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Additive Manufacturing of a Motorcycle Helmet Utilizing 7-Axis 3D Printing

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SANTA CLARA UNIVERSITY

Department of Mechanical Engineering

I HEREBY RECOMMENT THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Kyle McMorrow, Caleb Alleva, Luke Correnti, Danny Eckstein, Adam Fontana, Pranav Prabhakar

ENTITLED

ADDITIVE MANUFACTURING OF A MOTORCYCLE HELMET UTILIZING 7-AXIS 3D PRINTING

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Robert A. Marks   6/14/18
Thesis Advisor   date

T. E. Shoup   6/14/18
Department Chair   date

ADDITIVE MANUFACTURING OF A MOTORCYCLE HELMET UTILIZING 7-AXIS 3D PRINTING

By

Kyle McMorrow, Caleb Alleva, Luke Correnti, Danny Eckstein, Adam Fontana, Pranav Prabhakar

SENIOR DESIGN PROJECT REPORT

Submitted to
The Department of Mechanical Engineering

of

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Mechanical Engineering

Santa Clara, California

2018

Additive Manufacturing of a Motorcycle Helmet Utilizing 7-Axis 3D Printing

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June 13, 2018

Abstract

This project analyzes the structural properties of 7-axis 3D printing versus traditional FDM printing. The team worked with AREVO Inc to manufacture a motorcycle helmet and test samples made from carbon fiber in a PEEK matrix. A drop-test rig was designed and constructed in-house to test a traditionally printed carbon fiber helmet alongside commercial helmets of identical geometry. The lighter weight printed helmet experienced significantly lower peak deceleration in the test headform (223 G's versus 371 G's for average commercial), but fractured along a print layer on impact. Had time allowed for printing of a helmet utilizing AREVOS's true 3D printing technology with cross-hatched raster orientation, similarly printed test samples give strong evidence that this helmet would have reduced peak acceleration values and overall weight in comparison to similar commercial helmets, while avoiding fracture. This analysis exemplifies the significant capabilities and advantages of using true 3D printing methods where applications of traditional FDM printing would not suffice.

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Chapter 1: Introduction

Project Overview

The main objective of this project was to design and print a full face motorcycle helmet using AREVO Inc' new 7 axis 3D printing technology. The helmet was printed with a chopped carbon fiber filament in a PEEK matrix. AREVO Inc is a startup company in the Bay Area that is seeking to revolutionize the 3D printing industry by focusing on true 3D printing, as opposed to the more conventional 2.5D printing. This means their printers are able to print more complex 3D geometries, while increasing inter-laminar strength between fibers. Another objective was to test the carbon fiber filament used by AREVO's printers and compare these properties to those of polycarbonate, which is commonly used today for motorcycle helmet shells. Such materials tests include K1C and compression testing. From these tests properties such as fracture toughness, critical crack length, and failure mode were analyzed and compared. The final objective was to design a test structure that allowed us to perform a Department of Transportation (DOT) certification test for our completed helmet. Such a test was important to test the overall safety of the helmet and viability of its use for consumers on the road.

Problem definition

This project analyzes the structural properties of 7-axis 3D printing versus traditional FDM printing. The team is working with AREVO Inc to manufacture a motorcycle helmet made from carbon fiber in a PEEK matrix to pass DOT standards as a tangible representation of the capabilities of new additive manufacturing processes.

Review of Motorcycle Helmets

The primary purpose of a motorcycle helmet is to minimize the chance of a fatal head injury during an accident. The most common form of head injury in a motorcycle collision is a "closed head injury" where the skull remains intact, but the sudden deceleration causes the brain to hit off of the inside of the skull, which causes brain injuries. A motorcycle helmet seeks to reduce the energy transferred to the head to avoid these types of injuries.

A motorcycle helmet typically consists of six different components. The rigid outer shell, impact absorbing liner, comfort fit padding, face shield, chin bar, and a retention system [1]. For the purpose of this report, the design of the outer shell is most relevant. The hard outer shell distributes the impact force over a wider area allowing for the foam lining to maximize its energy absorption capabilities [1]. Some important design considerations for the outer shell include stiffness, geometry, and surface finish. The material properties of the carbon fiber determine the thickness of the shell. The thickness influences the level of deflection and direction of energy absorption. Thermoplastic helmets deflect significantly more than fiber reinforced composites and, as such, do not transfer energy as efficiently to the inner padding [1]. Thermoplastics such as polycarbonate are a commonly used material for motorcycle helmets, but a carbon fiber composite would deflect less and therefore be a better helmet material.

The helmet geometry also influences the effectiveness of its energy transfer by playing a crucial role in preventing shell fracture. Helmet shells should be free of any sharp corners or cutouts that induce stress concentrations, and as stated by Fernandez, “Helmet shells are stiffer when loaded at the crown, since that site has a double-convex curvature and is distant from any free edges.”

The surface finish is also an important design consideration, as it plays a pivotal role in the rotational acceleration of the helmet and head when in contact with the ground [1]. A smooth surface finish is important because in the event of an accident a smoother surface will allow the helmet to slide or skip across the ground or anything it comes in contact with, rather than catch onto something and cause a twisting motion. This twisting motion could cause serious injury or death to the user, so it is important to limit rotation of the helmet and, therefore the head, by making the helmet surface smooth.

Finite element analysis on the prototype helmet has been important for preliminary testing. An article by Kostopoulos, et al. [2] on simulating a point impact on a motorcycle helmet reveals some important factors to consider before setting up the model. Kostopoulos and his team designed a model to simulate the SNELL certification tests. Their model simulated the fractures at the surface. The boundary layer between the shell and the impact absorbing liner was simulated as a sliding interface with a friction coefficient of 0.5. These values and simulation parameters give a good baseline model to pull from when creating the FEM model.

Review of Additive Manufacturing

The vast majority of 3D printing today is done using layer manufacturing (Figure 1.1). The CAD model is sliced horizontally into 2D pieces in the XY plane. The machine then constructs one layer at a time, then advances in the z direction. There are some drawbacks to this. Typically the part is stronger within the x-y plane compared to along the z direction. During use, applied stresses are likely to be inclined relative to the x-y plane, at least around some regions of a part, resulting in a part that is less than optimal for stress distribution. Layering is also not optimal for curves or parts that have a lot of complicated curvature [3]. When the CAD model is sliced, the curved portion may not be smooth. Recently, several other methods have emerged as alternatives or, potentially, replacements.

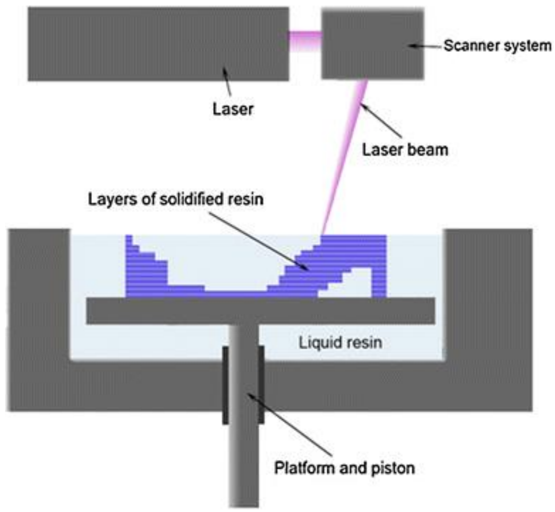


Figure 1: Layer method for 3D printing

AREVO does not use the layer method illustrated in Figure 1.1. Instead, they use a multi-axis robotic arm with a rotating base, an example of which can be seen in Figure 1.2. These robotic arms are most commonly used in assembly lines, but they also are being successfully used by AREVO to realize true 3D printing. Additionally, multi-axis arms have been used in CNC milling for decades [4]. Therefore, multi-axis arms can be freeform, meaning they can be used to not only deposit, but also remove material from any direction. Keating argues that they are a source of untapped potential. 3D printing companies could apply this technology to their manufacturing to gain better customization, which is what AREVO is doing now.

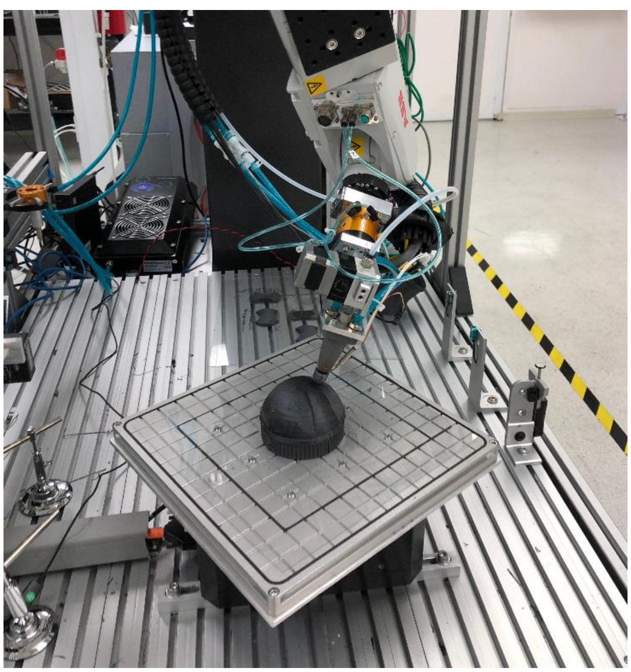


Figure 2: Multi-Axis Arm for 3D printing

Planning the path for a multi-axis system is more challenging than for the layer method, as it requires full 3D path planning as opposed to simpler 2D cross sections [3]. On the other hand, materials may be printed such that strength properties are optimized in different directions at different locations within the part, depending on the orientation of applied and/or induced stresses.

One of AREVO's goals is to 3D print continuous carbon fiber. 3D printing and carbon fiber complement one another as 3D printing has inherent drawbacks that carbon fiber can solve such as weak interlayer adhesion. This weak interlayer adhesion can be improved by continuous carbon fiber strands connecting layers, therefore strengthening the interlayer bond. "Finally, additive manufacturing and Carbon Fiber (CF) technologies complement each other in terms of emulating nature's complex, materially efficient construction" [5]. Love uses the term AM (additive manufacturing), as she envisions how 3D printing can go from its current state, which is slow prototyping, to rapid large scale manufacturing. "AM is extremely good at making small, complex shapes, whereas traditional CF technology is excellent at manufacturing strong, simple, lightweight structures. Combining these two technologies into a composite structure can significantly reduce the manufacturing time, weight, and cost of complex structures" [5]. Carbon fiber may be the ideal material for 3D printing and help 3D printing become the norm of manufacturing in the future.

Problem Design Specification (PDS) Summary

The major design criteria of this helmet is that it passes the impact portion of DOT standardized testing for helmet safety certification. The impact test, which tests the impact energy absorption of the helmet, was done using a drop-test rig designed and built by the team. The helmet is dropped from a height of 1.83m with a theoretical nominal impact velocity of 6 m/s. The headform inside the helmet can not experience more than 400 G's of acceleration nor experience more than 200 G's or 150 G's for more than 2 ms and 4 ms respectively. The specific criteria is laid out in Appendix A. The helmet should be a maximum of 5 pounds, but the goal is to weigh less than 3 pounds, the average weight of motorcycle helmets. To accomplish these goals, the helmet shell was 3D scanned and modeled after an existing commercially available helmet. The model was then printed at AREVO Inc using a carbon fiber PEEK material. Other goals included adding comfort padding and making the helmet aesthetically pleasing.

Team goals

This team used 3D scanning technology to create a file compatible with AREVO's technology, implemented finite element analysis, created a working prototype, and gained experience in product design from concept to manufacturing. The main goal of this project was to create the first DOT approved 3D printed motorcycle helmet, specifications of which are detailed in the Appendix A. To facilitate this goal a secondary goal of creating a test structure capable of testing

DOT standards while staying within the teams budget was set. Lastly, the goal of testing and finding fracture toughness strength of AREVO's material was also set.

Chapter 2: Helmet Systems Level

Functional Analysis

Motorcycle helmets are meant to reduce the risk of severe head injury during a vehicle collision. As such, the main purpose of the helmet is to reduce the impact energy experienced by the rider's head. The helmet reduces this impact energy by filling a stiff shell with up to three centimeters of a stiff expanded polystyrene foam. This foam acts similar to a crumple zone in a car in that the foam itself deforms and absorbs much of the impact energy during this deformation. The shell's function is to keep the foam padding in place for the duration of the impact and distribute the force of the impact more evenly around the helmet. In order to accomplish these goals, the helmet shell must avoid fracture during impact and be stiff enough to distribute force over a large area. The Department of Transportation outlines many criteria for a motorcycle helmet to be deemed legally safe to use. This project focuses on reducing the impact energy below 400 G's as outlined in the DOT safety criteria. The helmet printed during this project is printed using PEEK polymer filament with fragments of chopped carbon fiber suspended in the matrix whereas many motorcycle helmets use polycarbonate for the shell. This chopped fiber helps to increase the interlaminar adhesion between print layers and increase the overall stiffness of the shell.

Market Research

Before initiating detailed design of a helmet, it is crucial to understand the product's market and consumer's respective need. As a result, conducting a customer needs survey and market research analysis was a crucial first step in the design process. Strategic questions allow for primary concerns and key design criteria to be recognized and addressed early on. A series of riders with varying levels of riding experience were asked the following questions.

Interview Questions

- How much are you willing to spend for a helmet?
- Do you care about DOT vs SNELL certification; do you know the difference?
- Do you care about any additional components on a helmet (electronics, sensors, features, etc.)?
- And if so, what are you interested in, is there anything you care about most?
- Would you be interested in safety sensors that alert you of nearby cars you can't see?
- What is your preferred helmet color?
- What is your preferred helmet finish?
- Do you prefer full, half, etc. type of helmet and why? What helmet do you currently have?
- What do you like about your current helmet, and what do you dislike?
- How would you rate the ventilation on your helmet? Too cold or hot? Does it get sweaty?

- Aesthetically, what are your looking for

Table 1: Data from customer Interviews

Interviewee	**Stan Leszynski** Been riding motorcycles for 3 years. Has owned 1 helmet	**Andrew Eckstein** Been riding for 4 years. Has owned 2 helmets	**Pete Mitchell** Been riding motorcycles for 5 years. Has been involved in one accident. Has owned 3 helmets
Budget	250-400	500-700	300-500
SNELL vs. DOT Certification	Did not know about the difference, but owns SNELL certified	Strictly SNELL certified	Strictly SNELL certified
Additional Electronics Interest	High Interest: Bluetooth HUD	Little interest but would purchase at the right price	High Interest: Bluetooth Little interest in HUD
Safety Sensors Interest	High Interest	Potential interest	High Interest
Color Preference	Black	Black	Black
Finish Preference	Matte	Glossy	Glossy
Type of Helmet	Full (safety concerns)	Full	Full (safety concerns)
Current Helmet Likes	Ventilation (medium satisfaction), low price ($250)	Comfortable, low wind noise, aerodynamic, cool color scheme	Comfortable
Current Helmet Dislikes	Foggy Visor	Leaves fingerprints	Heavy

From these customer needs interviews, it is obvious that the most important factor people look for in buying a new helmet is the level of safety it provides. Furthermore, two people are interested in bluetooth along with other helmet additions, but are deterred by the high cost. Comfort and ventilation are also of primary concern when selecting a helmet.

For this helmet design, primary importance must be put on maximum impact absorption and safety ratings. The helmet shell design will also need proper ventilation channels to aid in the comfort and aerodynamic performance of the helmet. The customers we interviewed also expressed a high interest in incorporating bluetooth and other advanced technology into the helmet. Adding custom sensors to the helmet would be made significantly easier by utilizing AREVO Inc' ability to stop and resume prints in the middle of production. The price point is also of primary importance when buying a helmet. Typical carbon fiber helmets are a luxury safety product with a higher price point than competing helmets made of other,cheaper materials. However, the lack of material waste and minimal labor costs would make the 3D printed carbon fiber helmet competitive amongst high end helmets.

Important Needs

The PDS, team preferences, and interviews all indicate that the most important need for the motorcycle is that it be safe. It was found that most people and competitive manufacturers prefer SNELL certified helmets as they are much safer and trusted by more people. However, it is important to balance the level of safety with the retail cost, as SNELL certified helmets are roughly ~$300 more expensive than just DOT certified helmets.

Table 2: Tabulated Needs for a Motorcycle helmet

Primary Needs	High level of Safety (SNELL/DOT Certification) Moderately Low Price Point
Secondary Needs (Price Dependant)	Proper ventilation Overall comfort
Tertiary Needs	Aesthetics: Color, Finish Additional Technology, i.e. Bluetooth, Heads Up Display (HUD)

Helmet Types:

Figure 3: From left to right, examples of a full face helmet, half face helmet, half head helmet, and modular helmet (Revzilla)

Full face helmets (Figure 2.1) cover the entire face and provide the best overall protection from a safety standpoint, as well as from weather, debris, insects, etc. They have lower noise levels and minimal air resistance compared to other types. They are the second heaviest provided all comparative helmets are made of the same materials. Ventilation can be poor and they are especially uncomfortable in hot conditions; therefore ventilation is of chief concern when designing this type of helmet. An offshoot of full face helmets are off road helmets. They have much better ventilation and generally no face shield, so they also require goggles. Off road helmets also provide an additional sun shield and chin protection and are made of very light components.

