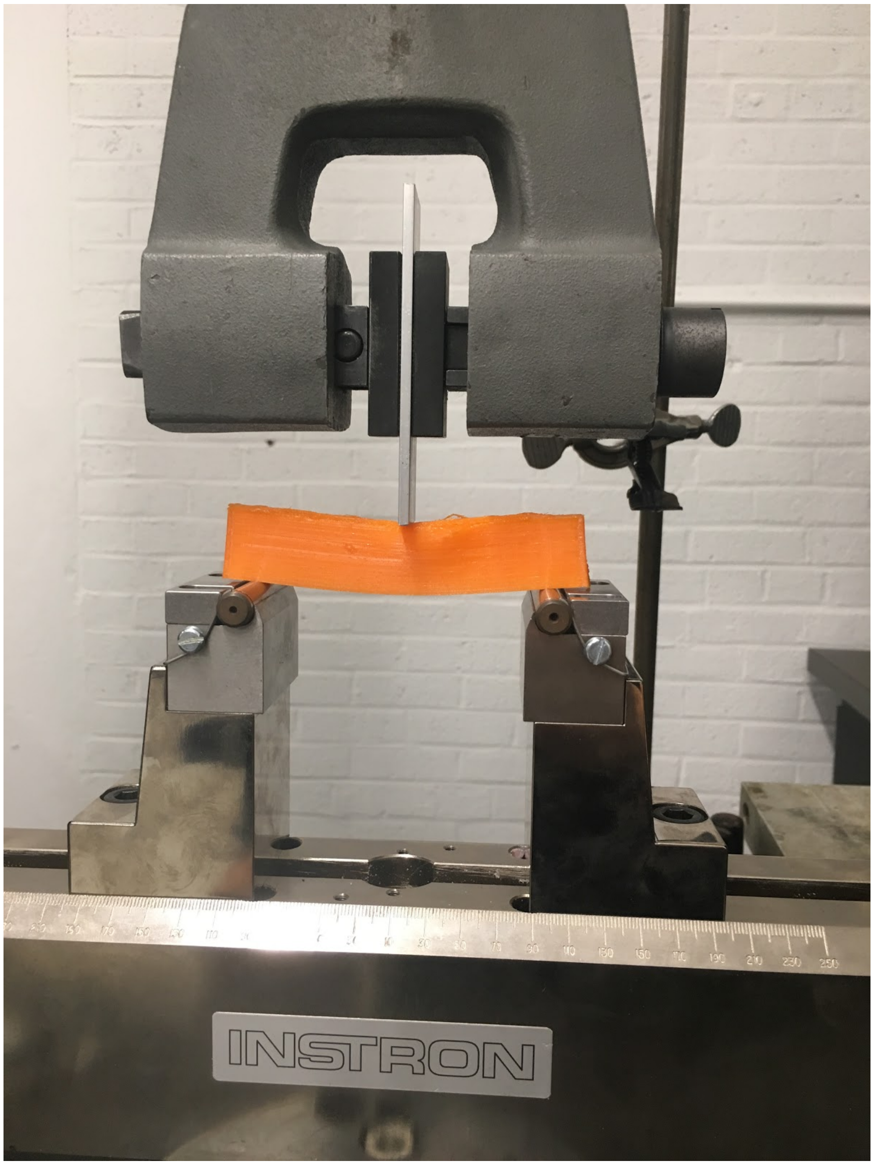


Figure (30): Image of Honeycomb in 3-point bending

These experiments measured how much force it took to deform the test samples. The deformation was done at increments of 0.02 inches according to ASTM standards [1,2]. Below are the graphs displaying force as a function of displacement.

