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Ballistic Impact Mitigation Pad

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Final Report for 4600:471 Senior/Honor Design, Spring 2022

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Abstract

Our senior design team was tasked by American Engineering to develop a ballistic pad to mitigate blunt force trauma resulting from a gunshot. The concept behind the Ballistic Impact Mitigation Pad project was to design an additional layer of protection to current bulletproof vests (BPVs) in order to reduce blunt force trauma experienced by victims. In other words when someone is shot wearing a BPV, the bullet is stopped but the force from that bullet is still absorbed by the victim's body, often resulting in internal damage which can be critical. In order to prevent further injury, the idea of this project was to design a protective pad to significantly reduce this force. The objective behind this project was to come up with a lightweight, comfortable design for law enforcement to wear in addition or integrated into their current BPVs to reduce the risk of serious injury. One main constraint in mind was that this pad was more geared toward female law enforcement as they have a higher risk of post ballistic injury while wearing BPVs. In order to do this, extensive research was performed by the group to get a full understanding of how bulletproof vests work and the government standards for them, the extent of injuries resulting from blunt force trauma while wearing BPVs, common testing methods for BPVs, and materials that could be used within our constraints that could improve current BPVs. The given research allows the group to come up with a design strategy and plan of action for the design portion of the project. In terms of design and plan of action, the group chose a few different samples of lattice structures that seemed appropriate for our application. These lattice structures combined the properties of a shear thickening material and a compressible material. The lattice structures were then simulated in ANSYS and tested on a

small scale. A final design was then constructed from this data and then verification testing was completed.

Contents

1. Introduction

American Engineering tasked our senior design group with the design and construction of a trauma pad for use behind a bulletproof vest. This pad is intended to be slim, lightweight, and capable of reducing the impact force felt by the wearer of the pad underneath a vest capable of stopping the projectile. If a person is impacted by a projectile while wearing a bulletproof vest, the projectile will not penetrate the vest if the vest is of a sufficient ballistic rating to stop the projectile. When a vest is impacted, the energy of the projectile is dissipated in different ways in accordance with the law of conservation of energy. The energy from the impact is dissipated primarily by the deformation of the projectile, the deformation of the ballistic resistant material, and the deformation of one's chest and abdomen behind the bullet-resistant vest. The deformation of a person's chest or abdomen presents a significant risk for injury even when the projectile is stopped [11]. The risk of injury necessitates the development of a trauma pad.

The risk of injury for women may be even greater from blunt trauma when compared to men. In addition to this, the current NIJ Standard-0101.06 standards were developed based on male-centered research [8]. With these considerations in place, our advisor Abraham Pannikottu from American Engineering has asked our group to develop this ballistic pad with women in mind.

Currently, there are commercial products designed to mitigate the blunt force trauma from a gunshot. However, these products have several disadvantages when compared to the product our design team is working toward developing. The current commercial offerings are lightweight, ineffective, and unintegrated into the armor vest. Our group's primary focus is on developing a trauma pad that will be lightweight, effective, and integrated into a bulletproof vest.

The trauma pad will not provide the wearer with any additional ballistic protection but will reduce the blunt force felt by the wearer. Integrating the trauma pad into the vest allows the vest to be lighter, more compact, and safer when compared to a bullet-resistant vest and trauma pad combination. The reason that an integrated trauma pad will be safer than a vest with a removable trauma pad is the lack of ability to remove the pad. With the option to remove the trauma pad it is likely that some officers will forgo the pad in favor of comfort. The National Institute of Justice states that comfort must be considered when selecting a ballistic vest in order to ensure that officers are likely to wear it.

The trauma pad our design team intends to develop is to be marketed towards and utilized by law enforcement officers. The targeted market demographic of law enforcement officers is a stable yet growing market. Bullet-resistant vests have a finite lifespan and need to be replaced after a few years of use. This means that companies such as American Engineering will have a steady demand for vests in the future. Law enforcement officers are frequently assaulted by firearms and thus need a reliable source of protection. "Between 2002 and 2011, the FBI reports that between 1,800 and 2,300 officers were assaulted with firearms annually [10]". Because of this, bullet-resistant vests are a necessary life-saving device for officers. There is also a growing demand for police officers in 2022. The Bureau of Labor Statistics states that there are currently 795,000 police officers employed and projected 10-year growth of 7% employment in the field [5]. In addition, there is also a growing number of women who are choosing to become law enforcement officers. According to the National Institute of Justice

(NIJ) women make up roughly 13% of officers, however, the NIJ is making efforts to increase the number of female officers [9].