Open face helmets (Figure 2.1) cover the top, back, and side parts of the head, while leaving the face area open. Due to this, they are lighter than full face helmets, offer ample ventilation, and offer better communication. On the flip side, this means there is no protection for the face, as the eyes are not protected from debris and insects, so they generally require additional goggles. Some may have an additional visor that comes down.

Half head helmets (Figure 2.1) only cover the top part of the head. Due to this, they are the lightest and have superior ventilation, visibility, and minimum impact on communication. Their main downside is extremely low protection and huge wind resistance, causing fatigue in the neck. They also have even lower protection against debris from almost all directions.

Finally there are modular helmets (Figure 2.1) which try to combine the comfort and convenience benefits of the half face helmet and the safety of a full face helmet. They have a detachable chin bar that can be flipped up allowing for conversion between a full face and open face helmet. For example, the full face mode can be used while riding, and at stops it can be converted to an open face which allows better communication, food consumption, and ventilation without removing the helmet. They have all the benefits of open face and full face helmets. However, they are the heaviest helmets, and have more noise while riding than full face helmets. They also have less reliability in the long term due to having more moving parts. Finally, they are significantly weaker on the sides due to the location of the side hinges.

Table 2.3 shows a table of the different helmet types and how they compare based on different helmet needs.

Table 3: Overview of Different Helmet Types

Type	Protection	Weather/Debris Insect	Cosmetic	Visibility	Weight	Ventilation	Noise
Full Face	Complete	Full Protection	Face Covered	Medium	Heavy	Poor	Low
Off Road	Complete	Full with Sun Visor	Face Covered	Medium	Lighter than Full	High	Low, High (in high speed)
Open Face	None for front/eyes	None for face	Open	High	Light	High	High
Half Head	None for front/eyes, side, back	None on all sides	Open	High	Lightest	Very High	Very High
Modular	Complete, but weaker on sides	Full in face mode	Both	Both	Very Heavy	Both	Medium

One area for improvement in the field of motorcycle helmets could be a modular helmet that is stronger on the connection between the stationary top of the helmet and the moveable chin bar.

Additionally there could be additional tech improvements including a heads up display built into the glass, navigation, a rearview camera, and so on. From a material standpoint, most helmets are made from polycarbonate, while a select few consist of carbon fiber, kevlar, or fiberglass. Carbon fiber helmets tend to be the strongest and lightest, but can cost over $1000 and require skilled labor to manufacture, while conventional helmets made of polycarbonate are weaker and heavier, but cost less than $200.

A full face 3D printed helmet was decided on as the focus of this project as the full face is the most popular among riders and provides the most protection. Additionally, during a meeting with AREVO early on in the design process, the engineers at the company introduced manufacturing elements that can set this helmet apart from conventional methods. Their printing process allows for the addition of layers in multiple directions across the spherical geometry of the helmet. As carbon fiber and 3D printing in general produce an anisotropic structure, the true 3D printing at AREVO will allow for the manufacturing of the helmet with print and fiber orientations that will maximize the strength of the helmet in key spots. The new helmet should also be cheaper due to less material waste and exchanging high labor costs for a fully autonomous machine in a streamlined manufacturing process. The helmet could potentially include customization to the headform of each individual user due to the customizable nature of 3D printing. Using photos or 3D scanning, the shape of one’s head could be measured and a helmet could then be shaped to a customer’s head. Carbon fiber helmets in the past have been very expensive, but AREVO’s technology allows for an even lighter helmet that can pass DOT standards and make it customizable to the consumer.

System-level Issues

To decide which type of helmet would be ideal, a sub-system matrix was created and a trade off table was used, as seen in the Appendix E. After filling in the weighting criteria and filling out the sheet as shown in the Appendix E, it was decided that the full helmet would be created based primarily on the safety it provides.

The main issue in creating a motorcycle helmet is creating a design that is ensured to be safe for commercial use. Current helmets in the United States use Department of Transportations testing safety standards to validate this safety requirement. Therefore, the new helmet design must be engineered to be comparable to, if not better than, current helmets on the market. Here, material properties, as well as overall design, must be taken into account.

The material properties of the chopped carbon fiber reinforced polymer to be used are comparable to the material properties of traditional injection polycarbonate with better impact absorption (Appendix D). Therefore manufacturing a helmet from chopped carbon fiber reinforced polymer with better properties and similar design to a polycarbonate helmet that has passed DOT standards suggests likelihood of meeting DOT standards as well. Manufacturing a motorcycle helmet through an additive manufacturing process that could pass DOT standards would empirically showcase the benefits of AREVO's true additive manufacturing process.

System-level Design

Figure 4: Fully assembled carbon fiber reinforced polymer 2.5D printed motorcycle helmet.

The helmet manufactured is based off of the DOT approved ILM Full Face Motorcycle Street Bike Helmet purchased on Amazon. The commercial helmet was purchased and disassembled for the shell to be scanned. The scanned file of the outer shell was extruded to match the thickness of the original shell, and was printed at AREVO using the 2.5D printing process. All geometry remained consistent with the original commercial helmet to isolate the shell as the sole new variable for testing DOT testing. Additionally, all original components such as interior foam lining, visor, and vents were reattached to the new printed shell to create a complete final helmet.

DOT Testing

The major design criteria of this helmet is that it passes the impact test for DOT certification according to National Highway Traffic Safety Administration FMVSS 218. This test was done using a testing rig built by the team, which tests the impact strength of the helmet. Based on a medium sized helmet it should be able to withstand an impact with 90 J of energy from a height of 1.83 m on a flat anvil and hemispherical anvil with 67.6 J of energy from a height of 1.38 m.

For both of these falls the acceleration inside the helmet can't exceed 400 G's. The specific criteria is laid out in the Appendix A (Department of Transportation).

Benchmarking Results:

In order for the helmet to be considered successful, the helmet must offer the same levels of safety and performance to current helmets on the market today. The key market players in the United States for motorcycle helmet manufacturing are Arai, Bell Motor Company, Shoei, and NOLAN (Mordor Intelligence).

Starting with the top of the line carbon fiber helmets, Bell produces a high end SNELL and DOT certified carbon fiber composite helmet known as "Carbon Star."

Figure 5: Bell "Carbon Star"

This helmet features a quick release shield and an advanced ventilation system to aid in the aerodynamics of the helmet. The shell itself is a "trimatrix composite shell" containing a proprietary mix of aramid, carbon, and fiberglass fibers. The overall weight of this helmet is only four pounds, but this helmet comes with a large price tag of $700 retail (Ravzilla).

The large majority of motorcycle helmets on the market today have a shell made from injected molded polycarbonate. The Z1R Strike Ops Helmet is an example of one of these helmets that boasts DOT certification and a weight of only 3 pounds, 10 ounce at a price point of only $100 (Ravzilla).

Figure 6: Z1R Strike Ops Helmet

The main goal of this project was to manufacture a 3D printed motorcycle helmet that is lighter and equally as safe as helmets currently on the market. Because of the nature of additive manufacturing, the material strength of the printed helmet will not be as high as a true carbon fiber motorcycle helmet, but the material properties are similar to those of injection molded polycarbonate with significantly more energy absorption capabilities (See test results in Appendix D). Our team was able to 3D print a motorcycle helmet utilizing traditional 2.5D printing methods that passed DOT impact testing while being lighter than the commercial helmet it was modeled from. Although the 2.5D printed helmet passed the DOT impact testing, because the helmet fractured at the top, it would not pass DOT striker testing.

Team and Project Management:

This team has an effective working dynamic, and has been successful in collaborating and continually improving the project design. An iterative design approach has been taken to constantly inspect, evaluate, and improve on the current helmet design and production method.

This team dealt with a number of challenges throughout the start of this project. With six members it was difficult to find times at which all members are available to meet. Members had to make sacrifices and meetings were planned out far in advance to compensate for the difficulty. Additionally, working in collaboration with AREVO provided many advantages, but also created the necessity for constant coordination via email and in person. Effectively communicating with AREVO was a major focus, especially given the timeline at hand. Unfortunately, AREVO's true 3D printing technology was not available for printing a full size true 3D helmet by the end of spring quarter, so the helmet had to be printed using a 2.5D printing method.

In terms of funding, AREVO Inc paid for all printing costs as well as some other miscellaneous costs for the material testing such as the hinges and adhesive for the fracture toughness testing. Our team received $3,000 from The Santa Clara University School of Engineering and used this money to build testing equipment and buy any materials for the helmet not covered by AREVO.

Chapter 3: Materials Property Testing

Fracture Toughness

Background

The fracture toughness of a material is the measure of a material's resistance to crack propagation. This value along with the fracture stress of the material determine a materials critical crack length. This critical crack length is the length of a crack inside of a part that would lead to fast fracture. This value is important to this project because 3D printing is inherently prone to small voids inside the part itself. Because the nozzle is always extruding a circular bead, occasionally there will be small gaps in between the beads. These gaps act effectively as cracks within the part and can lead to a very brittle part if the material does not have an adequate fracture toughness.

Procedure

Rectangular test specimens 100 mm in length and 25 mm in width were printed using AREVO Lab's Carbon Fiber PEEK filament. Halfway through printing, printing is paused, and a thin mylar film is inserted between the layers on half of the specimen. This film prevents any interlaminar adhesion, so that the specimen has a significant open section. The specimen is then loaded into an Instron testing machine and the machine is set to displace the jaws at a rate of 5 mm/min recording the displacement and load during the entirety of testing. The specimen is precracked approximately 5 mm. After the initial precrack, the specimen is removed and marked every 5 mm from the precrack. It is then reloaded into the machine and displaced until fracture.

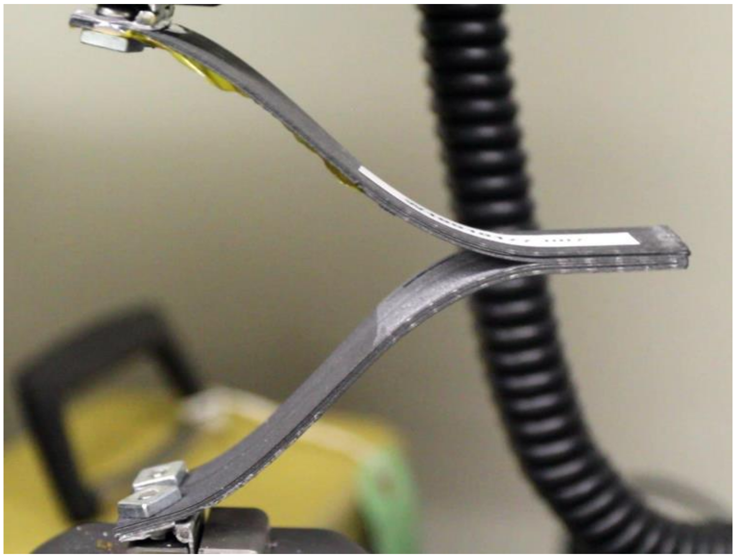


Figure 7: The material specimen is loaded into the Instron testing machine and displaced at the hinges until fracture. This sample pictured has delaminated approximately 30 mm.

With this information, the strain energy release rate can be calculated:

$$G_{1C} = \frac{3P\delta}{2ba}$$

Where *P* is the load [N], δ is lead point displacement [m], *b* is the specimen width, and *a* is the delamination length [m]. From the strain energy release rate, the fracture toughness can be calculated:

$$K1C = \sqrt{G_{1C}E}$$

Where *E* is the Young's Modulus [Pa]. From this fracture toughness, a critical crack length can be determined:

$$a_C = \frac{K_{1C}^2}{\pi\sigma_f^2}$$

Where σ_f is the fracture stress of the material and a_c is the critical crack length [m].

Results

The fracture toughness of the PEEK carbon fiber is about 72% greater than that of polycarbonate and has a critical crack length almost three times that of polycarbonate. This significant increase in fracture toughness and critical crack length show the advantages of using this material over traditional polycarbonate. This chopped carbon fiber in a PEEK matrix will resist crack propagation and fast fracture significantly better than that of polycarbonate.

Table 4: The results from the fracture toughness testing reveal that the material used for this 3D printed helmet is has a significantly greater critical crack length, effectively negating the effects of voids within the print.

	Polycarbonate	**Carbon Fiber PEEK**
Fracture Toughness [MPa*m$^{0.5}$]	2.1	3.61
Critical Crack Length [mm]	0.354	0.961

Dome Compression Testing

Background

This testing analyzes the failure modes of 2.5D printed parts versus true 3D printed parts. The failure mechanics of a shape similar to that of a helmet loaded in a similar fashion gives a good indication of how a true 3D printed helmet would compare to a 2.5D printed helmet in an impact scenario.

Procedure

Custom test fixtures for an MTS machine were machined and attached to the machine to allow for flat planes to compress the domes evenly. The testing mechanism was set to apply load at a set displacement rate of 1mm/s for 15mm. The time, displacement, and load data were saved and analyzed.

Results

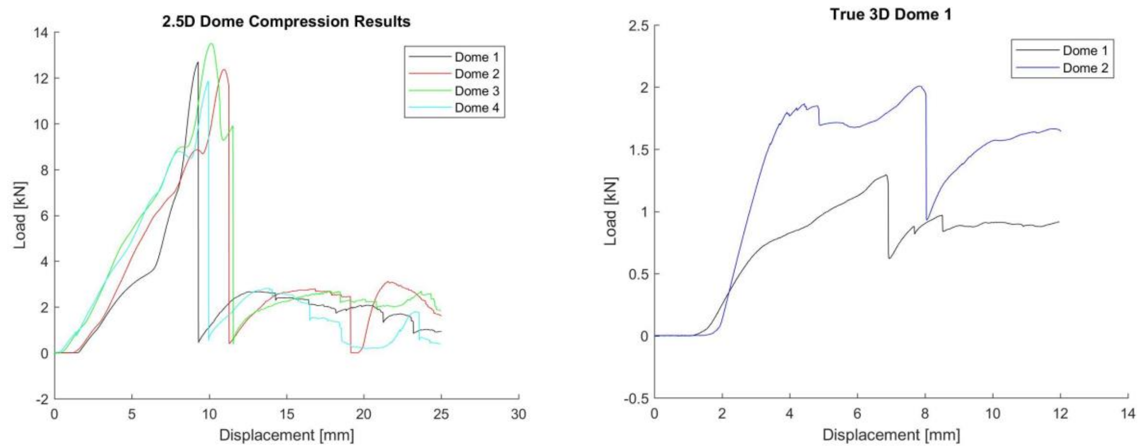


Figure 8: Graphical results from testing four 2.5D printed domes and two true 3D domes. The 2.5D domes experience a significant fast fracture and do not regain any strength while the true 3D domes retain their strength.

The true 3D domes and the 2.5D domes were not geometrically similar leading to significantly different values for a maximum load applied. The true 3D domes averaged 20.1g and the 2.5D domes averaged 61.2g; additionally, the thicknesses of the true 3D and 2.5D domes were 3.3mm and 2.2mm respectively. Because of these geometric inconsistencies, no comparison can be made between the loads before failure of the two types of domes. This test, instead, reveals the failure modes between a true 3D structure and a 2.5D printed structure. Because 2.5D printing builds layer by layer vertically, every individual layer acts as a slip plane in the part itself. When the load is applied vertically to the dome, eventually the shear flow through the dome lines up with a print layer and causes the top to shear off completely as seen in Figure 3.3.

Figure 9: 2.5D (left) and true 3D (right) domes after compression testing. The 2.5D domes experience catastrophic failure along the printed slip planes while the true 3D domes do not have these slip planes and experience a conventional compression failure mode.

The true 3D domes however do not experience the same catastrophic failure. Because the print orientations cross at 90 degree angles along the surface of the dome, these slip planes do not exist. Instead the true 3D domes experience an initial fracture, but maintain their shape. This behaviour is very important in motorcycle helmet design as a catastrophic failure like the failure of the 2.5D domes would completely expose the EPS foam underneath the shell and leave the rider susceptible to serious injury if any further impact would occur. The true 3D domes retain their shape and much of their original strength proving the increased stability of the true 3D method of 3D printing.

Chapter 4: Test Structure Subsystem

Department of Transportation Standards

The test structure is a result of the safety requirement of the helmet. The most critical aspect of a motorcycle helmet is the safety it provides. As mentioned before, there are motorcycle helmet safety standards defined by the Department of Transportation. These are self-tested standards, and thus the developer of a motorcycle helmet must build the equipment themselves or test their helmets via a third-party.

Figure 10: Example of a 3rd party impact test in which the helmet on a head form is dropped in a controlled fall onto a flat anvil. [6]

Due to budgetary concerns, the test structure was built in house. Of the three main DOT tests (impact, penetration, and dynamic retention), the impact test was most sensible. Note that the dynamic retention test is an evaluation of the chin straps, which is not a concern because ours is taken from a DOT approved helmet. The penetration test is done after the impact test, and can reuse most of the impact test structure. The test rig would be modified and this test would be done if there was time to print additional helmets for testing. Due to this, the test structure is primarily an adaptation of DOT standards for the impact test. The test rig is an attempt to replicate the official testing method as accurately as possible while operating within a limited budget. Initially a system was brainstormed in which the headform and helmet were swung towards the anvil. This design was initially considered; however, this was scrapped due to difficulties in mounting the headform. Additionally, this introduced unnecessary material and cost.