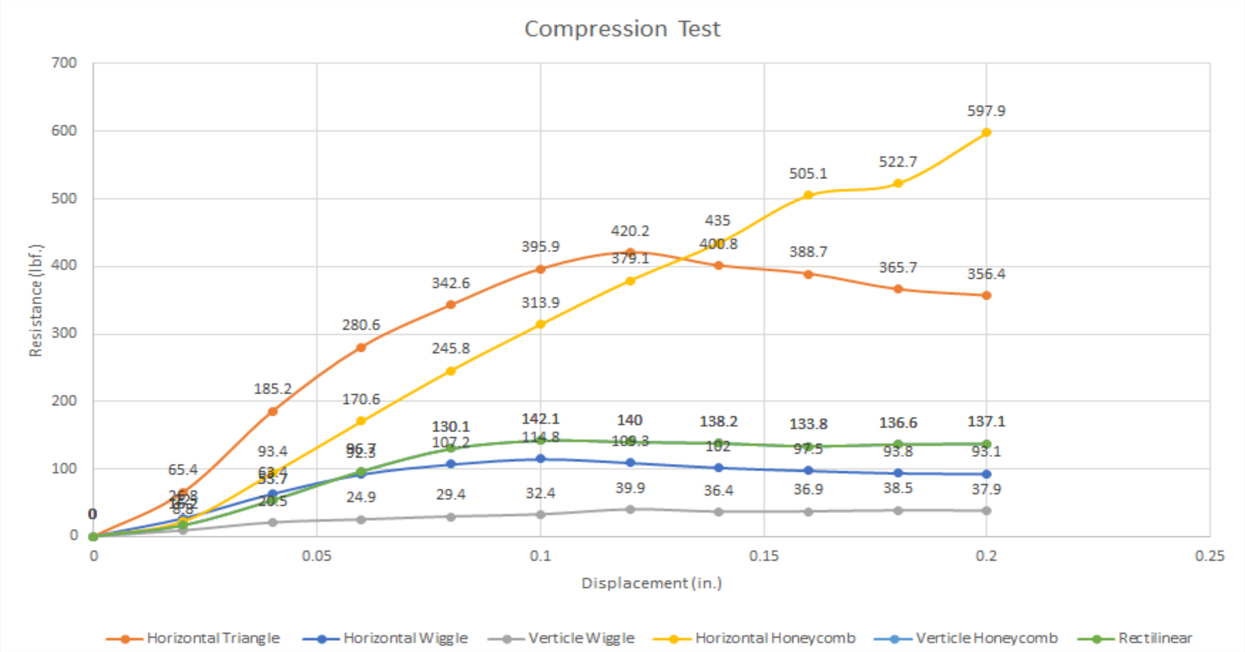


Figure (31): Graph displaying results of compression testing

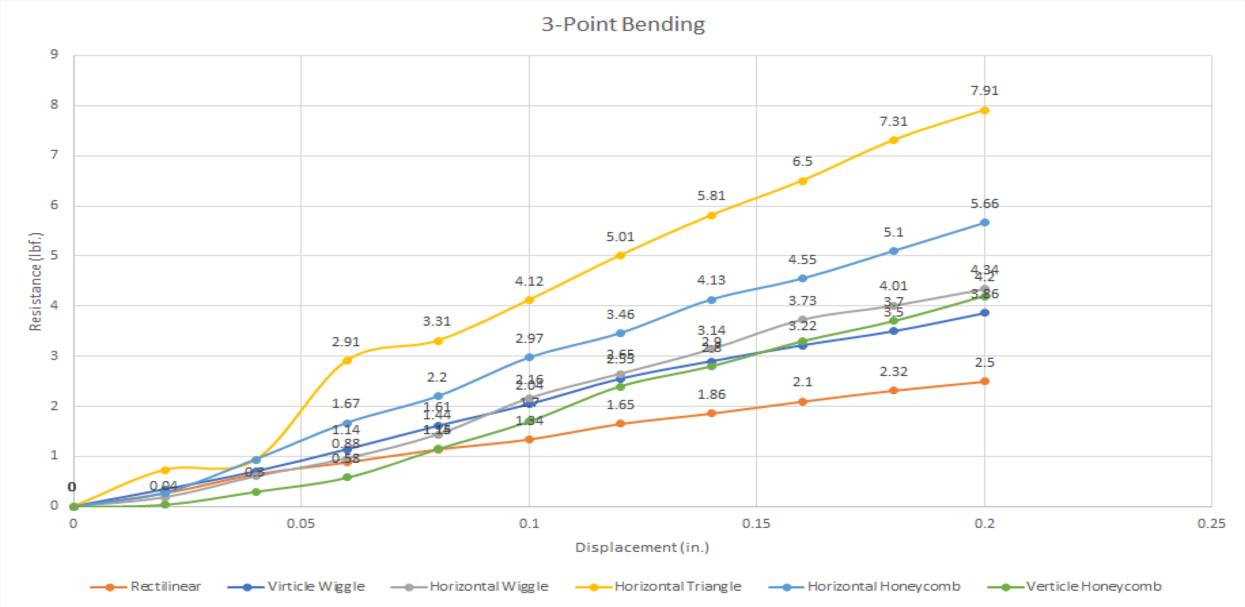


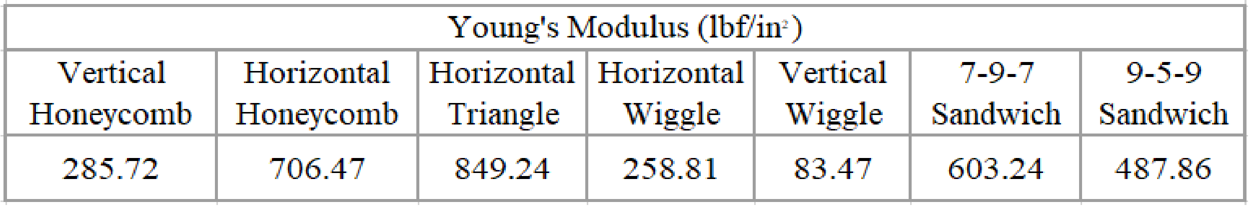
Figure (32): Graph displaying results of 3-point bending test

Using force and displacement, Young's Modulus could be calculated using the following equation.

Equation (1): Young's Modulus

$$E=(F/A)/(\Delta L/L)$$

Table (3): Young's Modulus of different infill patterns



Young's Modulus (lbf/in^2)						
Vertical Honeycomb	Horizontal Honeycomb	Horizontal Triangle	Horizontal Wiggle	Vertical Wiggle	7-9-7 Sandwich	9-5-9 Sandwich
285.72	706.47	849.24	258.81	83.47	603.24	487.86

From the results of the compression and bending tests, the wiggle geometry was the softness of all the patterns and the honeycomb was the hardest. Softness is great for impact absorption, however, after some displacement, the structural geometry of the soft patterns completely fails. To counter this, a middle ground was needed. The group decided to layer the infill patterns. Using the hardest geometry (honeycomb) as a middle layer to provide support for the outer, softer (wiggle), patterns. Two different variations of the layered infill were tested.

Testing Complications

Unfortunately, there were complications surrounding the testing equipment. The next step after compression and bending tests was to find impact resistance. This would have been done using the University's horizontal pneumatic ram impactor. The impactor ram was equipped with an accelerometer. This would have been used to strike the test sample. The acceleration would have been recorded, and the sample with the lowest peak acceleration would have the best impact resistance. The large changes of direction, or accelerations, are the main causes of head injuries resulting from impacts in sports. The lower the peak acceleration, the lower the trauma to the head. Due to unforeseen complications, the impactor was not operational for the last half of the semester.

Another issue came from the Instron machines used for the compression and bending tests. The machines were not initially calibrated correctly. The force feedback had a "creep" and could not be zeroed completely. This creep gave inaccurate force readings. This creep only shifted results about 8 lbf. Due to the relatively small creep, the issue was ignored, and the team kept the test results.

Future Testing

In the short term, the impact testing of the different geometries should be done. As stated above, the testing equipment was not available for use. Also, the group did not have the opportunity to test the Isomax geometry in the same fashion as the other geometries. This was due to time restraints. Performing the same compression and bending tests to the Isomax would give a side by side comparison of how all the geometries perform.

Other testing would include accelerated life models. These tests would examine how the final design of the helmet liner holds up under long periods of use. An accelerated life model could consist of repetitive impacts, with enough time for the structure to recover, over a long period of time. As stated in the design specifications, the average helmet in the NFL lasts up to 2 years. Each year, the average player experiences up to 600 hits, in practice, games, and off-season training. To accurately perform accelerated life models, the helmet liner would have to undergo around 1200 hits. After the hits are performed, the structure would be again tested and compared to performance before the repetitive hits.

Another future test could be the drop test used in NOCSAE standards. In these tests, a head form is fitted with an accelerometer and inserted into the helmet to be tested. This entire assembly is then dropped, using a wire guide, from varying heights. Peak acceleration is then measured. This test analyses the performance of the entire helmet assembly. This test would be useful for analyzing different types of TPU, different formations of the liner, and different thicknesses, would affect peak acceleration.

Due to the varying environments that this helmet would operate in, humidity and temperature testing should be tested as well. Since the TPU material is slightly porous, it is not resistant to water. If a game was played in a very humid environment, it might affect the performance of the Isomax structure.

Redesign

At the end of the first semester the group had proposed manufacturing a helmet liner that has sandwiched several infill patterns. The idea was to have an upper and bottom layer consisting of 30% wiggle infill (both having same thickness) and a 30% honeycomb infill in between two 1 mm thick top and bottom walls (100% rectilinear) which connects it to the wiggles. The wiggles are there to attenuate to the rotational deformation in 1 direction (the wiggles tend to buckle perpendicular to the direction of the way the wiggles were printed as shown above) both on the top and bottom, while the honeycomb would attenuate for direct linear blows to the head.