The trauma pad product also has the potential to be marketed to civilian and military markets as well. These markets could provide additional sources of revenue. The requirements of our senior design project have been defined by our industrial sponsor, American Engineering, as well as our technical advisor, Dr. Gerhardt. Our industrial sponsor instructed us to research and develop a trauma pad to function as described in the previous sections. In summary, the pad is to be lightweight, capable of reducing the likelihood of injury. Furthermore, AEG asked our design team to investigate the possibility of including a biomarker in our design. In our application, the inclusion of a biomarker means that the trauma pad will include a fully incorporated system that will indicate the likelihood of injury for first responders, doctors, and other medical professionals. With these general requirements in mind, our group defined these parameters and established criteria for success.

The current standard for testing the reduction of force in bullet-resistant vests is defined by the NIJ. The NIJ defines the standard of force reduction based on the deformation of the backface of a bullet-resistant vest when it is struck by a projectile. The NIJ limits the maximum back face deformation to 44mm [7]. However, our design team's research has indicated that this standard may not be enough to prevent injury. In our research for this topic, our group discovered that reducing the maximum allowed deformation to 34mm was associated with a 50% reduced probability of death. This study was conducted on live pigs as they are an accurate human analog [6]. With this research, our design team decided to design a trauma pad that will limit the maximum backface deformation to 34mm.

Our trauma pad is designed to be as light as possible while still meeting the previously defined engineering constraint for backface deformation. As police officers already have to carry a large amount of gear our design team attempted to develop a trauma pad that is under 2 pounds in weight.

Our design team also attempted to develop a biomarker. Our group was not able to develop an accurate assessment of the force transferred from the backside of the developed trauma pad to the wearer. However, with additional research funding and time our developed system could be adapted to incorporate a biomarker that will be discussed later in the report. This will allow the data that would be collected from the biomarker to be physical in nature. This means that the biomarker would have to deform in a measurable and consistent way. It was decided by our design group to avoid electronic sensors due to their durability and difficulty in reading without specialized equipment and knowledge. Our proposed system would be easily readable by medical professionals without the need for specialized equipment.

	Test Variables					Performance Requirements			Shot Requirements					
Armor Type	Test Round	Test Bullet	Bullet Mass	Conditioned Armor Test Velocity*	New Armor Test Velocity*	Hits Per Panel at 0° Angle	Maximum BFS Depth	Hits Per Panel at 30° or 45° Angle†	Shots Per Panel	Panel Size	Panel Condition	Panels Required	Shots Required	Total Shots Required
IIA	1	9 mm FMJ RN	8.0 g (124 gr)	355 m/s (1165 ft/s)	373 m/s (1225 ft/s)	4	44 mm (1.73 in)	2	6	Large	New Conditioned	4 2	24 12	144
										Small	New Conditioned	4 2	24 12	
	2	.40 S&W FMJ	11.7 g (180 gr)	325 m/s (1065 ft/s)	352 m/s (1155 ft/s)	4	44 mm (1.73 in)	2	6	Large	New Conditioned	4 2	24 12	
										Small	New Conditioned	4 2	24 12	
II	1	9 mm FMJ RN	8.0 g (124 gr)	379 m/s (1245 ft/s)	398 m/s (1305 ft/s)	4	44 mm (1.73 in)	2	6	Large	New Conditioned	4 2	24 12	144
										Small	New Conditioned	4 2	24 12	
	2	.357 Magnum JSP	10.2 g (158 gr)	408 m/s (1340 ft/s)	436 m/s (1430 ft/s)	4	44 mm (1.73 in)	2	6	Large	New Conditioned	4 2	24 12	
										Small	New Conditioned	4 2	24 12	
IIIA	1	.357 SIG FMJ FN	8.1 g (125 gr)	430 m/s (1410 ft/s)	448 m/s (1470 ft/s)	4	44 mm (1.73 in)	2	6	Large	New Conditioned	4 2	24 12	144
										Small	New Conditioned	4 2	24 12	
	2	.44 Magnum SJHP	15.6 g (240 gr)	408 m/s (1340 ft/s)	436 m/s (1430 ft/s)	4	44 mm (1.73 in)	2	6	Large	New Conditioned	4 2	24 12	
										Small	New Conditioned	4 2	24 12	
III	1	7.62 mm NATO FMJ	9.6 g (147 gr)	847 m/s (2780 ft/s)	-	6	44 mm (1.73 in)	0	6	All	Conditioned	4	24	24
IV	1	.30 Caliber M2 AP	10.8 g (166 gr)	878 m/s (2880 ft/s)	-	1 to 6	44 mm (1.73 in)	0	1 to 6	All	Conditioned	4 to 24	24	24
Special	-	Each test threat to be specified by armor manufacturer or procuring organization.				Armor performance and shot requirements shall depend on armor type.								