Design Process

The first design version is displayed in Figure 4.2. This is a rail slider system with a drop arm running along a stainless steel tube via two linear bearings. The frame is a simple cage structure made from 1.625 inch diameter steel tubing. Due to the tall height of the structure, a large base is implemented to prevent the test rig from tipping. The system operates using a quick release setup. The drop arm is placed near the top of the rig and attached to a rope on a pulley via a quick release. The rope extends far past the rig, and once pulled by the user, it releases the drop arm. The drop arm consists of a protruding shaft that acts as the mount for the headform and helmet. The helmet and headform are intended to drop in free fall onto the surface of an anvil placed at the bottom of the test rig. Finally, an accelerometer is placed in the headform for the duration of the test.

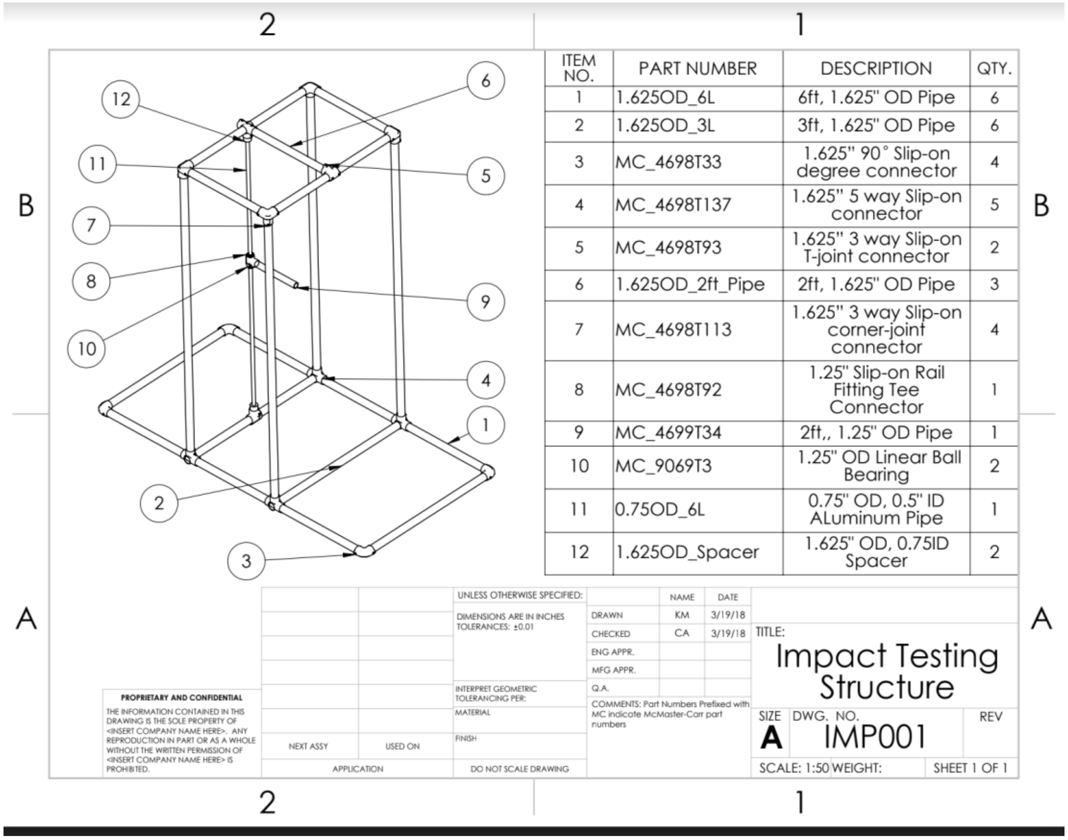
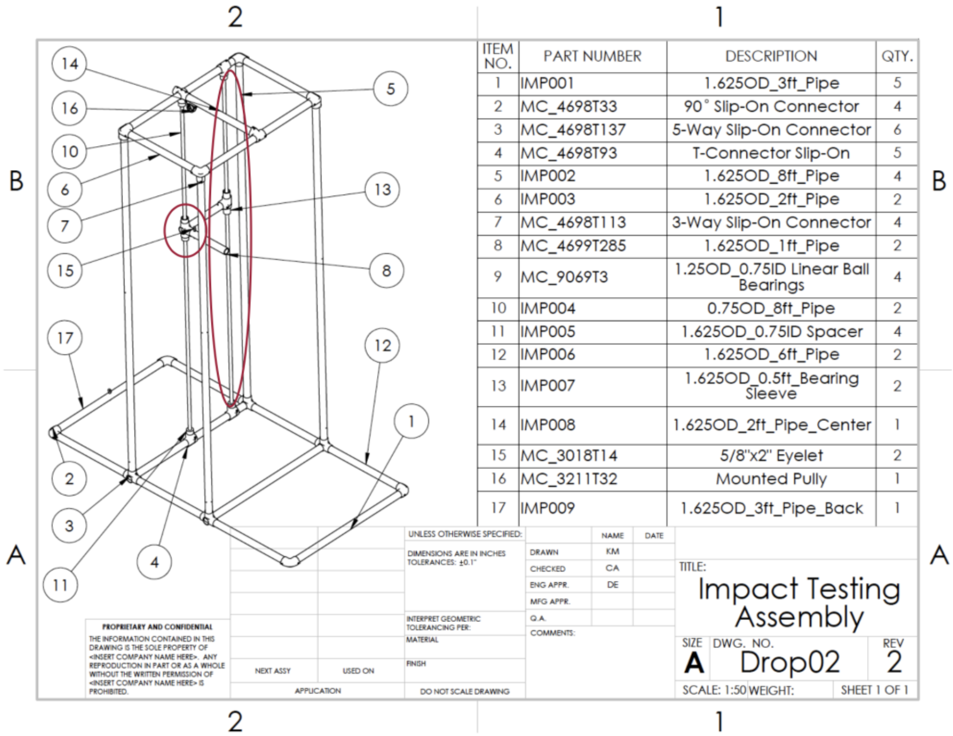


Figure 11: Drawing of first version of impact testing structure. This version of the structure is a monorail system.

This design had two major flaws. First, the linear bearings were likely meant for higher force applications, and proved to cause a high level of friction which prevented free fall. This was combated by machining aluminum bushings with extremely low tolerances to fit closely around the guide rail and into the drop arm, replacing the linear bearings. Oil based lubricant aided in the motion of the bushings, significantly improving drop speed over that achieved with the bearings. The second issue was that the drop arm was able to rotate along the guide rail. This meant there was no way to guarantee the helmet would strike the preferred position each drop. In redesign, a second guide rail and an additional bushing were added to prevent rotation as shown in Figure 4.3. The full drawings are located in Appendix G. As a precaution during testing, a safety shield was constructed out of wood and clear acrylic. The plastic was on the front to allow viewing of the test.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	IMP001	1.625OD_3ft_Pipe	5
2	MC_4698T33	90° Slip-On Connector	4
3	MC_4698T137	5-Way Slip-On Connector	6
4	MC_4698T93	T-Connector Slip-On	5
5	IMP002	1.625OD_8ft_Pipe	4
6	IMP003	1.625OD_2ft_Pipe	2
7	MC_4698T113	3-Way Slip-On Connector	4
8	MC_4699T285	1.625OD_1ft_Pipe	2
9	MC_9069T3	1.25OD_0.75ID Linear Ball Bearings	4
10	IMP004	0.75OD_8ft_Pipe	2
11	IMP005	1.625OD_0.75ID Spacer	4
12	IMP006	1.625OD_6ft_Pipe	2
13	IMP007	1.625OD_0.5ft_Bearing Sleeve	2
14	IMP008	1.625OD_2ft_Pipe_Center	1
15	MC_3018T14	5/8"x2" Eyelet	2
16	MC_3211T32	Mounted Pully	1
17	IMP009	1.625OD_3ft_Pipe_Back	1

Figure 12: Drawing of the revision of impact testing structure. The major change is the addition of second pole (large red circle) to prevent the rotation of the head form shaft (small red circle).

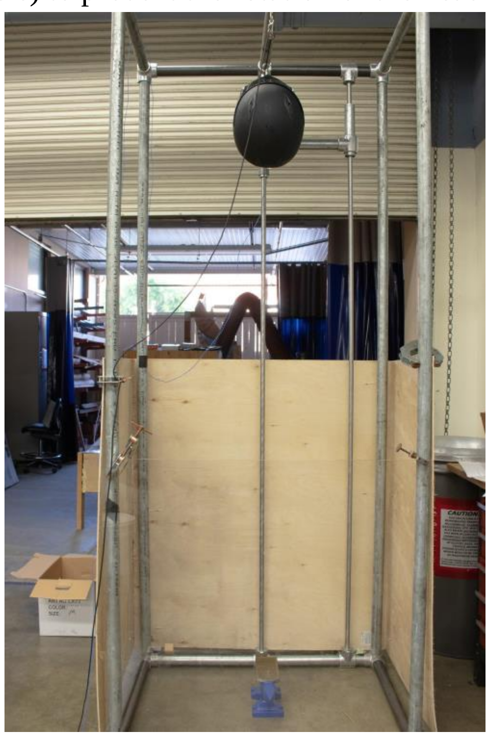


Figure 13: Picture of the complete test structure with the helmet mounted on the head-form, the safety guard installed, and the anvil placed at the bottom of the structure.

It is worth noting, that while an attempt was made to perfectly replicate DOT standards, the final design had some deviations. DOT standards require a magnesium head form to achieve the correct properties while maintaining a resonant frequency of the head above 2000 Hz. This ensures that the head does not resonate significantly upon impact, distorting the accelerometer readings. This item proved to be beyond the allotted budget, so a ballistics gel head form was used instead. This head form had ideal mass, but low stiffness and resonant frequency. This led to some additional acceleration readings after impact, but this data was filtered out. Additionally, DOT standards require the accelerometer to be placed at the center of the head form. This was not convenient for the ballistic gel head form due to its low stiffness. If the accelerometer was placed near the center, the head form would significantly dampen the acceleration and the reading would be very low. To avoid this, the accelerometer was placed near the back surface of the head form, closest to the location of impact.

Additionally, while attempts were made to reduce friction by using lubricated bushings, the final impact energy in testing was about half that specified for standard DOT impact testing.

Testing Validation

Table 5: Comparison of DOT standard slider and our slider weights, impact velocity, and energy released.

	Weight [kg]	**Impact Velocity [m/s]**	**Energy [J]**
DOT Standard	7	6	107.7
Our Impact	10.8	3	58.8

This discrepancy, however, was not a large concern. Commercial helmets were tested under the same conditions on this system and were used as a baseline comparison. So while there would be error in the baseline test, this same error should be present in all helmet tests. All setups and procedures were kept consistent across all tests. Ultimately, a relative comparison could be made (i.e., is the helmet safer or less safe than the commercial helmets that have passed DOT testing).

Chapter 5: Helmet Shell Subsystem

Shell Purpose

The role of this outer shell subsystem is twofold. First, it is meant to prevent the user's skull from getting punctured by sharp or pointed objects. Second, the outer shell provides the structure and shape for the helmet, allowing the inner shock absorbing material to adhere to something rigid, so as not to disintegrate upon impact.

Additionally, this subsystem will be the component that takes advantage of Arevo's new technology the most, since a strong curved geometry of the structure would be very difficult to print on a conventional printer. However, with Arevo's 7-axis "true 3D" printing, the printing process will be more straightforward and will allow us to achieve the desired geometry.

Shell Requirements

This subsystem is a crucial part of the helmet design and, therefore, there are several requirements that must be met. One of the most important is finding the right balance between strength and weight. Since the outer shell is usually about 70-80% of the entire weight of the helmet, it was clear that some research was needed here to determine the best way to maximize strength, while minimizing weight. After completing several FEA tests, we decided on a thickness of 3.5 mm for the outer shell. Ideally, the shell would be less than 4 pounds, while still being able to pass DOT certification. Strength properties can be enhanced by changing the print orientation of the carbon fiber. Another requirement is that the shell have an appropriate shape in order to fit properly on the user's head, while also providing extra protection in areas of stress concentration. The shell had to be thick enough in certain areas so that when a large stress was applied, it would still be able take the impact at the same time still containing the inner foam. The shell also needs to have vents for proper air flow so the user does not get too hot or sweaty while wearing it. Additionally, almost all the aesthetic appeal of the helmet will come from the shell design.

Shell Options

Since our group has decided on a "full face" helmet design, the shell design options were limited. It was crucial that the helmet we designed would fit the inner foam perfectly so we turned to a local 3D scanning company that could get us an exact CAD design of the helmet we purchased. For the material selection, AREVPO offers a filament that includes chopped carbon fiber in addition to PEEK that improves its material properties. A future print option would be continuous carbon fiber, which would allow for much better material properties and a faster print time. This would also showcase AREVO's "true 3D" printing capabilities. A final option is the use of a combination of carbon fiber and Kevlar in the printing process. Ideally, the shell would have been printed continuously using a carbon fiber/ Kevlar matrix. This would yield better material properties, while showcasing AREVO's technology. Hopefully this option will be available also in the future.

Shell Design Process

As with any engineering design, the process for design and optimization of the helmet shell was an iterative process. Initially, our group decided to try to make a simple CAD model of a motorcycle helmet in SolidWorks. The design was very rudimentary and lacked any sort of detail, such as visor mounts or air vents. This initial design did allow us to perform some preliminary FEA analysis, which provided insight into stress concentrations due to impact. From this we were able to conclude that the shell should be about 3.5mm thick. However, there were several drawbacks to this original design. Due to the complex geometry of a helmet, it was very difficult to resize the helmet or increase thickness around areas of stress concentrations. Additionally, since padding is custom made to the shape of production helmets, it would have been nearly impossible to find padding that would fit perfectly inside the CAD modeled helmet. Because of these issues, a new method of design was needed.

Figure 14: Initial CAD design of reinforced carbon fiber PEEK helmet using SolidWorks

The interior padding proved to be one of the biggest issues facing our design team, since buying the materials and shaping them ourselves proved to be nearly impossible and very costly. Therefore, we decided we must strip the padding from the inside of a mass produced helmet and fit it into our shell. This required us to come up with a design that would exactly match a mass produced helmet. We figured that this could be accomplished by 3D scanning a helmet bought online and converting the scanned file into a CAD file. We contacted a few different companies in the area and finally found a company called Zip-Bit Inc. This company was generous enough to offer us a substantial student discount so we could afford this design method. To get the helmet properly scanned, we bought a helmet online, stripped out the interior padding and visor, and brought the shell to Zip-Bit. After many hours of work, the staff was able to scan the helmet shell and provide our team with a CAD file. This method provided several advantages over the initial design. First, it allowed us to solve the big problem of getting proper interior padding, as we were able to assemble the padding we had stripped out of the purchased helmet, inside the 3D printed shell. Also, by buying a few of the same helmet, we were able to compare the mass produced, polycarbonate helmet directly with our 3D printed carbon fiber helmet, since all the dimensions and interior padding were the same. By performing the same impact tests on each of the helmets, we could determine if our carbon fiber helmet was an improvement over the polycarbonate shell. Finally, since our carbon fiber shell was modeled off of a production helmet, it was relatively comfortable and provided good airflow for the user.

Figure 15: Final CAD design achieved from using Zip-Bit's 3D scanner

Though this 3D scanned helmet shell was almost perfect for our project, one more problem arose right before the print that caused us to have to adapt a bit more. The issue was that the helmet shell was slightly too big to fit fully on the print bed of AREVO's printer. Therefore, it became necessary to cut the shell into two pieces, print these pieces separately, and then somehow fasten these pieces together. After quite a bit of discussion with AREVO and our advisors, we decided the best place to cut the helmet would be at the chin bar. We figured this would be the best way to minimize any strength depletion, while still meeting the dimensional requirements of the printers. We also had to figure out how to fasten the two pieces together. We concluded using a two part polymer epoxy would be the best solution. Though cutting the helmet shell was not ideal for our design, it ended up being a necessary step in the design process and did not have too great of a negative impact on our testing.

Helmet Shell Analysis

To complete this analysis a simplified motorcycle helmet was modeled in order to find the location and values of the maximum stresses on the helmet during impact. This system was analyzed in order to decide the thickness the helmet, so that the helmet will be strong enough to not fracture during impact. The modeling approach consists of using the program Abaqus to conduct finite element analysis on the 3D model. In addition to this the SolidWorks simulation toolbox was used to simulate a drop test in order to further test the strength of the helmet before doing real testing. The biggest assumption made for the analysis was that the shell material was isotropic. While this made calculations and modeling easier, it is an idealization of the reality, since the real printed material will be anisotropic. Additionally, the loading conditions were modeled as a point force, while in reality slight deformation of the shell would lead to a larger contact patch, and a greater distribution of force, resulting in lower maximum stresses at the region of impact (Fish).