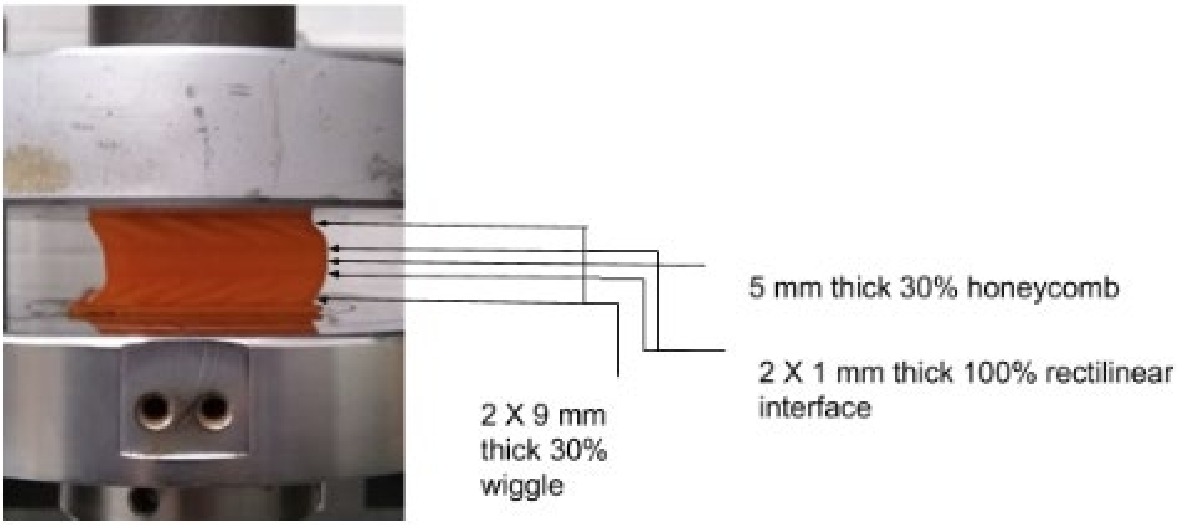
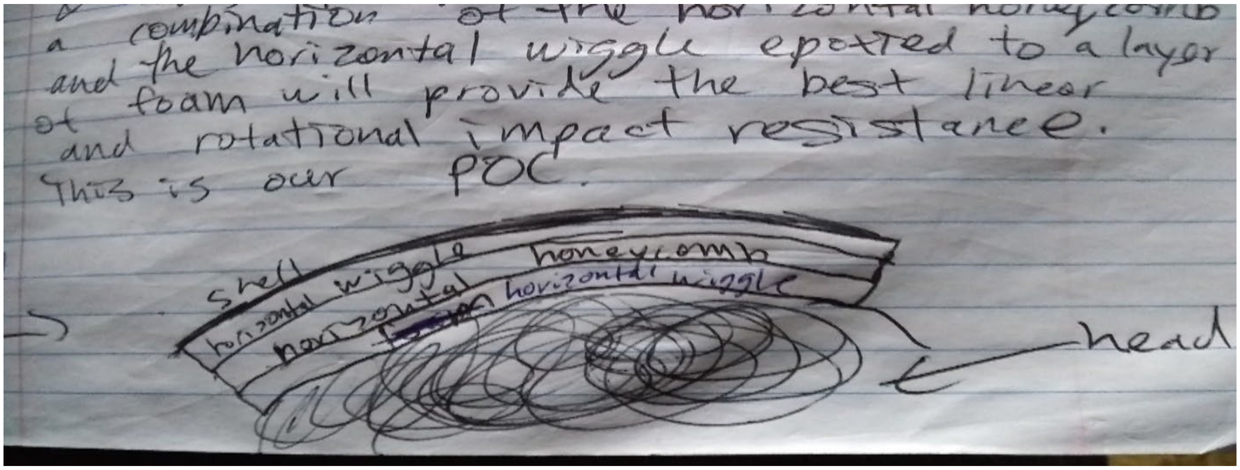


Figure (33): Sandwich assembly being compressed

However, there is not a slicing software available to allow the infill patterns of these sandwiches to be completely orthogonal to the curvature of the helmet liner while printing. The sketch of this theoretical design provided below supplements the above description.



a combination of the horizontal honeycomb
and the horizontal wiggle epotted to a layer
of foam will provide the best linear
and rotational impact resistance.
This is our POC.

Figure (34): Theoretical helmet liner design

So unfortunately, this design can only attenuate linear blows and shearing in 1 direction and can only be printed feasibly for flat rectangular pieces. However, the Isomax cell was designed to resist crushing and shearing forces in all directions. Also, the idea was to minimize the amount of material used. So instead of printing things with a low infill, the Isomax cell was designed to be printed with 100% rectilinear infill. The geometric design of the Isomax cell has air pockets which makes it light but also has interconnecting cell walls which make it highly stiff in all directions.

Redesign Overview:

Once the group settled on using the Isomax cell as a base lattice structure for the football helmet liner the next step was to figure out how to alter the base cell so that it could be utilized to fit in the place of the liner for an old youth football helmet. The first step was to print an Isomax cell that fits within a 30 x 30 x 30 mm^3 cube out of the Polyflex TPU. After that lines were drawn on the outer edge of the preexisting foam liner 6 times, indicating that exactly 7 of those cells fit across the outer edge that spanned over a 90-degree angle. Then the arc angle was devised by taking the 90 degrees and dividing it by 7. Knowing that the cell size must reduce as the arc get closer the head, the size of the base cell in the liner was chosen to be 20 x 20 x 20 mm^3 arbitrarily. Afterwards a video describing the flex function in Solidworks was utilized. The flex function shown below was used twice to alter the angle of the outer edges the Isomax model with the arc angle described above.