*Target measurement velocity. Fair hit measurement velocities must be within ± 9.1 m/s (± 30 ft/s) of this value, as defined in Section 7.6.
†Each armor that is to be shot at angles other than 0° shall be shot once at a 30° angle and once at a 45° angle.

Table 1: NIJ Vest Performance Requirements

Below is the block diagram for this project that shows the general order of tasks that allowed us to successfully complete this project.

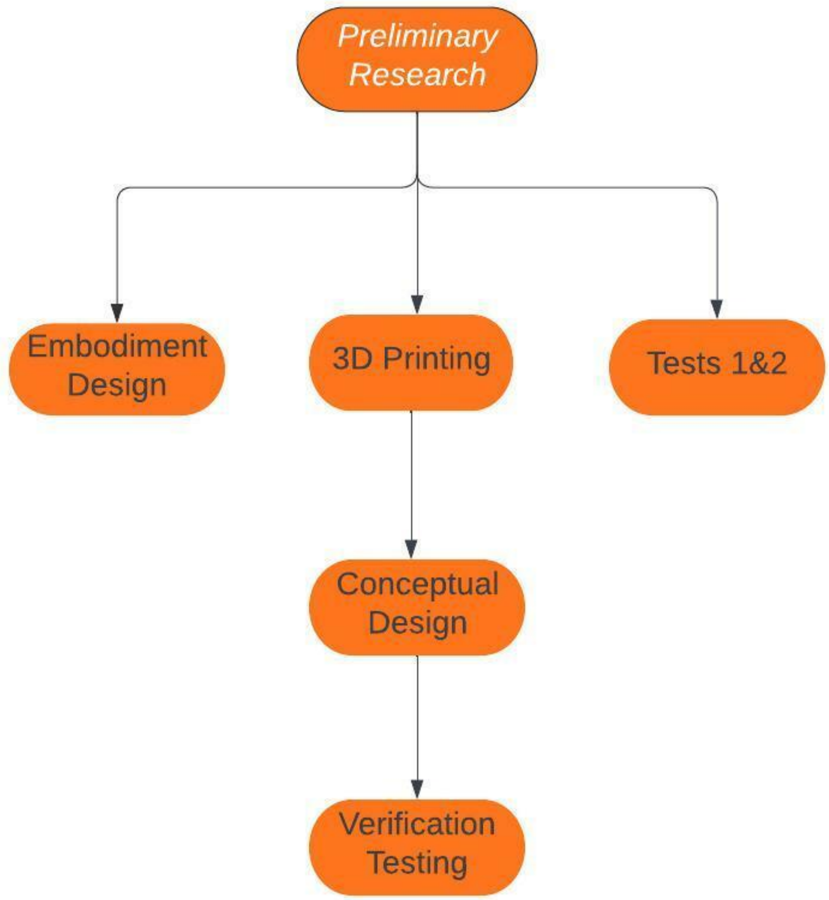


Figure 1: Block Diagram

2 Design Overview

The following sections outline the entire design process from start to finish. Before designing, we had to do extensive research to develop constraints, choose a material, and a manufacturing method. Once we had our constraints, material, and manufacturing figured out, we were then able to test our material with varying shapes to determine the most effective structure with our chosen material to come up with a final design. Through design, we also utilized several software applications which gave us all the information we needed through our design and testing.

2.1 Research

Before beginning on design, the group had to perform extensive research on this project. In our research, we gained a thorough understanding of injuries resulting from blunt force trauma, NIJ standards for current bullet proof vests, testing standards set by the NIJ, and material research.