Table 6: The material used in this model is carbon fiber in a PEEK matrix, but because Poisson's ratio and density vary, and are not known by the team, the analysis was done with these properties estimated based off of values from similar materials.

	Young's Modulus [GPa]	Poisson's Ratio	Density [kg/m^3]
Carbon Fiber in PEEK Matrix	66.06	0.33	1300

An important thing to note is that the FEA was done with an isotropic material definition, whereas all carbon fiber is anisotropic. However, this is still useful because the final true 3D printed helmet should resemble a more isotropic material than traditional 2.5D printing.

To model this part in Abaqus there was a point force of 7.5kN, which was found with hand calculations shown in the Appendix F, applied across multiple points. Then five points on the base of the helmet were encastered in order to not move. Five points close to each other were used because this is the smallest number of points we were able to identify in order to avoid execution errors with the program. A small number of encastered points is preferred since there are no hard fixed points when a helmet is situated on a human head.

The SolidWorks model required less input, the helmet was set to drop on the back of the head and the drop speed was set to 6 m/s in order to simulate the DOT tests. The plane the helmet hit was set to no displacement.

The results show that in both the cases with SolidWorks and Abaqus, the helmet will not break under the expected force from the drop test. From Abaqus, Figure 5.3 shows the results. The units had to be done in terms of mm because of the way the model was defined in the SolidWorks model. After using mm as the base units for inputting the Young's Modulus and yield strength, the resulting stress was not reported in Pascals. In order to get the actual results in

Pa, the numbers must be multiplied by 100. The maximum in the figure is seen to be 146 MPa, but because it is only near the encastered area, rather than where the force is applied, it can be ignored. This can be ignored because no helmet is ever held in place in all directions like it is in this simulation. Therefore, the meaningful maximum is where the point force is applied, which is an average of a 12 MPa, which is below the yield strength of the material, therefore it should not break on the point of impact when the material is isotropic.

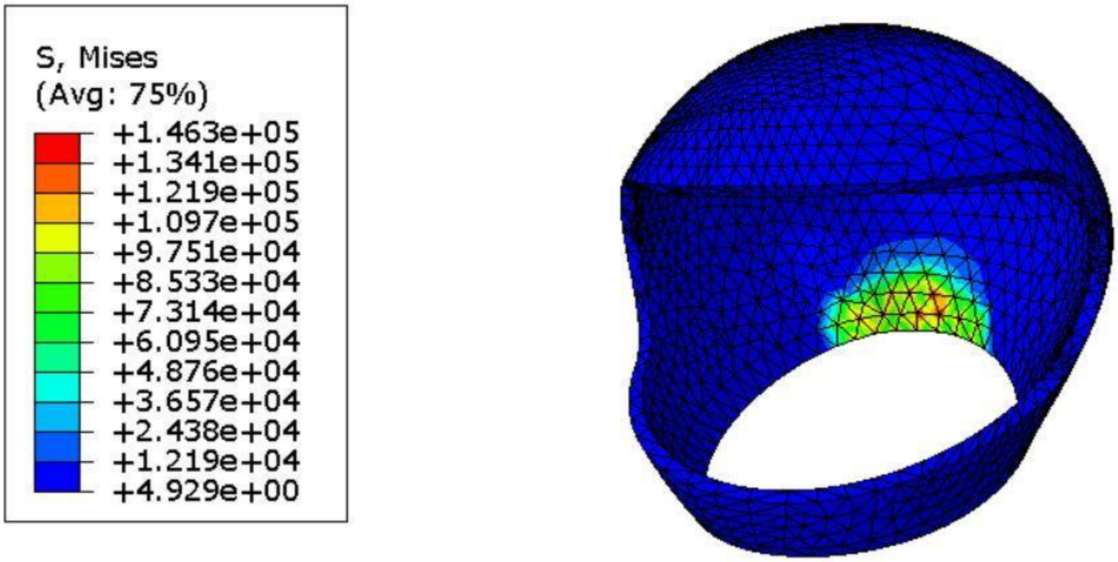


Figure 16: Point force Von Mises stress results, showing a max stress of 146 MPa, and an average of 12 MPa at the point of force

In Figure 5.4 the drop test results are shown. These results are correct units, and it can be seen that the max Von Mises stress is 29 MPa. This again shows that the part will not break due to the drop test

Figure 17: shows the results of the drop test in SolidWorks with a maximum Von Mises of 29 MPa

The results of this analysis based on a 3.5 mm thick shell with the AREVO materials properties, assuming the material is isotropic, show that the helmet should not crack due to stress from the drop test. Hand calculations showing the force for the impact as well as calculations for the stress can be found in the Appendix F.

Subsystem Test and Verification

The helmet was tested utilizing a drop test similar to the testing outlined by the Department of Transportation. The design and implementation of this testing structure is outlined in the next section. The drop testing was performed on two commercially available helmets and the 3D printed helmet. The commercially available helmets were the same model and size of the 3D printed helmet to eliminate as many variables as possible during testing.

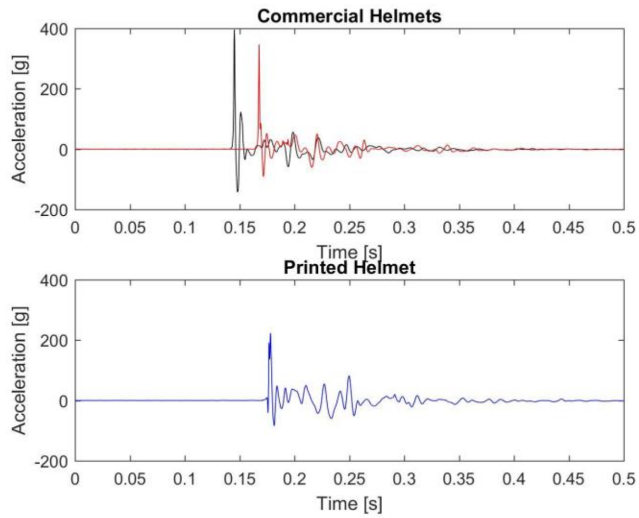


Figure 18: Results from the impact testing on two commercial helmets and the 3D printed helmet. The acceleration on the head form experienced between 340 and 396 g's during the commercial helmet testing and less than 230 g's for the 3D printed helmet.

The acceleration data for the drop tests indicate that the commercial and the 3D printed helmets all experienced accelerations less than 400 G's and technically passed DOT impacting testing. Unfortunately, a top section of the 3D printed helmet sheared off between one of the top layers, so while the helmet passed the impact testing, it very likely would not pass the subsequent penetration testing.

Table 7: Tabulated results of the impact testing. The printed helmet outperformed the commercial helmets in almost every DOT standard. DOT standards indicate that the acceleration above 200 G's cannot be present for more than 2 ms or above 400 G's for more than 4 ms. The prolonging of these accelerations is due to the lack or rigidity in the ballistics gel head form.

	Commercial Helmet 1	**Commercial Helmet 2**	**Printed Helmet**
Max Acceleration [G]	346.47	396.20	223.01
Time Above 200 G's [s]	0.0009	0.010	0.006
Time above 150 G's [s]	0.011	0.014	0.012

The testing of the 2.5D printed helmet indicates that the helmet design would experience significantly less deceleration compared to identical commercial helmets. The top of the printed helmet did shear off, but this result is not unexpected. As seen from the dome compression testing, 2.5D printed structures will fail critically along a layer as these layers act as slip planes. The 2.5D printed helmet followed this behavior exactly and completely delaminated between two layers. The true 3D domes, however, did not experience this critical failure along the print layers, as the the alternating layers printed perpendicular to the surface eliminate these slip planes. Additionally, the fracture toughness testing indicates a significantly larger critical crack length compared to polycarbonate, indicating a further resistance to this fast fracture experienced by the 2.5D helmet. Although a true 3D helmet was not able to be completed, our material testing indicates with a high degree of certainty that the true 3D helmet would not experience the same critical fracture experienced by the 2.5D helmet.

Chapter 6: Business Plan

Based on Statista, about 500,000 motorcycles are sold each year in the US. Considering state law in nearly all states require helmets to be worn while operating a motorcycle, and helmets are replaced often due to wear and disposal after accidents, it is likely that at least 500,000 helmets are bought each year. With over half of these sales attributed to high-performance luxury helmets, it is safe to assume there is a large market for this type of helmet.

Competition for this market would be any helmet producer making premium helmets, especially manufacturers of carbon fiber helmets.

The goal for this company is to produce the first safe 3D printed motorcycle helmet that can be manufactured on a large scale. Further down the line there are also objectives to make fully customized helmets in order to increase safety due to more closely matching every person's exact head shape. Lastly, the 3D printing process would also allow people to have custom patterns or designs grafted into the helmet, making each product special to the owner.

The compelling technology for this helmet is that it is the first, and only, 3D printed helmet available on the market that meets DOT standards. The 3D printing technology allows the PEEK carbon fiber material to effectively distribute the impact force better than a regular helmet. This force distribution will make provide for increased safety for riders in the case of an accident.

As stated previously, about 500,000 bikes are bought each year, which suggests over 500,000 helmets will also be purchased [7]. The number is greater than 500,000 because some users will buy new helmets as an upgrade, as well as people needing new helmets after any accident.

Technavio Research states that "The conventional premium helmets segment dominated the market in 2017 with a market share of close to 76%" [8]. Conventional premium helmets simply refer high performance helmets, generally tested at a more rigorous standard and with a higher price tag . With this information, we know that most of the helmets being purchased are higher end. This shows that there is room for our helmet to succeed, especially since it is an exciting new technology, which will interest helmet purchasers who appreciate modern advances in technology.

To break into the market, this helmet will begin with standard helmet sizes, so it will not be as customized as possible. The company will start with the business model of selling only via the internet. This model will keep profit margins high, as we won't be paying any middle man. In order to grow we will spend more money on marketing. With only internet sales, our business will not have to continuously expand into more stores, the only cost will be storing our products and shipping them. Therefore as we grow we only need to invest money into more printers and storage space.

Competition

The following companies are the market leaders in motorcycle helmets and account for most of the sales of motorcycle helmets worldwide: Shoei, Bell Helmets, Scorpion Sports, HJC, and Arai. The most popular helmet model for each company will be compared to our helmet and pros/cons will be analyzed below.

Shoei: RF-1200 Helmet

- Description: Full face design, 3.5lb weight, SNELL/DOT certified, shell made from layers of fiberglass, price is $490
- Pros: provides a higher level of safety than our 3D printed helmet at similar price
- Cons: Weighs more than our 3D printed helmet, shell material not as strong as carbon fiber

Bell Helmets: Qualifier DLX Blackout Helmet

- Description: Full face design, 3.34lb weight, DOT certified, shell made from polycarbonate, price is $150, ability to house Bluetooth stereo and communication systems
- Pros: same safety certification as our 3D helmet for lower price, capability for additional technology
- Cons: Weighs more than our 3D printed helmet, shell material not as strong as carbon fiber

Scorpion Sports: EXO-R420 Helmet

- Description: Full face design, 3.3lb weight, SNELL/DOT certified, shell made from advanced LG polycarbonate, price is $160, slots available for speaker system
- Pros: provides a higher level of safety than our 3D printed helmet at a reduced price, capability for additional technology
- Cons: Weighs more than our 3D printed helmet, shell material not as strong as carbon fiber

HJC: RPHA 11 Pro Helmet

- Description: Full face design, 3.12lb weight, DOT certified, shell made of a fiberglass composite (includes carbon fiber, fiberglass, and aramid in composite), price is $400, slots available for speaker system
- Pros: provides the same level of safety than our 3D printed helmet at a slightly reduced price, shell comparable in strength to our 3D printed helmet, capability for additional technology
- Cons: Weighs more than our 3D printed helmet

Arai: Signet-X Helmet

- Description: Full face design, 3.53lb weight, SNELL/DOT certified, shell made of PB-SCLC material, price is $650, slots available for speaker system, includes large ventilation system
- Pros: provides a higher level of safety than our 3D printed helmet, capability for additional technology, more advanced ventilation system
- Cons: Weighs more than our 3D printed helmet, costs significantly more than our 3D printed helmet

Highlight personalization

While the increased safety is objectively the biggest benefit, and it should play a part in the marketing, it should be marketed as an additional benefit. The main focus should be personalization that every user could relate too. The best marketing is one where everyone can relate.

"Because one size does not fit all!"

Internet Marketing

In this era of the internet, the wise and economical way to market is to use the instant reach of the net. This could be through social media and user engagement which is the cheapest way to market as the infrastructure (facebook, twitter, etc) is free. Additionally, ads could be produced for youtube or other video sites.

Salespeople

For this project, it makes sense to outsource this to an ad agency. Within our company, there may be a few people assisting this agency, but in the beginning start-up phase, it makes sense to put the majority of effort into working on the core technology.

Product Cost and Price

The cost of raw material for this helmet was $50 plus $25 for the necessary padding, visor, and chin strap. In addition to the material, it took 70 hours to print. It is important to note that this print time is unsupervised, so we do not have to pay someone to produce most of it. To pay for the print time, AREVO will receive 50% of all profit from these helmets. After some time, we will discuss the possibility of leasing a printer in order to begin independant manufacturing. As sales increase, we will lease more units and move into larger spaces. The only labor necessary is the final assembly of the padding, visor, and chin strap. This labor should take less than 10 minutes per helmet/ The only cost is material, printer upkeep, power, and labor for final helmet assembly. Therefore, the cost of the helmet will start at $500. Compared to competition, this price is extremely reasonable. Many helmets online that are carbon fiber cost anywhere from $400 to in the thousands. This price points puts us near the bottom of the competition in price.

This fact, plus the helmet being a completely new technology puts us in a strong position to succeed in the market of premium helmets.

Warranty and Service

Genuine AREVO reinforced carbon fiber PEEK helmets are engineered and manufactured to precise factory tolerances advertised through the product description. One year warranties are offered to all helmets that are purchased through AREVO, which includes any deficiencies that may have occurred in the manufacturing process of the helmet. Warranties do not cover changes to the physical appearance, or color of the the outer structure including rips, scratches, tears, cracks, wrinkles, or other damage caused by normal wear and tear. The warranty also excludes damage caused from accidents, abuse, or improper installation.

Servicing of helmets will be provided by AREVO with a monetary fee determined on a case to case situation. The helmet users will receive free quotes to determine the cost of servicing the helmet. Upon receiving the serviceable helmet, the manufacture will perform any fixes needed and return the helmet back to the user.

Financial Plan

As mentioned, production would initially be done in-house at AREVO using their printer, splitting revenue 50/50 with the company. AREVO would ideally lend three printers for continuous use, and at 70 hours of print time pre helmet, an average of one helmet would be printed per day. Given near continuous printing, an expected 360 helmets would be produced the first year. At $500 a helmet, this brings in $180,000 of revenue. After splitting revenue with AREVO and covering material costs, an average of $170 profit is expected per helmet, totaling to $61,200 profit per year.

In terms of investment, relatively little initial cost is needed, as AREVO is covering equipment cost and using. An estimated $20,000 would likely cover completion of R&D, as well as patenting. An investor could expect this initial investment back within the first year, at 15% interest. After the first year, the team could start devoting profit towards purchasing some of AREVO’s printers. As AREVO has not yet disclosed the cost of their equipment, it is not known how long it would take to be self sufficient. However, the team would continue to split revenue with AREVO while purchasing equipment and increasing production, until the partnership is no longer necessary, and the team receives 100% of revenues.

Chapter 7: Summary

This project analyzes the benefits and capabilities of AREVO Lab's new additive manufacturing process using a seven axis printing method. This seven axis 3D printing method allows for a final part to avoid much of the anisotropic properties of traditional FDM printing. This project focused on the manufacture of a motorcycle helmet not only because it showcased true 3D printing's abilities to print perpendicular to a spherical surface, but also allowed for a direct comparison to commercially available helmets and utilization of standardized test procedures.

Prior to printing the helmet, FEA analysis and material property testing was performed to analytically depict how a true 3D printed helmet would perform as expected and pass DOT standards. The FEA analysis examined the Von Mises stresses on the helmet as it strikes a rigid plate, similar to DOT impact testing. This FEA analysis revealed that the Von Mises stresses do not exceed that of the compressive strength of the PEEK carbon fiber material, so the helmet would not fail during the DOT testing. Additionally, interlaminar fracture toughness tests were performed to account for any voids within the printed part itself. Because the print beads are circular and many layers of beads are required to print the final part, there is ample opportunity for small voids to form inside the print and act as cracks within the part. Completing this fracture toughness testing revealed a critical crack length of 0.961mm before fast fracture. This critical crack length is approximately three times that of polycarbonate used in most motorcycle helmets. This large critical crack length ensures that the part will not suffer from fast fracture during the impact testing and any small voids can largely be neglected. The modes of failure of 2.5D printing and true 3D printing were also examined to give insight into the benefits of true 3D printing during a compressive failure scenario. Domes were printed in true 3D and 2.5D and compressed in an MTS machine until failure. The 2.5D domes experienced dramatic fracture and total failure of the part after initial fracture. The vertical layers of the 2.5D domes act a slip planes and when the compressive load exceeds the shear strength of the layers, the part suffers a catastrophic failure. Because the true 3D domes are more isotropic than the 2.5D printed domes, their modes of failure were significantly less dramatic. After initial failure and cracking, the true 3D domes maintain their shape and do not experience this catastrophic shear failure like the 2.5D domes.