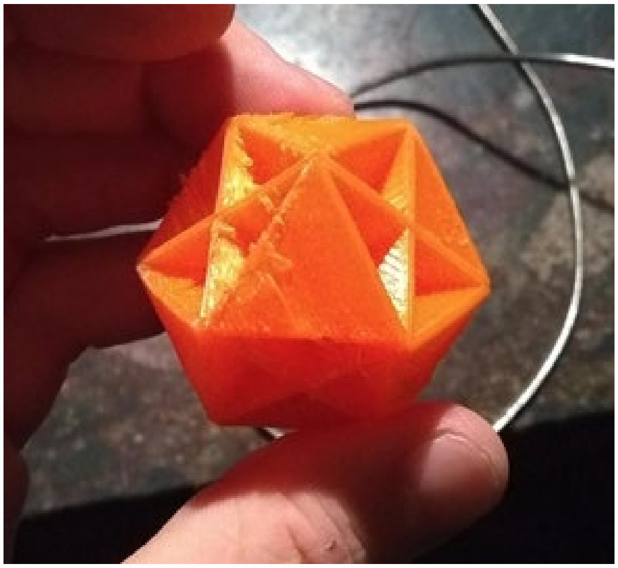


Figure (35): Isomax cell

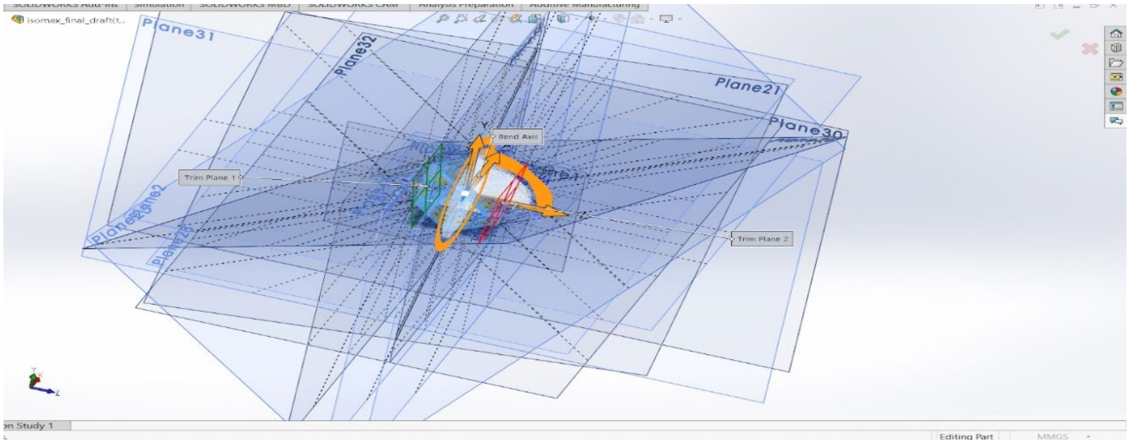


Figure (36): Isomax cell in Solidworks

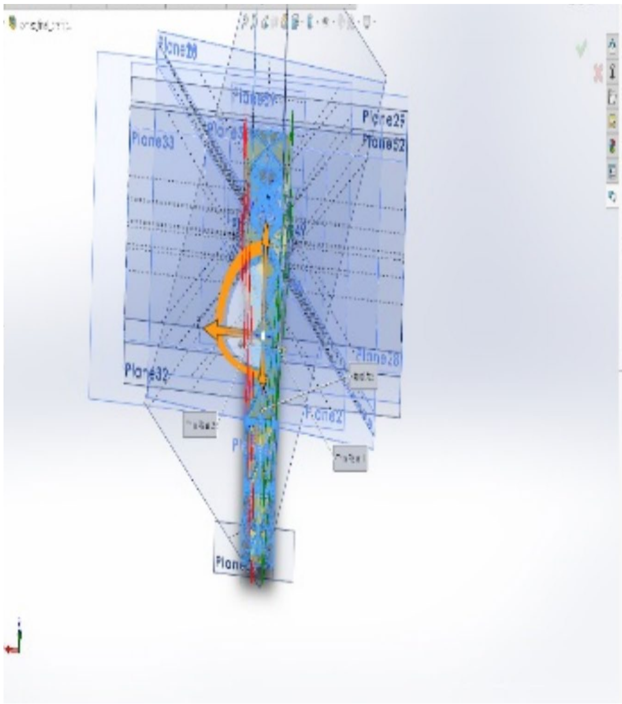


Figure (37): Isomax bar formation in Solid Works

This was to create "circular patterns" which spanned up and around making the final dome section full of "flexed" Isomax cells.

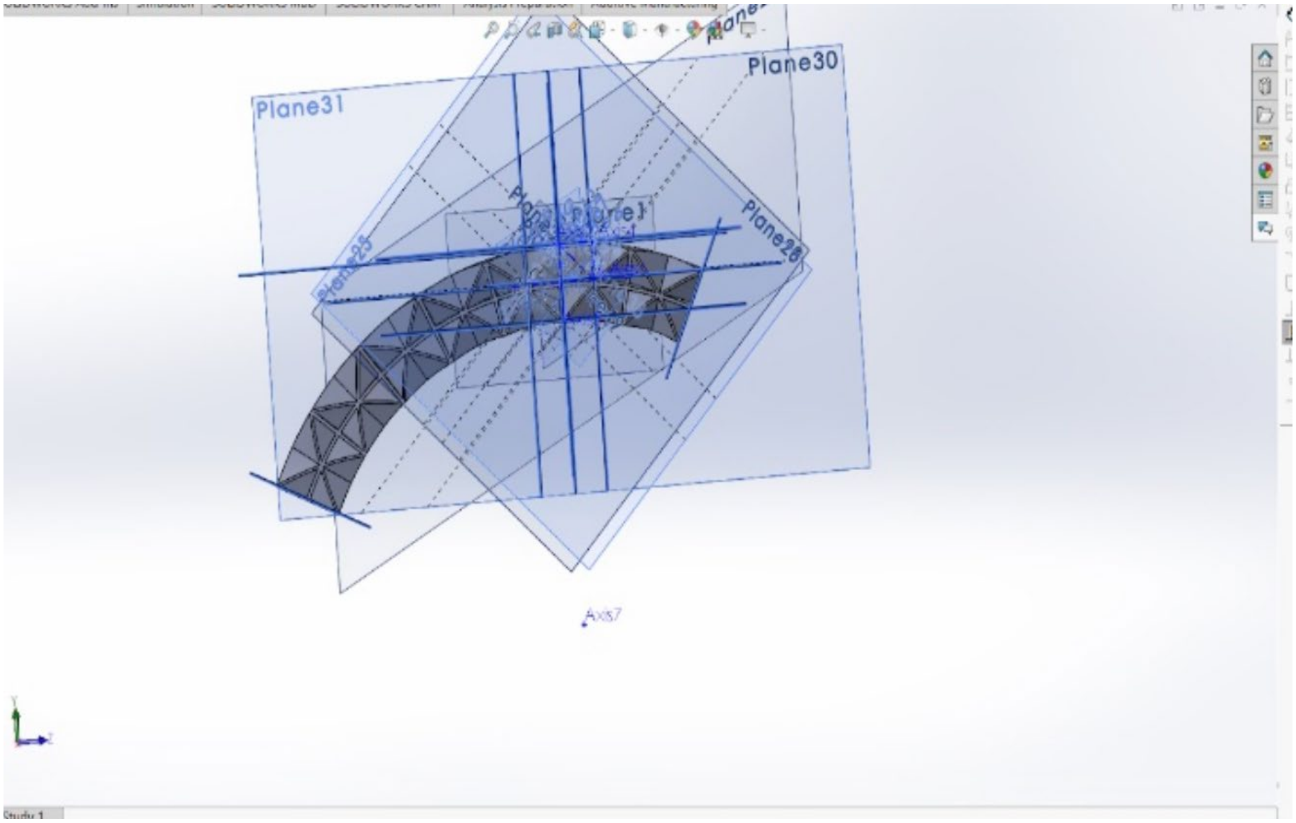


Figure (38): Curved Isomax in Solidworks

However, if the dome section were to be printed as is, there would have to be an extremely large amount of support material. This would be detrimental to the feasibility of this design for it would take far too long for it to print.

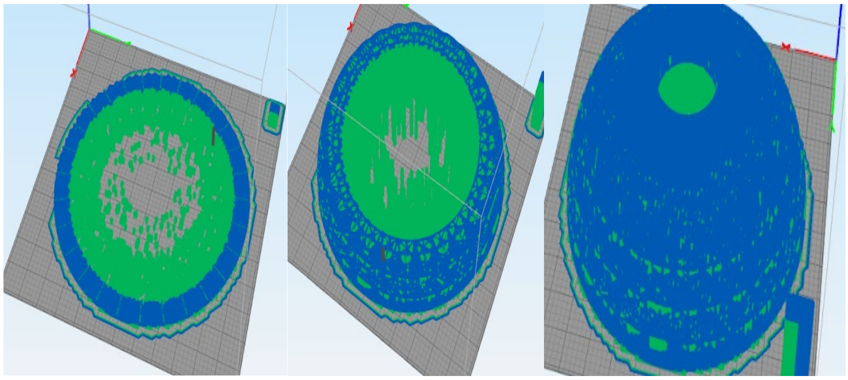


Figure (39): G-code of helmet liner

To decrease the amount of support, the half dome section of flexed Isomax cells was reduced to an eighth section. This section was then rotated so that the longest flat face mated with the build platform. This allowed for the least amount of curvature of the helmet liner to span outwards from the bed, therefore the least amount of structure material necessary for that model. Although the printing time is still high, taking about 55 hours to print this section. This would correspond to about 18.34 days of printing, which would still be too expensive to produce given that the cost of running the printers is $4 per hour.

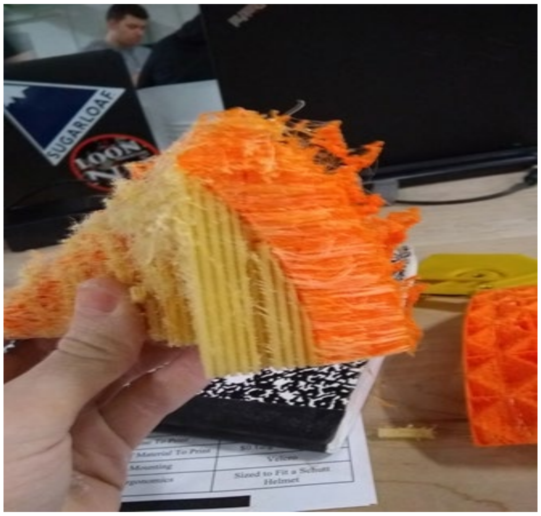


Figure (40): Completed print

However, there is exactly 28 columns of flexed Isomax cells that spans the 360-degree hemisphere. So, the last model proposed was a twenty-eighth section, which was rotated and placed flat on the bed in the same manner as the eighth section.