In order to test the final printed helmet and compare to commercial helmets, a test structure was built to perform DOT impact testing on these helmets. Two commercial helmets were tested and experienced accelerations at the headform from 340-396 G's. A 2.5D printed helmet was also tested and experienced an acceleration of less than 230 G's, but experienced shear failure at the top of the helmet. Even though this 2.5D printed helmet experienced a shear failure, the FEA, fracture toughness tests, and dome compression tests all point towards the prospect of success of a true 3D printed helmet in the same impact testing. This exemplifies the significant capabilities and advantages of using true 3D printing methods where applications of traditional FDM printing would not suffice.

Chapter 1: References

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[1] F.A.O. Fernandez, R.J. Alves de Sousa, “Motorcycle helmets—A state of the art review”, *Accident Analysis & Prevention*, Volume 56, 2013, Pages 1-21
This source provides an in depth analysis of the key components and design considerations for developing a motorcycle helmet.

[2] Kostopoulos, V, et al. “Finite Element Analysis of Impact Damage Response of Composite Motorcycle Safety Helmets.” *Composites Part B: Engineering*, vol. 33, no. 2, 2002, pp. 99–107.
This source provides an example for how to use finite element analysis to model the impact of a helmet onto an anvil, essentially modeling the SNELL impact tests.

[3] Oropallo, William, and Les A. Piegl. "Ten challenges in 3D printing." *Engineering with Computers* 32.1 (2016): 135-148.
This source explains the challenges and pitfalls of modern 3D printing. Some information does to apply to AREVO’s new technology, but much of the information is still relevant.

[4] Keating, Steven, and Neri Oxman. "Compound fabrication: A multi-functional robotic platform for digital design and fabrication." *Robotics and Computer-Integrated Manufacturing* 29.6 (2013): 439-448.

[5] Love, Lonnie J., et al. "The importance of carbon fiber to polymer additive manufacturing." *Journal of Materials Research* 29.17 (2014): 1893-1898.
This source describes how carbon fiber and 3D printing are natural fits for one another.

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[7] “U.S. Motorcycle Sales 2016 Statistic.” *Statista*, www.statista.com/statistics/252261/us-motorcycle-salesin-units/.

[8] Maida, Jesse. “Global Premium Motorcycle Helmets Market 2018-2022 | Increasing Sales of Ultra-Luxury Motorcycles to Boost Growth.” *Business Wire* , Technavio, 2 June 2018, www.businesswire.com/news/home/20180602005074/en/.

[9] "How to Identify Unsafe Motorcycle Helmets." *DOT HS 807 880*. National Highway Traffic Safety Administration, n.d. Web. 16 Oct. 2017.

Appendix

Appendix A: PDS

National Highway Traffic Safety Administration guides (NHTSA) [9]

- Liner Thickness must be at least one inch thick of firm polystyrene foam
- Chin strap is required, and must be attached in a way that nothing protrudes from the helmet more than 5 mm
- Safe helmets usually weigh at least 1 kilogram including the shell and all padding
- Nothing can extend more than 5 mm off the surface of the helmet
- Peripheral vision from the helmet midline must be at least 105 degrees

DOT FMVSS 218

- DOT FMVSS 218 defined by the National Highway Traffic Safety Administration
- The DOT safety standard is not tested by the government, it is self tested and there is no official guarantee on whether or not the helmet meets the requirements.
- DOT standards include dropping helmets onto flat and hemispherical anvils and measuring the acceleration experienced by the headform
- DOT standards specify a headform constructed from an alloy with a resonant frequency above 2000 Hz
- The accelerometer is to be mounted to the center of gravity of the headform
- The headform cannot experience more than 400 G's of acceleration at any point during the impact
- The acceleration can't be larger than 200 G's for longer than 2 milliseconds, and can't exceed 150 G's for longer than 4 milliseconds
- DOT penetration testing is performed after initial impact testing
- Steel striker is dropped from a height of nine feet and cannot penetrate through the shell to the headform

Table A1: Impact Testing Standards

Item	DOT Standard
Flat Anvil	S - 63 J / 63 J M - 90 J / 90 J L - 110 J / 110 J Nominal Fall 1.83 m
Hemispherical Anvil	S - 47.3 J / 47.3 J M - 67.6 J / 67.6 J L - 82.5 J / 82.5 J Nominal Fall 1.38 m
Allowed Peak Acceleration	400 G
Allowed Duration Requirement	2 ms over 200 G 4 ms over 150 G
Impact Test Rig Type	Monorail
Headforms	Variable Weight DOT configuration S = 3.5 kg M = 5.0 kg L = 6.1 kg

Helmet Design Specification

- Outer shell thickness: between 3.5mm and 5mm thick when polycarbonate shell, the necessary thickness may be lower for the carbon fiber helmet. The thickness is increased based on where the helmet will receive the toughest blows, usually the front and crown.
- Vents will be places at the front, top, back of the helmet, and on the chin. The vents will be able to be opened and closed to help keep the user warm or cooler. The vents, when open, will provide stabilization at higher speed because of the air flowing from the front to the back.
- On the chin part of the helmet, there will be a guard to direct airflow from the chin vents and mouth down, so that the visor will not be fogged up.
- There will be a visor on the helmet that can be flipped up and down, which must be attached to the helmet in a way that nothing protrudes more than
- Chin strap is required and will be attached via a rivet
- Inner circumference should be 53 cm - 70 cm depending on head size

Additional Criteria

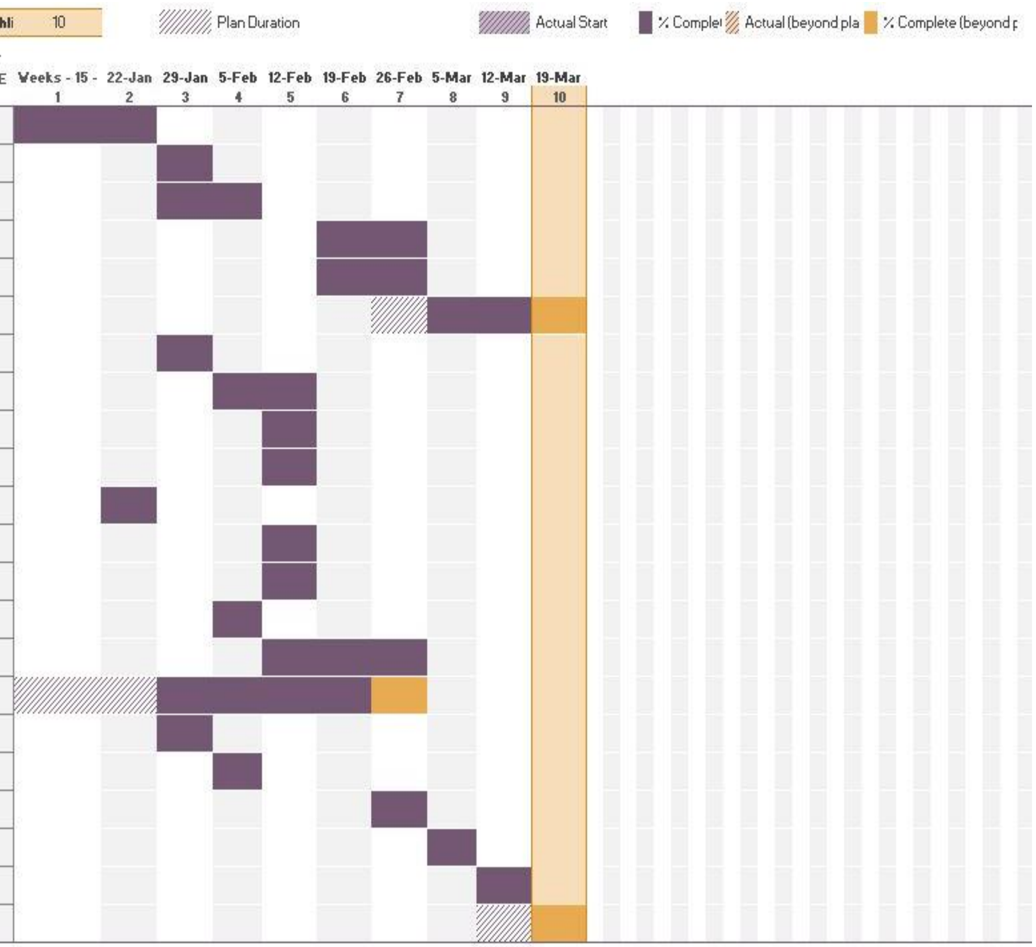
- Helmet should be lighter than a commercially available helmet of the same design
- Surface finish should be smooth and glossy to avoid rotation suring vehicle crash
- Geometrically identical to 3D scanned helmet

Appendix B: Timeline and Budget

Mid-Fall	End Fall	Mid-Winter	End Winter	Mid-Spring	End Spring
-Create initial CAD model of helmet -Complete AREVO printing constraint analysis	-Finalize helmet concept -Finalize materials testing plans and procedures -Work with AREVO to schedule tentative print schedule	-Finalize helmet FEA analysis -Print material testing specimens at AREVO Inc -Finalize print schedule with AREVO Inc -Begin Test structure design and procedures	-Obtain completed helmet 3D scan -Finalize test structure design and procedures -Begin manufacture of test structure -Complete material testing	-Print full 2.5D helmet at AREVO Inc -Finish manufacturing of test structure -Verify test structure design as close to DOT standards as possible -Senior Design Conferences	-Print and test true 3D helmet at AREVO Inc -Complete penetration testing on commercial and true 3D helmets

Period Highli 10

ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Create Specimen Test Procedure	1	2	1	2	100%
Update Budget - due 1/29	3	1	3	1	100%
Detailed Drawing - due 2/5	3	2	3	2	100%
Analysis Report and oral presentation - due 3/5	6	2	6	2	100%
Formal Written report due, oral progress report - due 3/12	6	2	6	2	100%
Assembly drawings and hardware goals - due 3/21	7	3	8	3	100%
Retrieve Specimen from AREVO	3	1	3	1	100%
Run Tests on Specimen	4	2	4	2	100%
and Write technical Report for Specimen, compare results to pol	5	1	5	1	100%
Acquire Cheap Helmet	5	1	5	1	100%
Practice taking EPS foam from cheap helmet	2	1	2	1	100%
Order Helmets to be used in final product	5	1	5	1	100%
FEA	5	1	5	1	100%
FEA - practice using solidworks cad in Abaqus	4	1	4	1	100%
FEA - complete actual FEA analysis of helmet	5	3	5	3	100%
DOT TESTING - prep	1	6	3	5	100%
DOT TESTING - conceptual design of test structure	3	1	3	1	100%
DOT TESTING - first draft of test procedures	4	1	4	1	100%
DOT TESTING - CAD all parts for test structure	7	1	7	1	100%
DOT TESTING - assemble CAD parts for test structure	8	1	8	1	100%
DOT TESTING - write test procedures	9	1	9	1	100%
DOT TESTING - order all materials	9	1	10	1	100%



ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
Table of Contents, Intro, Drawings,	1	1	1	1	100%
Experimental Protocol, PDS update	2	1	2	1	100%
Senior Design Conference	5	2	5	2	100%
Draft of final	1	8	1	8	100%
Patent Search or Business	5	1	5	4	100%
Hardware Due (Open House)	5	2	3	2	100%
Final Report	8	4	8	4	100%
Order Parts for testing	1	2	1	1	100%
Assemble Test Structure	3	2	3	2	100%
Print Helmet	2	3	2	3	100%
Plan test	2	2	2	2	100%
Order test	4	1	4	1	100%
Complete tests on test helmets	5	1	5	1	100%
Assemble Prototype	5	1	5	1	100%
Test Prototype Helmet	5	1	5	1	100%
Analyze Tests	5	2	5	2	100%
Finish true 3 d domes	7	2	5	1	100%
Test True 3d	8	1	5	1	100%
Analyze True 3d dome tests	9	1	5	1	100%

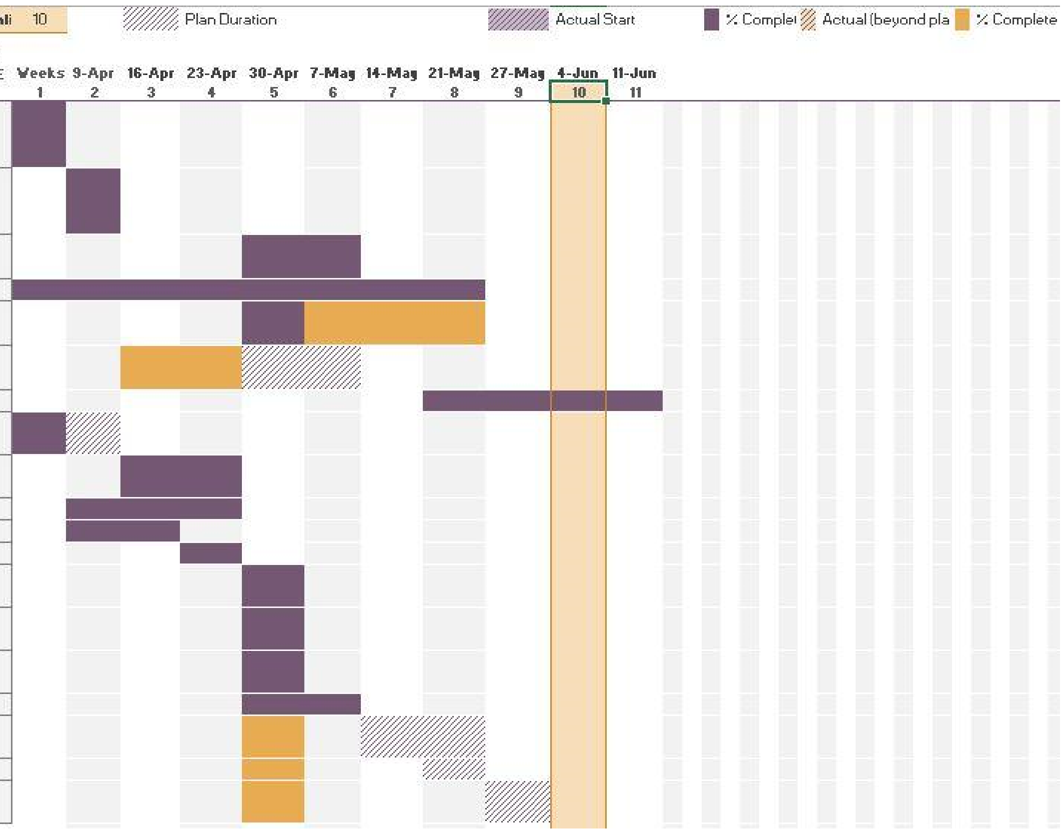


Figure B2: Spring Gantt chart

INCOME			
Category	**Source**	**Sought**	**Committed**
Grant	AREVO Inc	N/A	N/A
	Senior Design Grant	$3,000	$3,000
	TOTAL	$3,000	$3,000
EXPENSES			
Category	**Description**	Estimated Cost	Spent
Helmet (x3)	3 of the same helmet	$200	$179.97
Helmet Scan	Zipbit scanning services	$500	$452.20
Helmet Testing Equipment	Accelerometer Sensor	$250	$421.99
	Head Form	$280	$132.07
	Steel Tubing	$400.00	$454.37
	Slip on Guides	$200.00	$391.38
	Linear Ball Bearings	$120.00	$136.40
	Pulley	$20.00	$20.00
	Anvil	$50.00	$47.32
	Safety Shield	$100	$80.00
	Plywood	$40	$24.00
	miscellaneous nuts and bolts	$50	$60.00
	Fuel		$78.00
	TOTAL	**$2,210.00**	$2,399.70
	NET RESERVE		$600.30

Appendix C: Company Contacts

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Testing Engineer

These contacts informed the team about 3D printing. They have shown the group the capabilities and limitations of the 3D printer to be used to produce the helmet shell.

Appendix D: Material Properties of Chopped Carbon Fiber

All material property data is from AREVO Lab's own in house material testing. Raster orientation refers to the orientation the filament was laid down to make the print. A "0 degree raster orientation" refers to a print path along the length of the test sample. "90 degree raster orientation" refers to a print path along the width of the test sample. A "0/90 degree raster orientation" refers to multiple players being put down at 0 degree raster orientation and 90 degree raster orientation.