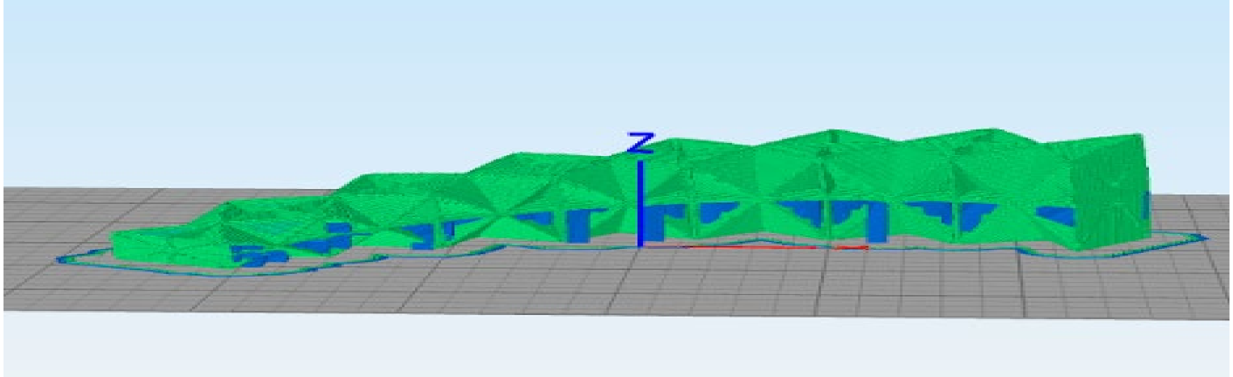


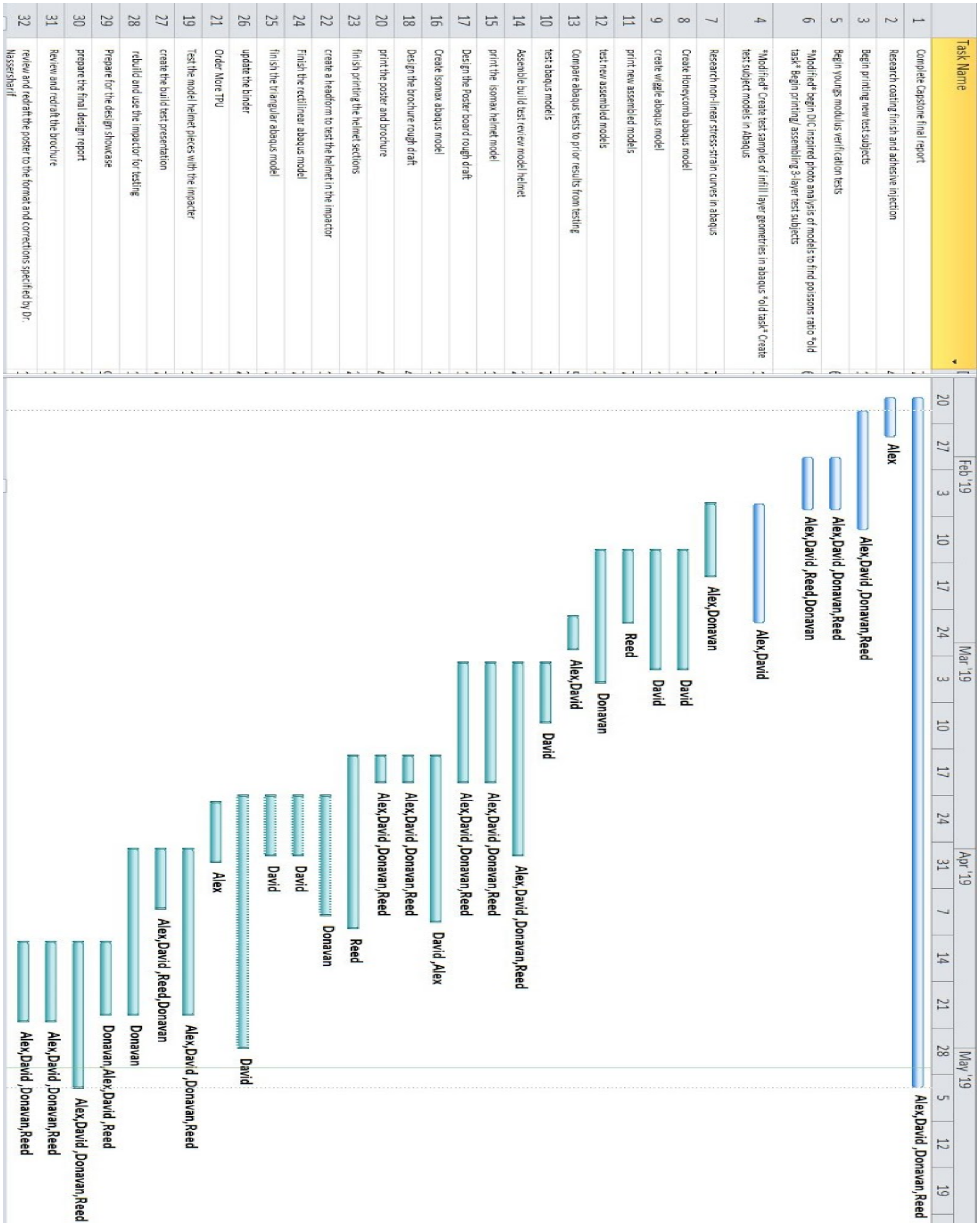
Figure (41): G-code of 1/8th section

That section was able to be printed in about 9 hours, corresponding to about 10.5 days of printing to get the full dome in 28 pieces. The main reason for printing such small sections was to reduce the amount of support needed (as shown above), which almost cut the printing time in half. The other things that were considered was turning off retraction for printing the Polyflex TPU to prevent pooling of hot plastic in the upper portion of the hot end. This setting was recommended for this material because it often causes jamming. The jamming happens when re-extruding because the semiflexible material doesn’t have the stability to push the molten plastic back through the hot end. The next consideration was to have a settling temperature or not.

This would be a temperature that both the support and main material go to when not printing. This would prevent oozing and possible jamming. However, when printing the 28th section that isn’t necessary due to there being a much smaller waiting period for either main or support material to settle. Also, this causes some minor down time in the print depending on how long it takes for the extruders to cool down or heat up. The last thing that was needed is an ooze shield. This is a barrier that follows closely to the edges of the part allowing the main material to wipe off any oozing filament as it passes by. This is important because the less extra filament dripping on the proposed model, the lighter it will be.

Project Planning

The project was organized using a variety of methods. These methods include using a Microsoft Project to create a Gantt chart and organize tasks, creating weekly reports for the project sponsors, and team members staying in regular communication with each other to collaborate and remind each other of approaching deadlines. Team tasks were regularly assigned during the weekly class meeting on Monday or Wednesday, to be completed in one week or more, depending on the difficulty of the assignment. Overall, this semester the team completed approximately 75 % of the overall tasks and goals.



	Task Name	Resources
1	Complete Capstone final report	Alex,David ,Donavan,Reed
2	Research coating finish and adhesive injection	Alex
3	Begin printing new test subjects	Alex,David ,Donavan,Reed
5	Begin youngs modulus verification tests	Alex,David ,Donavan,Reed
6	*Modified* begin DIC inspired photo analysis of models to find poissons ratio *old task* Begin printing/ assembling 3-layer test subjects	Alex,David ,Reed,Donavan
4	*Modified* Create test samples of infill layer geometries in abaqus *old task* Create test subject models in Abaqus	Alex,David
7	Research non-linear stress-strain curves in abaqus	Alex,Donavan
8	Create Honeycomb abaqus model	David
9	create wiggle abaqus model	David
11	print new assembled models	Reed
12	test new assembled models	Donavan
13	Compare abaqus tests to prior results from testing	Alex,David
10	test abaqus models	David
14	Assemble build test review model helmet	Alex,David ,Donavan,Reed
15	print the isomax helmet model	Alex,David ,Donavan,Reed
17	Design the Poster board rough draft	Alex,David ,Donavan,Reed
16	Create Isomax abaqus model	David ,Alex
18	Design the brochure rough draft	Alex,David ,Donavan,Reed
20	print the poster and brochure	Alex,David ,Donavan,Reed
23	finish printing the helmet sections	Reed
22	create a headform to test the helmet in the impactor	Donavan
24	Finish the rectilinear abaqus model	David
25	finish the triangular abaqus model	David
26	update the binder	David
21	Order More TPU	Alex
19	Test the model helmet pieces with the impacter	Alex,David ,Donavan,Reed
27	create the build test presentation	Alex,David ,Reed,Donavan
28	rebuild and use the impactor for testing	Donavan
29	Prepare for the design showcase	Donavan,Alex,David ,Reed
30	prepare the final design report	Alex,David ,Donavan,Reed
31	Review and redraft the brochure	Alex,David ,Donavan,Reed
32	review and redraft the poster to the format and corrections specified by Dr. Nassersharif	Alex,David ,Donavan,Reed

Figure (42): Gantt Chart

Financial Analysis

Materials Cost

The material used to print the test specimens was a TPU filament made by Polyflex. This filament could be readily found online for around $60. The exact filament we used was ordered from Amazon for $56.99[5]. This filament has a net weight of 750g. A label on the spool used for gauging how much material is left has a maximum of 500g. It is assumed that the spool itself weighs 250g while the total filament weighs 500g, this comes to the total of 750g. Taking that the filament has a total weight of 500g, the price point of the filament comes down to $0.12 per gram of filament. The helmet liner weighs a total of 452g. Multiplying this weight by the cost per gram to print, gives the total material cost for the helmet liner.

The helmet shell that was used in this project was found to be, on average, around $300.00 [Reference ??] 8 Velcro strips at $0.50 were used to secure the TPU liner to the helmet shell. [Reference?]

Total Material Cost

Below is a table explaining the material cost of each helmet to be made

Table (4): Material costs of the project

Material Costs	
Filament	$54.20
Helmet Shell	$300.00
Velcro	$4.00
Total	$358.20

Electrical Cost

The printers used were the Raise3D N2 and N2 Plus. These printers are sold for $3,999.00 and $5,999.00 respectively. The simply 3-D program that the group used to convert STL models to G-code (the format of file used to run the printers) has an initial, one-time, cost of $100.00 [4]. The power requirement for these printers is 360 Watts. On average, the cost of electricity in the United States is $0.12 per Kilowatt-Hour. When multiplied with the maximum power requirement, the operational cost for running this printer comes to $0.043 per hr. However, since group 13 used the facilities at the University of Rhode Island, the printing cost used in this analysis will be the one that URI provided ($4.00 per hr.). When this is multiplied by the total print time, electrical cost for printers can be calculated.

As of now, the total print time is around 480 hours. This is due to the extremely complicated structure of the curved Isomax geometry. A discussion of print time can be found in the additional content of this report.

Other electrical costs include the lab equipment used during testing, and the computers used in the Finite Element Analysis. The lab equipment costs $100.00 per hr. to use, and the computers cost $5 per hr.

Personnel Cost

Over the course of the spring 2019 academic semester each group member spent numerous hours on different aspects of the project. The breakdown of how each team member spent their time is shown in tabular format on below. The tables separate time into the categories of research, calculations, design, which includes 3-D modeling, testing, and engineering analysis. A percentage of time spent on each task compared to total time is also provided.

Table (5): Donovan Blanpied's time allocation

Task	**Hours spent on task (h)**	**Percentage of total time (%)**
Research	32	27.1
Calculations	8	6.8
Design	22	18.6
Testing	52	44.1
Engineering Analysis	4	3.4
Total	118	100.0

Table (6): Reed Nelson's time allocation

Task	**Hours spent on task (h)**	**Percentage of total time (%)**
Research	46	40.4
Calculations	11	9.6
Design	36	31.6
Testing	4	3.5
Engineering Analysis	17	14.9
Total	114	100.0

Table (7): David Silverstein's time allocation

Task	Hours spent on task (h)	Percentage of total time (%)
Research	37	27.6
Calculations	22	16.4
Design	21	15.7
Testing	5	3.7
Engineering Analysis	49	36.6
Total	134	100.0

Table (8): Alex Snyder's time allocation

Task	Hours spent on task (h)	Percentage of total time (%)
Research	32	30.2
Calculations	19	17.9
Design	35	33.0
Testing	5	4.7
Engineering Analysis	15	14.2
Total	106	100.0

The cost of labor for students is set at $20.00 per hr. Also, a professor at the University of Rhode Island provided some assistance. The labor cost of the professor is set at $100.00 per hr. The sponsor of our project was also called in for small consulting issues at $60.00 per hr. These labor costs are set by URI. Below is a table showing all labor costs of this project.

Table (9): Total labor costs

Personnel	Time (h)	Total Cost ($)
Donovan Blanpied	118	$1,180
Reed Nelson	114	$1,140
David Silverstein	134	$1,340
Alex Snyder	106	$1,060
Professor Taggart	1	$100
Dr. Rafanelli	3	$180
Total		

Total Project Cost

Below is a Pie Chart explaining the total cost of this project including, Material, Labor, electrical and overhead costs. The overhead cost set by URI is 50% of the total cost.

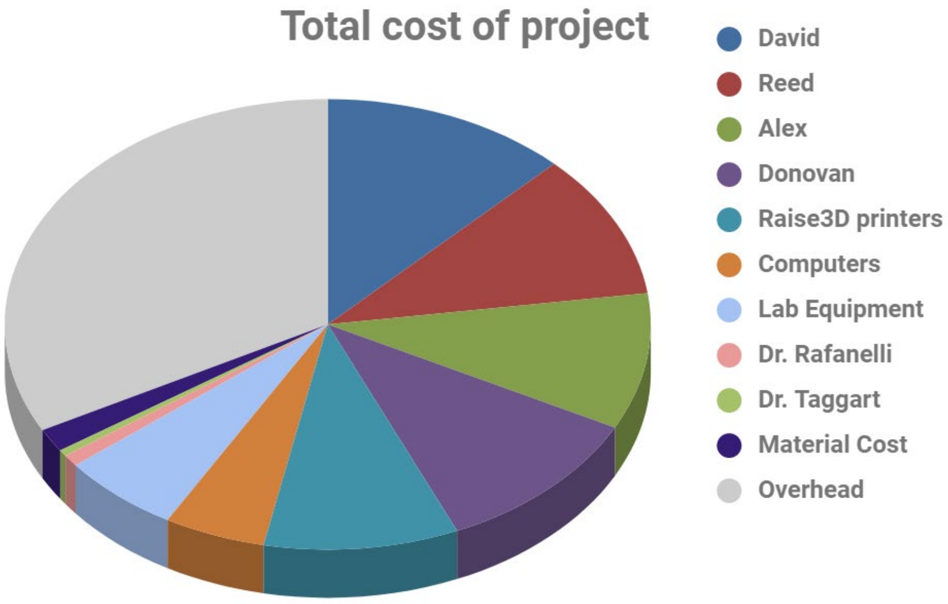


Figure (43): Breakdown of total costs of project

Return on Investment

The advantages of additive manufacturing are not limited to ability. Financially, additive manufacturing can be extremely advantageous. Parts can be made with the same strength or structural integrity that perform the same but can be much lighter. This is due to the infill geometry. This project focuses on strength of these infill patterns. More testing will be done that may show that the parts made with additive manufacturing can be lighter and stronger. Weight reduction can mean immense amounts of saving for certain industries. NASA states that it takes $10,000 to put a pound of payload into orbit [3]. In the automotive industry, weight reduction can be crucial for fuel economy. After the initial investment of the printer and the software is made, the filaments that are used are relatively cheap. In sports equipment, the pursuit of lighter and more durable equipment is a constant effort. By printing parts, traditional processes of manufacturing, such as milling, machining, or casting can be eliminated. This reduces waste, machine time, and operator costs. Additive manufacturing can also eliminate or extremely reduce transportation and assembly parts and time. This is because complete parts can be printed without having to be assembled in another part of a factory, or even off site.

Maintenance

To assure athletes are protected as best as possible from concussions and other head injuries, maintenance must occur to the football helmet. The primary concern for team 13's helmet liner is the TPU itself getting worn out. The helmet liner is designed to be effective up to two years. The helmet liner is attached to the shell of the helmet via Velcro. This makes it easy for the user to simply replace the helmet liner after 2 years. The current TPU that is being used is not biodegradable however, there is a type of TPU that is biodegradable. This biodegradable TPU is currently available on the market and takes 3-5 years to completely degrade. This could possibly be the future material used for the helmet liner. Because the current TPU being used for the helmet does not biodegrade easily team 13 has discovered a way to use the material so the TPU does not hurt the environment, the answer is rebound. Due to TPU's ability to take absorptions so well it makes for an excellent rebound cushioning for carpet underlay. In 2010 nearly a billion pounds of TPU was reclaimed and make into carpet cushioning.

Operation

Since the final design is of a helmet liner, there are no operational procedures necessary other than proper installation or removal of such static structure. The idea is to adhere both outer and inner curved edges to Velcro strips with superglue. The Velcro strips on the outer curved edge are to be connected directly to the viscoelastic polymer sheets that are fixed to the helmet shell. On the other side of the curved helmet liner slices, the Velcro connects to the foam cushioning which would then rest on the football players head directly. Once the helmet liner is installed with the viscoelastic sheet and foam cushioning, the final steps for the player is to adjust and snap in the chin strap, if the facemask is already installed. Finally, as a safety precaution the football player must also be wearing a mouth guard for it is the rules of the game. Any additional equipment for stabilizing the players head and neck, like a neck brace, could be added at the players discretion. After that player would be all set until the helmet liner fatigues to the point at which it cannot absorb blows to the head as efficiently as it was designed to. The point at which this helmet liner fatigues would have been determined if the proper impact testing was performed. However due to the limited equipment available at Schneider electric, the peak accelerations from impact was not able to be measured. So unfortunately, this design for a helmet liner was purely theoretical. Although at least the final models were more feasible, expense wise, due to reducing the print time through optimization of the printing parameters. In the future it is suggested that this could be more measurable by testing the 20 x 20 x 20 mm^3 Isomax cell with FEA, given that the Poisson’s ratio and young’s modulus would be calculated using DIC on the dog bone test pieces of 100% rectilinear infill. Also, in hindsight this model could have been FEA tested with the parameters found online given that the model was able to be read. Unfortunately, it was just realized that the model needed being rebuilt in solidworks due to it not slicing properly. That explains why the model crashed several times and how it had to be re-meshed before completing the simulation.