Table D1: Tensile Testing data from AREVO 3D printed composite material

Raster orientation [°]	Ultimate Stress [MPa]	Yield Stress [MPa]	Fracture Stress [MPa]	Young's Modulus [GPa]	Max. Elongation [%]
0	71.36	34.68	70.29	2.87	5.01
0	74.49	45.77	73.8	2.83	3.99
0	73.19	46.3	72.49	2.64	4.45
Average	73.01	42.25	72.19	2.78	4.48
Stand. Dev.	1.28	5.36	1.45	0.1	0.42
90	53.91	45.93	53.5	2.85	2.29
90	57.69	45.29	57.69	2.69	2.86
90	50.63	43.13	50.24	2.67	2.29
Average	54.08	44.78	53.81	2.74	2.48
Stand. Dev.	2.88	1.2	3.05	0.08	0.27
0/90	67.75	40.4	67.75	2.73	3.93
0/90	74.46	50.79	72.21	2.48	6.77
0/90	57.35	41.2	57.15	2.79	2.84
Average	66.52	44.13	65.7	2.67	4.51
Stand. Dev.	7.04	4.72	6.32	0.13	1.66

Table D2: Compression Testing data from AREVO 3D printed composite material

Raster orientation [°]	Ultimate Stress [MPa]	Yield Stress [MPa]	Modulus of Rupture [MPa]	Young's Modulus [GPa]	Max. Elongation [%]
0	83.61	71.15	83.1	2.02	6.87
0	79.67	63.46	79.62	2.03	6.09
0	79.33	63.58	78.18	2.06	6.99
Average	80.87	66.06	80.3	2.04	6.65
Stand. Dev.	1.94	3.6	2.07	0.02	0.4
0/90	69.7	52.35	68.19	1.94	7.9
0/90	64.15	47.03	63.06	1.93	7.45
0/90	84.49	61.63	83.75	2.32	5.84
Average	72.78	53.67	71.67	2.06	7.06
Stand. Dev.	8.58	6.03	8.8	0.18	0.88

Table D3: Flexure Testing data from AREVO 3D printed composite material

Raster orientation [°]	Ultimate Stress [MPa]	Yield Stress [MPa]	Modulus of Rupture [MPa]	Young's Modulus [GPa]	Max. Elongation [%]
0	114.16	86.26	114.16	1.97	10.6
0	109.18	104.61	109.18	1.87	8.12
Average	111.67	95.44	111.67	1.92	9.36
Stand. Dev.	2.49	9.18	2.49	0.05	1.24
90	83.59	65.9	83.59	1.95	5.81
90	76.85	65.78	76.85	2.04	4.33
90	78.63	65.88	78.63	1.98	4.7
Average	79.69	65.85	79.69	1.99	4.95
Stand. Dev.	2.85	0.05	2.85	0.04	0.63
0/90	88.7	66.5	88.7	2.15	6.58

0/90	95.22	75.78	95.22	2.5	5.67
0/90	102.1	76.96	102.1	2.59	8.84
Average	95.34	73.08	95.34	2.41	7.03
Stand. Dev.	5.47	4.68	5.47	0.19	1.33

Table D4: Charpy Impact Testing data from AREVO 3D printed composite material

Raster orientation [°]	Energy Absorbed [Nm]	Elasticity [MPa]
0	18.43	613.63
0	16.6	551.58
0	17.63	586.05
0	20.74	696.37
0	13.88	468.84
Average	17.46	583.29
Stand. Dev.	2.25	74.59
90	1.68	53.78
90	1.15	37.92
90	1.26	42.06
Average	1.36	44.59
Stand. Dev.	0.23	6.72
0/90	0.94	32.41
0/90	0.42	13.79
0/90	0.73	24.82
0/90	0.62	21.37
Average	0.68	23.1
Stand. Dev.	0.19	6.7

Appendix E: Concept Scoring

Table E1: concept scoring matrix for shell subsystem

Design Project =	**Fiber Freaks**				**system**	**Shell**	
	TARGET	**DESIGN IDEAS**					
	or						
CRITERIA	**FACTOR**	**1 = Baseline**		**2**		**3**	
Time – Design	3	3		5		1	
Time – Build	3	3		4		1	
Time – Test	3	3		2		1	
Time weighting	30		30		36.67		10.00
Cost – Prototype	$ 100.00	$ 100.00		$ 80.00		$ 150.00	
Cost – Production	$ 150.00	$ 150.00		$ 100.00		$ 200.00	
Cost weighting	20		20		14.67		28.33
Weight	4	3	12	5	20	2	8
Strength	6	3	18	4	24	6	36
Adaptability	4	3	12	5	20	1	4
Speed of Printing	4	3	12	4	16	2	8
Chin Bar Safety	12	3	36	4	48	5	60
Forehead Safety	10	3	30	3	30	4	40
Crown Safety	10	3	30	3	30	4	40
	TOTAL		150.0		186.7		207.7
	RANK						
	% MAX		72.2%		89.9%		100.0%
	MAX	**207.7**					
Light blue areas filled from prioritization matrix							
BASELINE =	**Chopped Fiber**						
Design Descriptions							
two	Continuous Fiber						
three	Kevlar						

	Fiber						

Table E2: concept scoring matrix for mold subsystem

Design Project	Fiber Freaks				System	Print Mold			
	TARGET	DESIGN IDEAS							
	or								
CRITERIA	FACTOR	1 = Baseline			2		3		4
Time – Design	3	3		3		4		3	
Time – Build	3	3		1		4		3	
Time – Test	3	3		3		3		3	
Time weighting	30		30		23.33		36.67		30.00
Cost – Prototype	$ 50.00	$ 50.00		$ 20.00		$ 5.00		$ 60.00	
Cost – Production	$ 50.00	$ 50.00		$ 20.00		$ 5.00		$ 60.00	
Cost weighting	40		40		16.00		4.00		48.00
Weight	1	3	3	2	2	1	1	3	3
customizability	10	3	30	3	30	1	10	3	30
thermal strength	5	3	15	5	25	5	25	1	5
manufacturability	14	3	42	2	28	1	14	3	42
Ease of Use	4	3	12	1	4	2	8	3	12
Reusability	9	3	27	2	18	2	18	3	27
Accuracy	9	3	27	1	9	0	0	3	27
Surface Finish	6	3	18	2	12	1	6	3	18
Mold Release	8	3	24	1	8	1	8	5	40
Repeatability	8	3	24	1	8	1	8	5	40
	TOTAL		222.0		174.7		127.3		236.0
	RANK								
	% MAX		94.1%		74.0%		54.0%		100.0%
	MAX	**236.0**							
BASELINE =	**3D Printed (100%) at Arevo**								

Design Idea Descriptions										
two	**Full Mold, made with slow drying silicone mold, created by using a precise 3d printed mold first, printed at Machine shop**									
three	**Aluminum Plate Mold with ~10% 3d printed fill material**									
four	**3D printed at SCU, making 4 parts that can be clamped and unclamped in order to take apart after printing; cover printed part in epoxy to provide temperature resistance**									

Table E3: concept scoring matrix for Linear subsystem

Design Project =	Fiber Freaks				System=	Liner
	TARGET or	DESIGN IDEAS				
CRITERIA	**FACTOR**	**1 = Baseline**		**two**		
Time – Design	1	1		10		
Time – Build	1	1		10		
Time – Test	1	1		10		
Time weighting	30		30		300.00	
Cost – Prototype	$ 150.00	$ 150.00		$ 25.00		
Cost – Production	$ 10.00	$ 10.00		$ 25.00		
Cost weighting	20		20		26.67	
Weight	15	3	45	2	30	
ease of design	10	3	30	1	10	
reusability	25	3	75	4	100	
energy absorption	10	3	30	3	30	
safety	5	3	15	3	15	
Comfort	5	3	15	2	10	
	TOTAL		210.0		-81.7	
	RANK					
	% MAX		210.0%		-81.7%	
	MAX	**100.0**				
BASELINE =	**EPS Foam (Standard on Helmets), obtained from existing helmet. Unable to purchase as is.**					
Design Idea Descriptions						
two	team designed 3D printed auxetic geometry					

Appendix F: Analysis Details

Hand Calculations

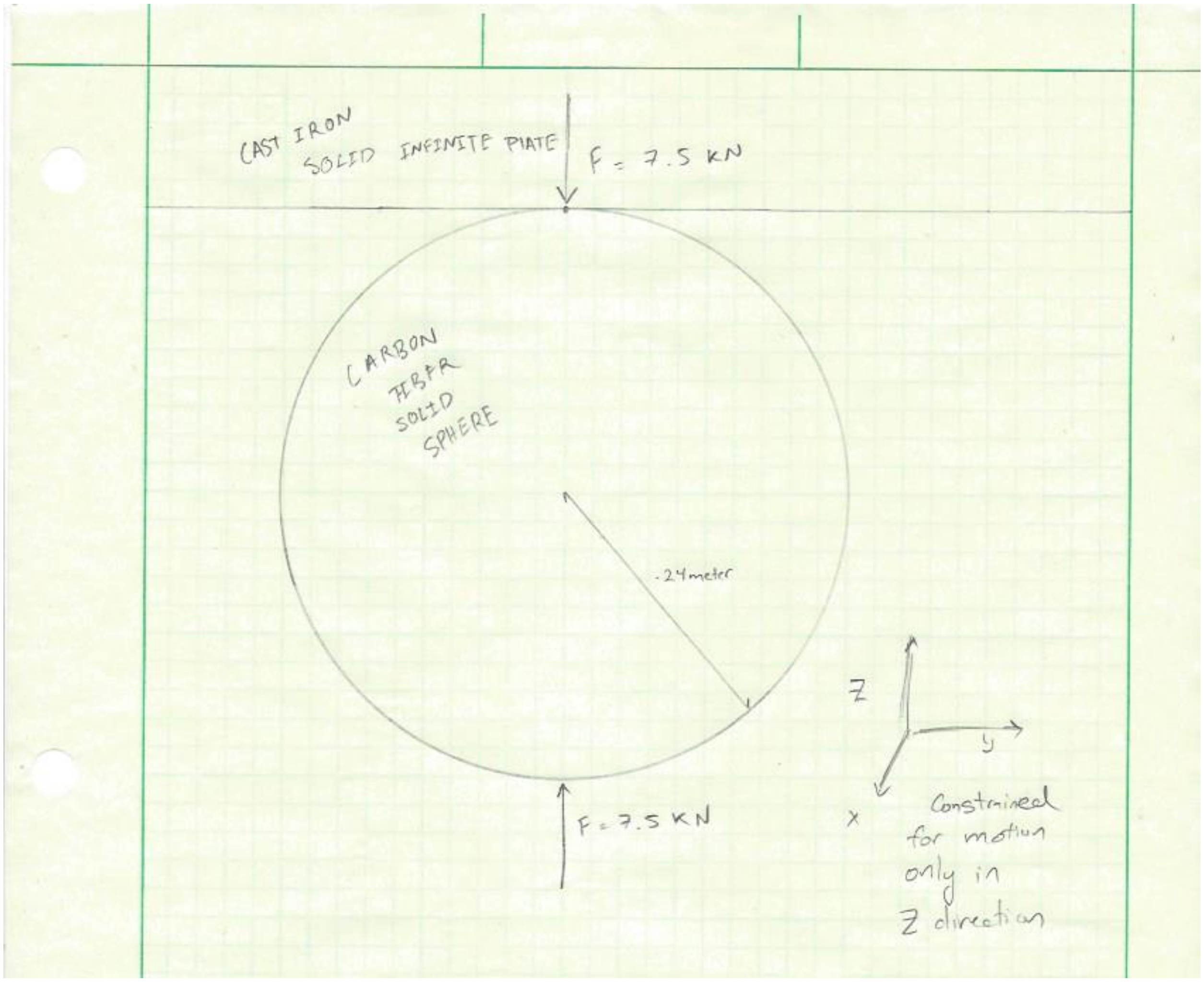


Figure F1: Free body diagram showing the carbon fiber sphere in contact with the cast iron plate for simplified hand calculation of maximum achieved stress.

Hand Calculation Explanation

The point load of 7.5 kN, which was discussed earlier was found with a simple calculation using the height and headform mass from the DOT test standards along with an assumption of 4ms contact (National Highway Traffic Safety Administration). See Figure 2A for hand calculations. The two places where the point force is applied are on the top of the helmet and on the back of the helmet, which is where the tests for DOT testing are done.

A simple hand calculation was done to model the maximum stress achieved in the impact. The collision is assumed to be all contained at a single point. No deformation is assumed to take place. The flat plate is modeled as cast iron and the sphere is carbon fiber. This simple model is shown in Figure 2 in the systems diagram section.

The equation (1) used is for two spheres (Figure 1A), but a flat plane can be modeled as an infinitely large sphere. F is the force applied. K_D is a parameter relating to the diameters. Within it, d_1 is the diameter of the first sphere (assumed to be a medium size helmet where r = .24m (“Helmet Size Chart for HJC, Bell & KLIM”)), and d_2 of the second (∞ in this case). C_E is a parameter relating to the poisson’s ratio and the modulus of elasticity of the two materials. Within it, μ_1 and μ_2 are the poisson’s ratios of the materials. E_1 and E_2 and the modulus of elasticity of the materials. These values were sourced online (Amesweb) and from AREVO. α is an intermediate term which uses equation 3 and 4. Finally the stress ($\boldsymbol{\sigma}_{max}$) is found using equation 1. The stress equations comes from *Manufacturing Engineering and Technology* by Serope Kalpakjian and Steven Schmid (“Hertz Contact Stresses”).

$$\sigma_{max} = \frac{-3F}{2\pi\alpha^2} \quad (1)$$

$$\alpha = \sqrt[3]{\frac{3F C_E K_D}{8}} \quad (2)$$

$$K_D = \frac{d_1 d_2}{d_1+d_2} \quad (3)$$

$$C_E = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \quad (4)$$

From the hand calculations, the stress was estimated to be 460 MPa. It can be noted that this is from a point force so the stress is on one extremely small node, rather than spread out over a space as it should be.

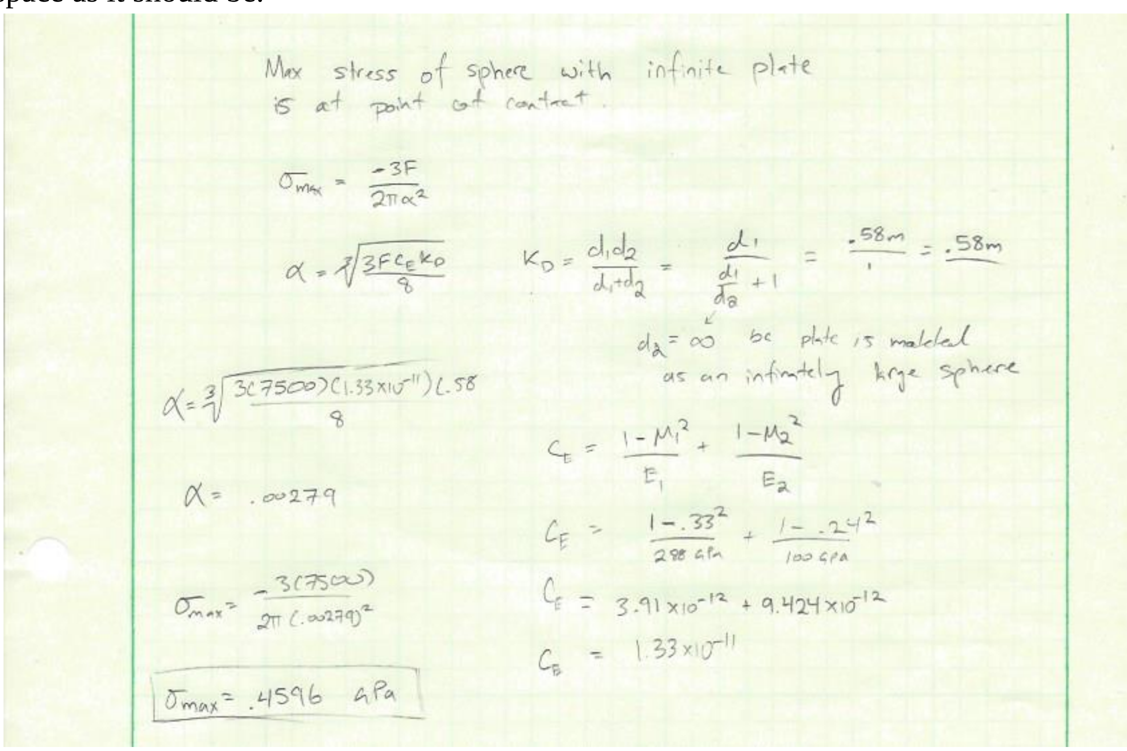


Figure F2: These hand calculations are done by modeling the system as a sphere in point Contact with a rigid infinite plate. The sphere is assumed to be made from carbon fiber in a

PEEK matrix and material properties were given by AREVO Inc. The plate is assumed to be cast iron

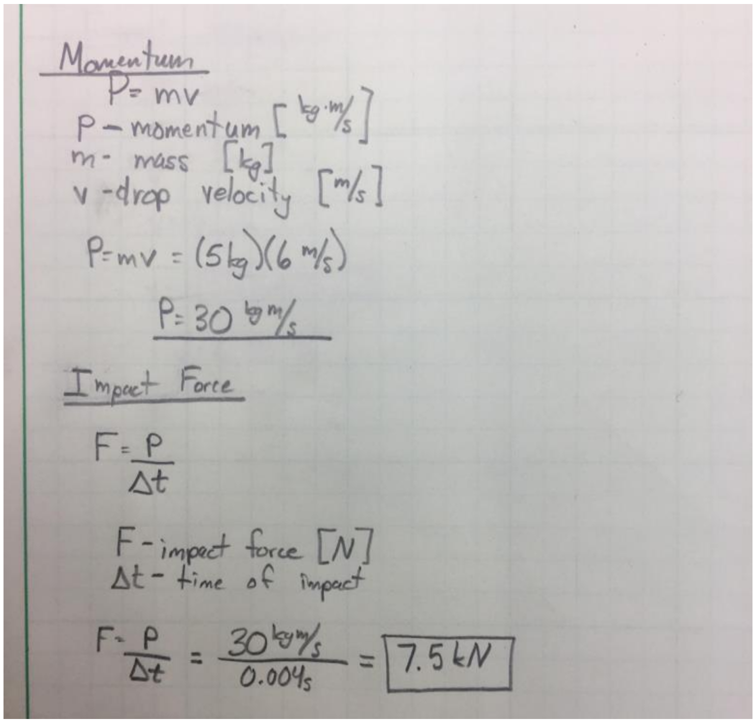


Figure F3: Hand calculations for the impact force imparted on the helmet. The impact velocity, *v*, and time of impact, *Δt*, were taken from a DOT technical report [9].

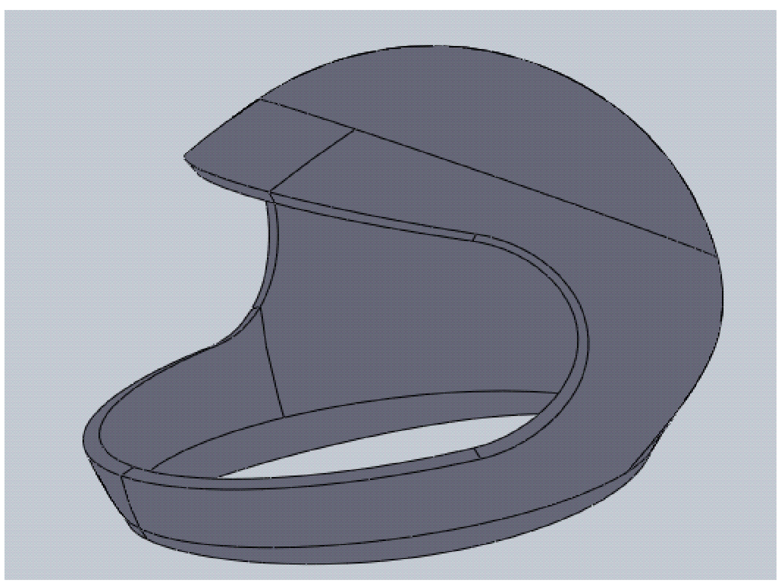
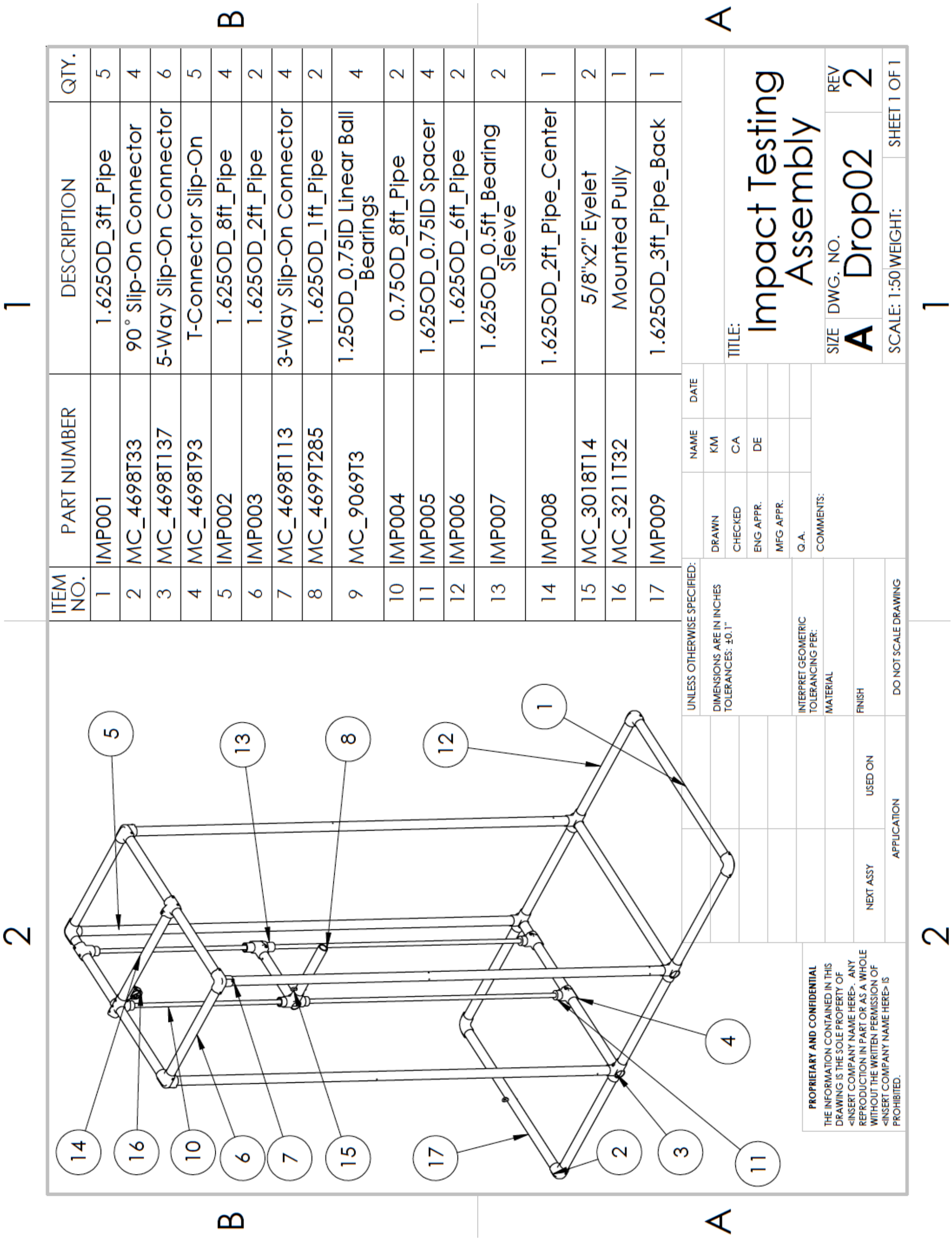


Figure F4: Simplified helmet used for the FEA modeling

Appendix G: Testing Structure Drawings



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	IMP001	1.625OD_3ft_Pipe	5
2	MC_4698T33	90° Slip-On Connector	4
3	MC_4698T137	5-Way Slip-On Connector	6
4	MC_4698T93	T-Connector Slip-On	5
5	IMP002	1.625OD_8ft_Pipe	4
6	IMP003	1.625OD_2ft_Pipe	2
7	MC_4698T113	3-Way Slip-On Connector	4
8	MC_4699T285	1.625OD_1ft_Pipe	2
9	MC_9069T3	1.25OD_0.75ID Linear Ball Bearings	4
10	IMP004	0.75OD_8ft_Pipe	2
11	IMP005	1.625OD_0.75ID Spacer	4
12	IMP006	1.625OD_6ft_Pipe	2
13	IMP007	1.625OD_0.5ft_Bearing Sleeve	2
14	IMP008	1.625OD_2ft_Pipe_Center	1
15	MC_3018T14	5/8"x2" Eyelet	2
16	MC_3211T32	Mounted Pully	1
17	IMP009	1.625OD_3ft_Pipe_Back	1