Additional Considerations

Economic Impact

This helmet liner improves economic efficiency by minimizing the amount of raw material necessary to provide protection to a head form. Using less than 500 grams of raw material and ~250 grams of support plastic, the final design is very material-efficient. Additionally, the raw material used was already cheap, approximately $0.12/ gram. The prototype does take a long time to produce, approximately 20 days. If a company were to print it on a printer that costs $4/hour to run, one helmet liner would cost $1800. This is too expensive, and a more efficient means of production would need to be found before this product could enter the market. This improved efficiency could come from a more price-efficient printer, or from economies of scale that would allow a company to fabricate this product in large quantities quickly.

The strength-optimized design could still be useful in specific industries. Aerospace and automotive companies design products that become significantly cheaper as they become lighter and stronger. With further testing, Isomax geometry could be used to save weight in aircraft, satellites, and automobiles, improving their efficiency. By some estimates, reducing aircraft weight by one pound can increase fuel efficiency and save around ten thousand dollars per year. This helmet liner demonstrates a significant weight reduction and Isomax geometry could be used to further reduce weight on aircraft by replacing traditional items like arm rests, tray tables or even aircraft structural components with lighter variants created with additive manufacturing.

Societal and Political Impact

Football is a long-beloved American pastime, but youth participation in football has been steadily declining. Additionally, the NFL reports diminishing viewership and game attendance in recent years. This has been attributed to the rising public awareness of traumatic brain injuries and risk associated with playing football. Parents and youths are more aware of the risk associated with playing football and choosing other options, thereby reducing the support for local football organizations and pushing football as a sport further from mainstream thought. By improving on the strength and effectiveness of football helmet liners, the risk of traumatic brain injuries can be reduced. If the reduction is significant enough to make football safer overall, the sport may be able to thrive and grow again.

Additionally, the strength optimized design itself has further societal impacts. If the design can be manufactured cheaply, and in large quantities, larger structures can be produced with this design that weigh less and use less material. Bridge supports might use Isomax cells in the future, or automobile bodies might have an outer shell made of Isomax that is both lightweight and impact-resistant.

Ethical considerations

Since the helmet liners are important safety gear, every effort must be taken to ensure that they are effective and thorough. If a helmet liner fails or is ineffective at shielding a player's head from an injury, the responsibility falls on the design team who created a defective product. Therefore, before the product is thoroughly tested and is effective at protecting football players from injury

Health, Ergonomics and Safety Considerations

The helmet liner does not contain any materials that could cause an allergic reaction, or skin irritation from long term usage. Polyflex TPU does not create jagged or sharp edges when broke but creates flexible strands of thermoplastic that do not ordinarily lead to skin abrasions. It is also designed to fit snugly inside of a standard football helmet shell, and around an average human male head. The helmet liner contains many air pockets as part of the design and allows airflow so that the player feels comfortable wearing the helmet. to the helmet liner is printed in sections. This was done both to make the printing process easier, and so that if any individual section of the helmet was damaged, the section could be replaced. This will make it more affordable and common to examine helmet liners for damage and replace broken or sub-optimal parts when necessary.

Environmental Impact and Sustainability Considerations

The helmet is made from a thermoplastic, and plastics are very damaging to the environment when improperly disposed of. Microplastics are one of the most widespread forms of pollution, and this helmet liner may contribute by having stray strands of printed thermoplastic fall off or be created as a waste product. These miniscule strands can enter the environment and cause harm to insects and animals that may try to consume them. The cheap and easy availability of Polyflex TPU and other thermoplastics indicates that the supply of thermoplastics is abundant, and production can be sustained.

Conclusions

Team 13-Design to Achieve was selected by professor Nassersharif to work with Raytheon to determine if a strength optimized design can be achieved using additive manufacturing. The challenge Raytheon presented us with was "Can a strength optimized design be achieved using additive manufacturing/3-D printing?" With this issue there were a lot of requirements, including: thorough literature search on additive manufacturing and 3-D printing processes and materials, research lessons learned with respect to geometries as well as material properties tailoring, research lessons learned with feasibility of complex geometries, research any patents, formulate a problem statement,, a simple assembly process, dimensional stability, make a practical application, low mass, low density, low volume, high cte, and a nontraditional shape that is original.

Team 13 came up with a design that meets these requirements. The multi layered infill geometry/Isomax helmet demonstrates a strength optimized design. The helmet has 3 different layers of a specific geometry infill, and each one serves its own unique purpose. The first layer (farthest away from the skull) is a vertical wiggle infill pattern. The vertical wiggle is a relatively soft pattern and flexes easily in a side to side motion when a shearing force is applied. This will act as a great first line of defense against a rotational force, that is not a direct 180-degree impact. The second layer (middle layer) is a horizontal honeycomb, this is the backbone of the helmet. Upon much research and testing, it was discovered that the honeycomb infill was the overall strongest infill pattern in a linear direction. The honeycomb layer will absorb most of the force by providing the most amount of strength to the helmet liner. The only down side to having the Honeycomb as a section of the helmet, is that the honeycomb infill has the longest print time, weighs the most, and uses the most material. The final layer (layer closest to the skull) is another vertical wiggle infill. The reason for choosing the vertical wiggle again is for its softness, compressibility and ability to absorb rotational energy well. This will be beneficial because when a large impact occurs, the dense honeycomb section does not slam against the user’s head. The other method the team used to strength optimize a helmet liner is by choosing a specific infill structure called the Isomax structure and revolving the Isomax in half circular fashion. After conducting a tremendous amount of research team 13 found out that the Isomax structure has the heist strength to weight ratio compared to any other structure.

The material being used is a material called TPU. TPU is a thermoplastic that is currently being used by a top football helmet brand Schutt. The reason TPU is a good choice for football helmets because it is flexible and elastic. The current design of the TPU helmet liner has been strength optimized due to its multiple layer design to absorb impact and force in all directions while still following all the requirements stated above.

The next step for this project is to test this design in other aspects. Possibilities for these next tests include an impact test, humidity test, maximum temperature test and a life cycle test.

Using these strength optimization methods does not have to be limited to football helmets. 3-D printing has a limitless amount of applications ranging from protective phone cases with very small details, shoes, or even large-scale house that can be printed in under a day. The method of using the wiggle honey comb wiggle infill sandwich or the iso max structure to strength optimize other applications is very doable and could lead to an advancement in 3-D printing.

References

[1] "ASTM D695-15 Standard Test Method for Compressive Properties of Rigid Plastics". https://doi.org/10.1520/D0695-15,2015

[2] "ASTM D790-17 Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials". https://doi.org/10.1520/ D0790-17,2017.

[3] BOEN, B. "Advanced Space Transportation Program: Paving the Highway to Space". https://www.nasa.gov/centers/marshall/news/background/facts/ astp.html,April12,2008.

[4] BERGER, J. B.; WADLEY, H. N. G.; McMEEKING R. M. ”Mechanical metamaterials at the theoretical limit of isotropic elastic stiffness”. https://www.nature.com/articles/nature21075.

[5] NOCSAE. “Football Helmet Standards Overview”. https://nocsae.org/wp-content/uploads/2018/05/NOCSAE_Football-Helmet-Standards-Overview-_May-2018.pdf