Figure G1: Test structure drawing

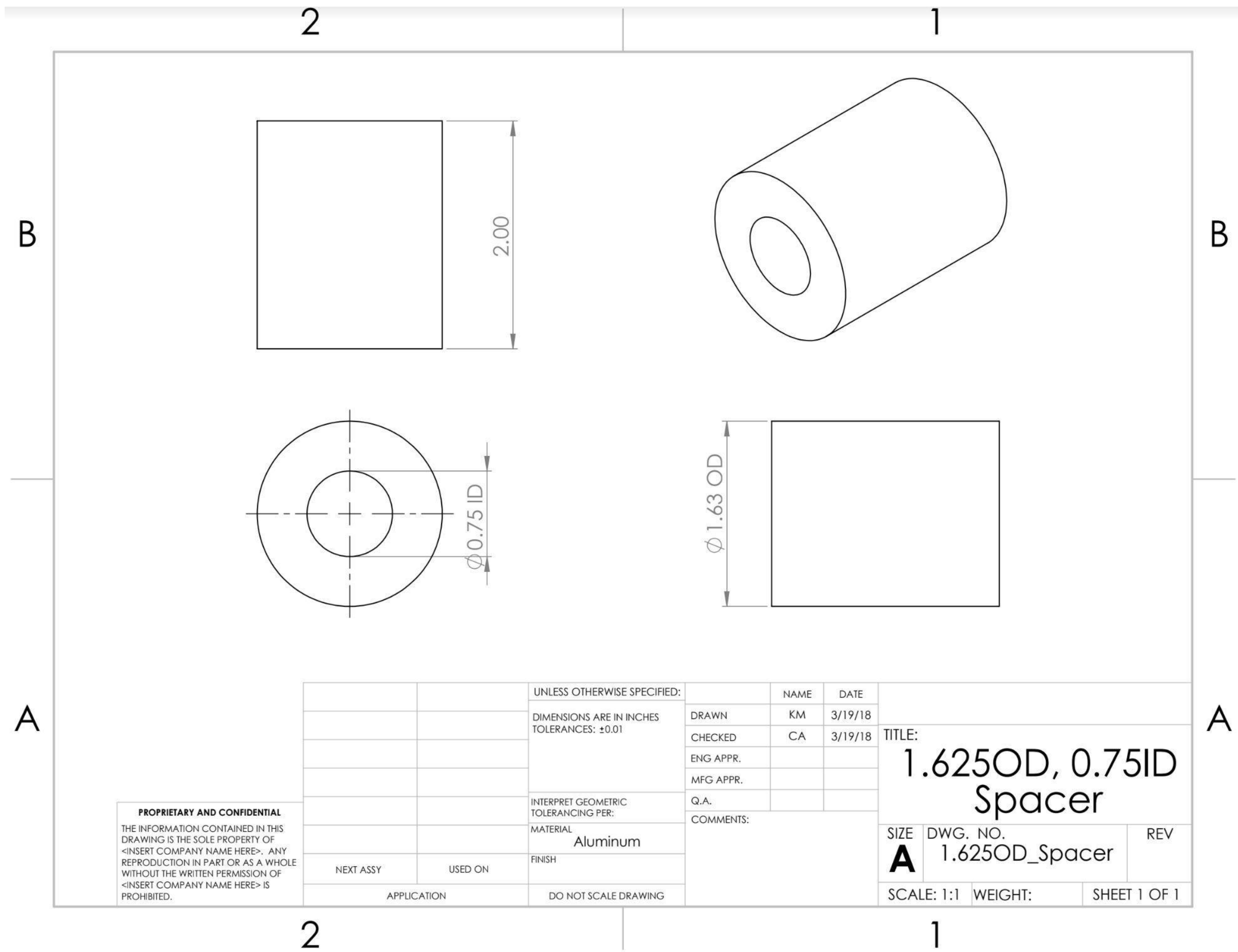


Figure G2: bushing drawing

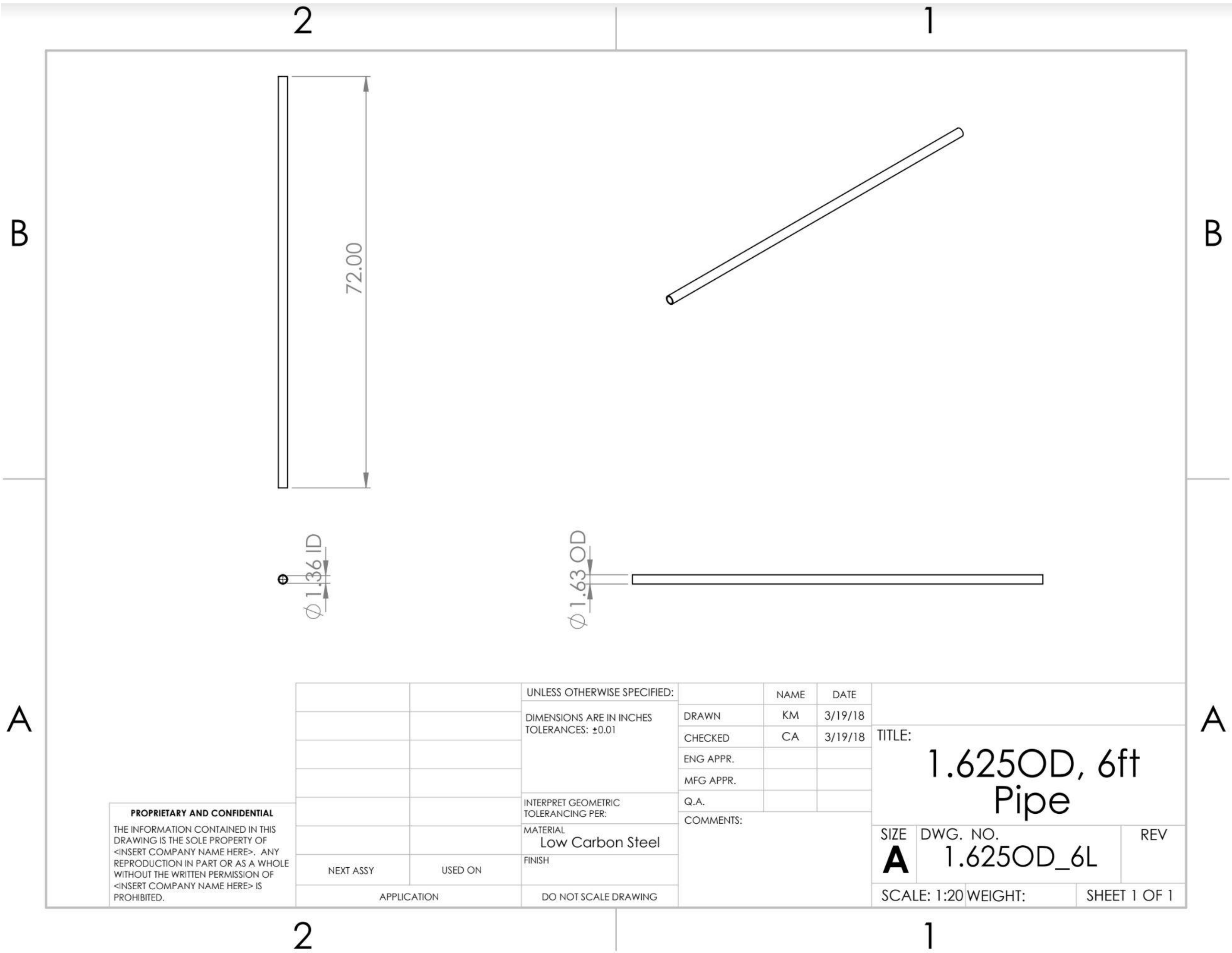


Figure G3: 6ft vertical pipe drawing

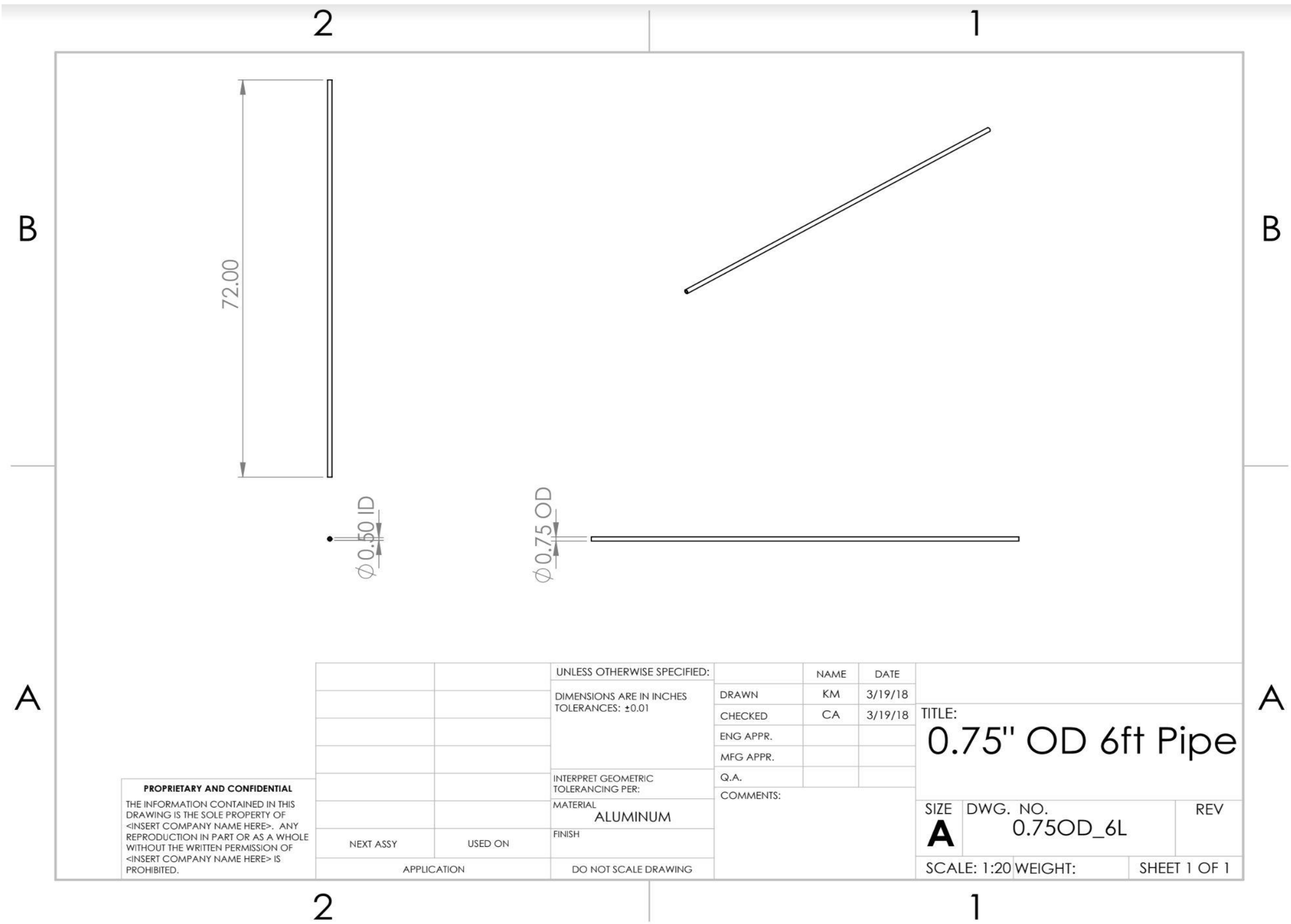


Figure G4: 6 ft vertical guide pipe

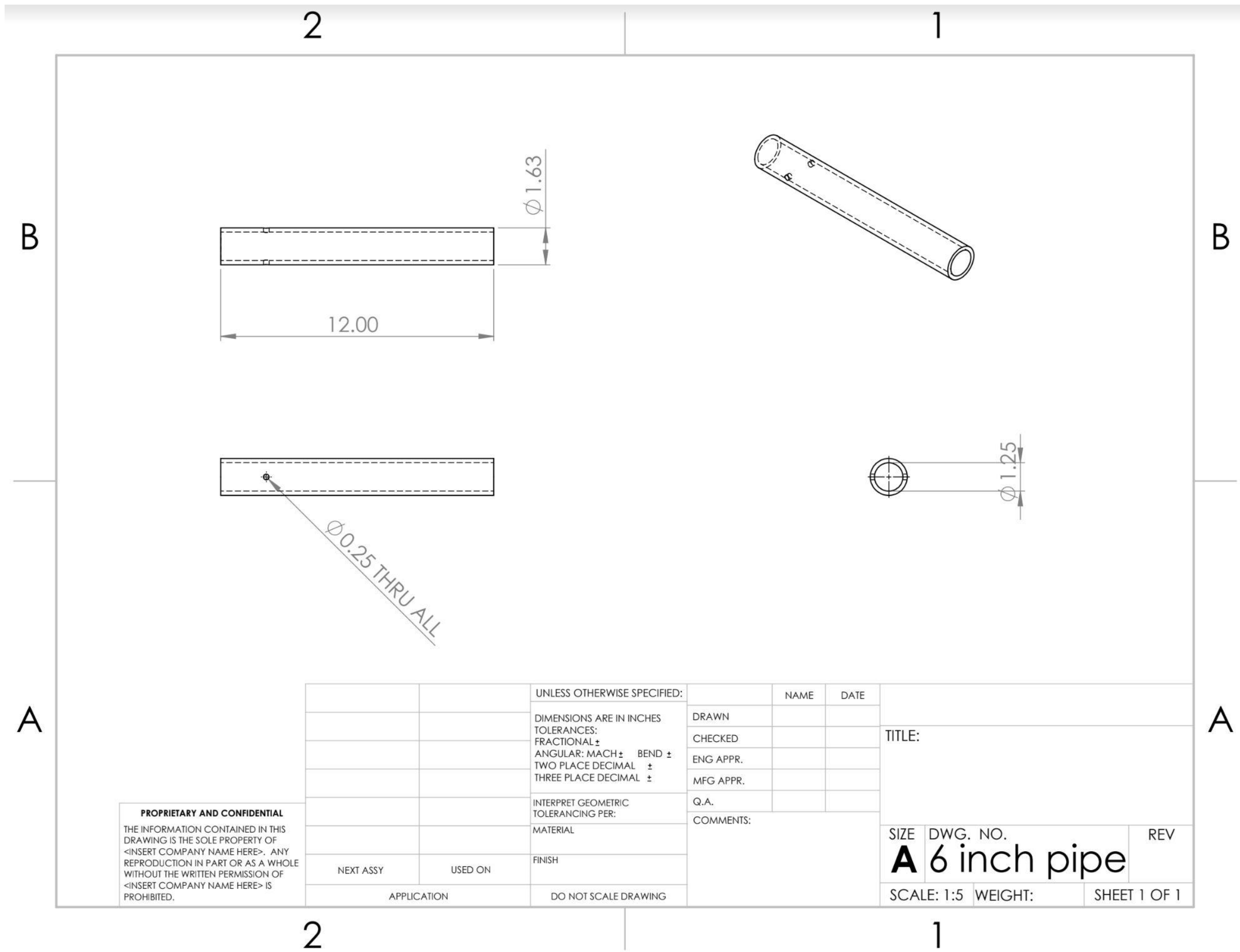


Figure G5: drop arm drawing

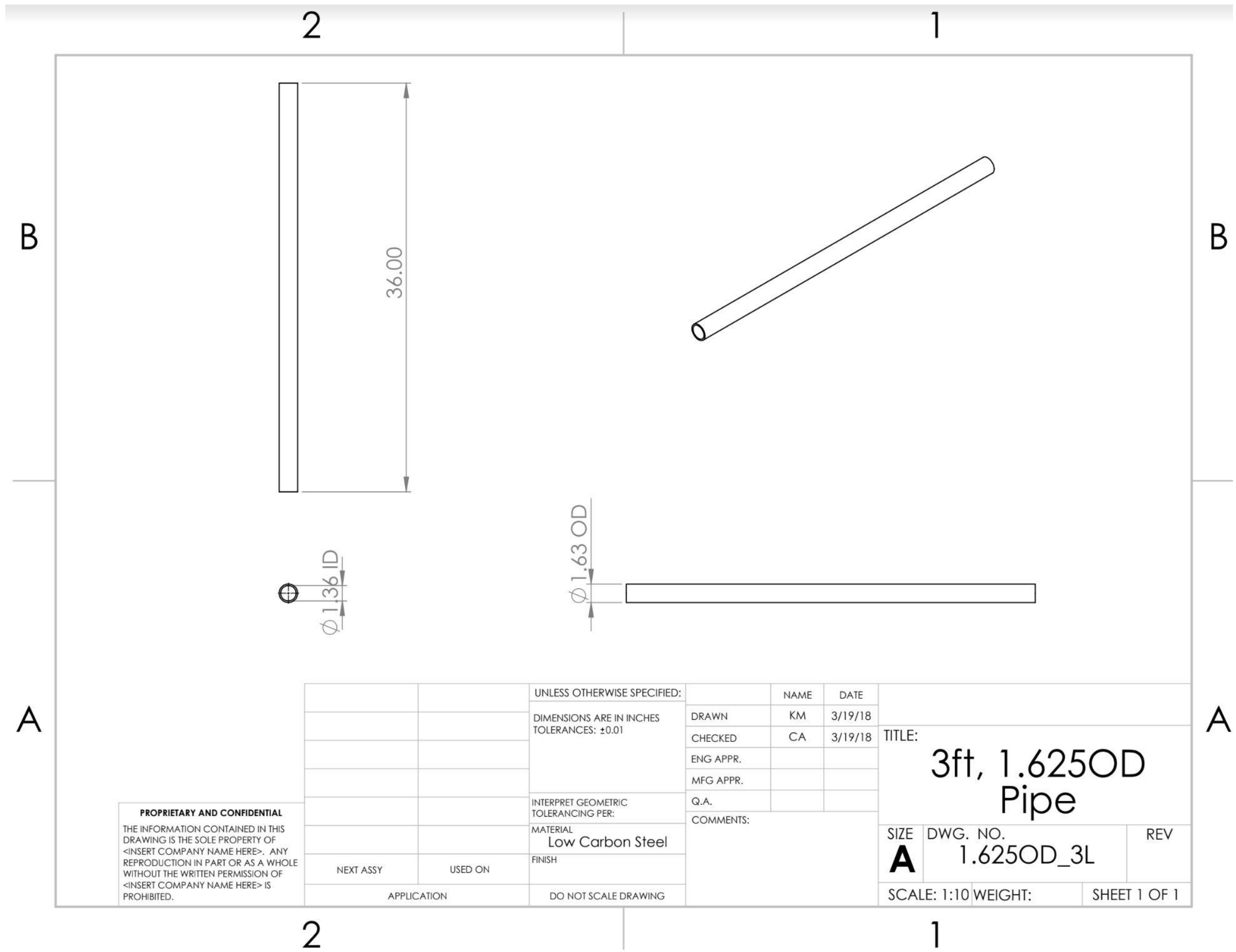
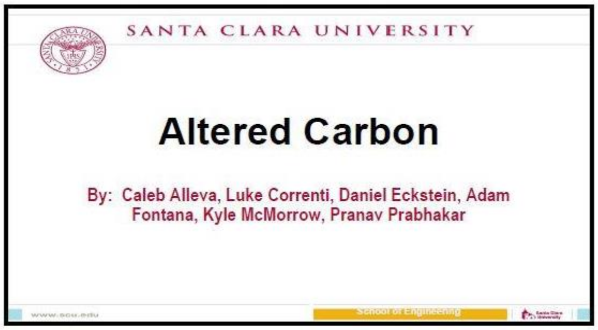
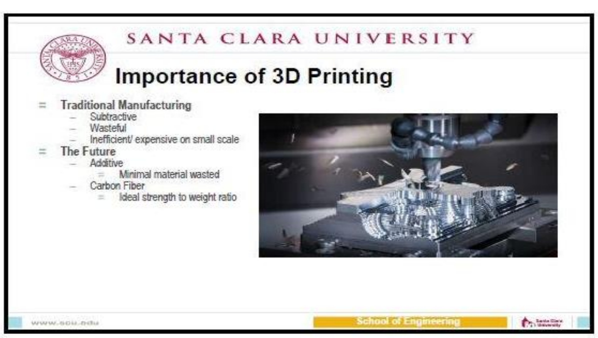
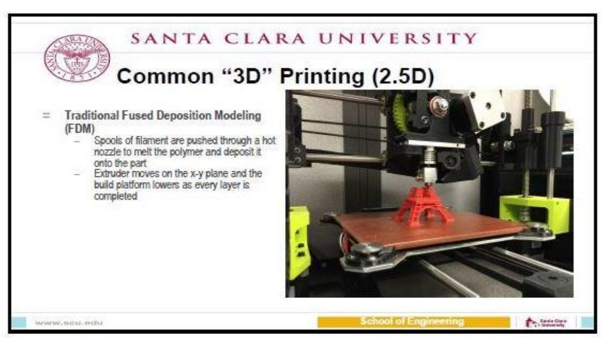


Figure G6: Test structure base support pipe drawing

Appendix H: Conference Presentation Slides







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Pros and Cons of FDM Printing

- Advantages
  - Less Waste
  - Rapid Prototyping
  - Custom Parts
  - Small Businesses
- Disadvantages
  - Anisotropic
  - Limited material candidates

"Virgin Atlantic estimated the reduction of just one pound in weight from all of the planes in its fleet would save 14,000 gallons of fuel per year (stated at a time when Virgin Atlantic had about 52 airplanes)"

Jeff Kerns
Machine Design
Technical Editor

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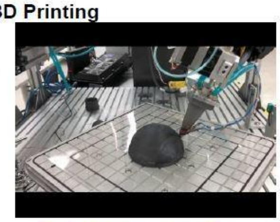
AREVO True 3D Printing

- Utilizes a 6-axis robotic arm with a rotating base
- Prints perpendicular to a surface in any orientation
- Reduces the anisotropic properties of traditional printed structures



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Why a helmet?

- Complicated geometry to showcase AREVO True 3D printing
- Existing DOT standards exist as a guide to testing

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DOT STANDARDS

- Self-tested safety standard
- NHTSA (National Highway Safety Administration) tests random batches of helmet to enforce
- 3 tests
  - *Impact Test*
  - *Penetration Test*
  - Retention Test
- Misc. Requirements
  - Peripheral Vision at least 105°
  - Any object/projection normal from helmet surface must be less than 5mm
  - Sturdy chin straps and solid rivets

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Helmet Design Process

- First helmet iteration
  - Used for early analysis
- 3D Scan
  - Commercial Helmet's geometry
    - Geometry is constant between printed and commercial helmet
    - Allows use of foam helmet liner

Zip-Bit, Inc.

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Finite Element Analysis

	Polycarbonate	PEEK Carbon Fiber Material
Young's Modulus (GPa)	2.0-2.4	2.1
Compressive Yield Strength (MPa)	80	53.7
Poisson's Ratio	0.37	PEEK = 0.38

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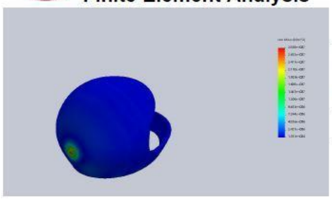
Finite Element Analysis



Max allowable Von Mises Stress	Actual Max Von Mises Stress
53.7 MPa	29 MPa

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Fracture Toughness

- Purpose
  - Determine the interlaminar fracture toughness and critical crack length of the material
- Avoiding Fast Fracture
  - A high fracture toughness value indicates a larger resistance to crack propagation

$$\sigma_f = \frac{K_{1C}}{\sqrt{\pi a_c}}$$

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Fracture Toughness Results

- PEEK-Carbon Fiber material more than doubles that of polycarbonate
- Crack length until fast fracture is more than 4x that of polycarbonate
- Accounts for bead width

	Fracture Toughness [Mpa $m^{1/2}$]
Polycarbonate	2.2
PEEK-Carbon Fiber	3.3

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Dome Compression tests

- Purpose
  - Draw a direct comparison between True 3D printing and traditional FDM printing
- Procedure
  - MTS machine compressed domes
  - Inconsistencies in dome geometry

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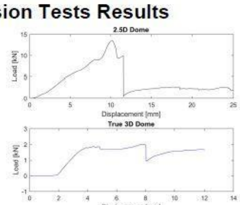
Dome Compression Tests Results

- Geometric inconsistencies lead to much lower failure load
- True 3D domes do not fail catastrophically
  - Recover their strength properties after initial fracture
- True 3D resolves the anisotropic nature of 3D printing



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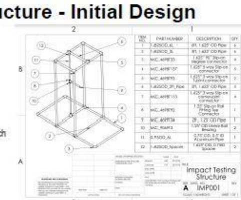
Impact Test Structure - Initial Design

Design Process

- Adaptation of DOT standards
- CAD design
  - Rail slider system
  - Linear bearings
  - 1¾ OD steel tubing
- Adaptation of original design
  - Due to friction in slider system, there was a switch from linear bearings to bushings
  - Switch from monorail to dual rail system



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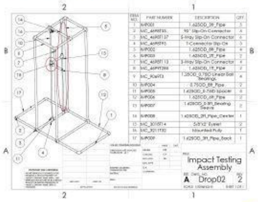
Final Test Structure



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2.5D Helmet

- Printing of True 3D helmet incomplete
- Printed PEEK carbon fiber helmet with traditional FDM methods
- Design based off purchased commercial helmet
- Fiberglass resin added to the interior for strength
- Refitted with original padding for testing purposes
- 2.5D assembled weight = 1280 g
- Commercial helmet weight = 1365 g

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Impact Testing

- Testing peak acceleration in headform
- DOT Standards:
  - Must not exceed peak of 400 G's
  - Must not sustain over 200 G's more than 2ms and 150 G's more than 4ms
- Conducted baseline testing on commercial helmets
- 2.5D helmet performance varied significantly from expectations of a true 3D helmet

[redacted]

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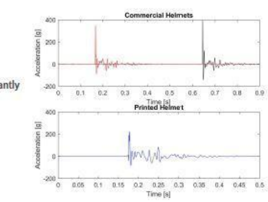
Test results

- Commercial Helmets reached peak acceleration of 340-390 G's
- Printed Helmet peaked at 230 G's
- Advantages of true 3D would significantly enhance performance
  - Evidence from dome testing, fracture toughness and FEA



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Next steps

- Print a true 3D helmet and test to verify expectations of enhanced performance
- Continue onto DOT standard penetration testing to analyze effect of improved fracture toughness over polycarbonate

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Summary

- Analysis Conducted
  - Fracture toughness
  - Finite element analysis
  - Failure modes
- Goals Achieved
  - Designed and conducted DOT impact testing on commercial and printed helmets
  - Helmet lighter than commercial
- Goals in Progress
  - Print true 3D helmet
  - Complete DOT penetration testing

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