2.1.1 Injury Research

As mentioned before, even though bullet proof vests are effective at stopping a bullet, the resulting force from that bullet usually leads to blunt force trauma which can lead to serious injury. Unfortunately, statistics for these types of injuries are either not recorded or not publicly available, but there have been some research papers on this topic. We found there are varying degrees of injuries that can result from being shot while wearing a bullet proof vest. In blunt ballistic trauma, which is the type of injury where the vest spreads the force from the bullet over a large area which causes a global deformation in the wearer's chest or abdomen, it can cause injury ranging from moderate and sever bruising to rib and other bone fractures [11]. Furthermore, we found that the risk of injury for women may be even greater from blunt trauma when compared to men , and that the current NIJ Standard-0101.06 standards were developed based on male-centered research [8]. With this information in mind, our group knew there was a real problem at hand and there was a real necessity to develop a trauma pad with a further consideration to protect women.

2.1.2 NIJ and Testing Research

Initially, the group knew our purpose for this pad was for law enforcement, which gave us the constraint that all standards we were to follow were to be consistent with level IIIA body armor. From there, we were able to obtain a lot of information from the National Institute of Justice, which defines all standards for law enforcement body armor. The NIJ defines the standard of force reduction based on the deformation of the backface of a bullet-resistant vest when it is struck by a projectile. The testing standard we decided upon was the clay block test. This test involves shooting a vest from a specified range with a clay block behind it and measuring the deformation into the clay to determine the severity of a potential injury. Further details about this test and the results are provided in the verification section of this report. The NIJ limits the maximum backface deformation to 44mm [7]. However, our design team's research has indicated that this standard may not be enough to prevent injury. In our research for this topic, our group discovered that reducing the maximum allowed deformation to 34mm was associated with a 50% reduced probability of death. This study was conducted on live pigs as they are an accurate human analog [6]. With this research, our design team decided to design a trauma pad that will limit the maximum backface deformation to 34mm. Our trauma pad was to be designed to be as light as possible while still meeting the previously defined engineering constraint for backface deformation. As police officers already have to carry a large amount of gear our design team attempted to develop a trauma pad that is under 2 pounds in weight.

2.1.3 Material Research

The material research the group performed for this project was thorough as this was one of the free variables we had for our design. We knew we needed a lightweight, comfortable material with effective material properties for our requirements. Initially, we wanted to explore light weight shear thickening fluids from some research we found. As we looked into this material further, we realized that with our given resources and knowledge, as well as manufacturability concerns, that this would not be the best material to choose for this project. After more research, we found Flexible 80A Resin created by Formlabs that is lightweight, easily manufactured with 3D printing and had shear thickening and compressible properties we were seeking. More detail about the resin and printing process is provided in the printing section. Once we had our material selected, we were then ready to begin on the design process for this project.

2.2 Design

2.2.1 Conceptual Design

Our team spent the fall 2021 semester of our project becoming very knowledgeable on materials, injury, and currently available market products. We established basic design parameters to be kept in mind from this research when making selections.

The first priority of our design is to create a pad that is easy to manufacturability. Our team found that many high-energy absorbing materials are challenging to manufacture in our research. These materials often contain shear-thickening substances that are manufactured on a molecular scale. Before finding out the cost and difficulty of manufacturing these materials, we intended to impregnate a cloth or sponge-like material with these substances so it would become dense when impacted. It was ultimately decided to be unattainable for our group with little chemical knowledge when speaking with different members of the chemical engineering department due to the intensive manufacturing process that would be necessary. We also investigated available foams that could be used. Our group decided against pursuing this route because commercially available pads using these materials did not meet our group's standards. This led us to the ultimate choice of use of SLA additive manufacturing. SLA additive manufacturing allows for a wide range of material choices. Because of this, a rubber-like material can be selected. An additively manufactured rubber-like material allows for the combination of compressibility and shear thickening properties. We have access to a Formlabs Form 2 in the laboratory, so we narrowed down our selections to materials with elastic properties for impact resistance and chose a proprietary material (Flexible 80A) that will be effective for our purposes. This material is a part of the Formlabs catalog and will be able to be bought in bulk for large production. Formlabs also offers a higher quality elastic material with improved mechanical properties. However, it is unavailable for purchase in small quantities.

After finding the material and process that we are to use for our project, we then wanted to ensure that the design could be integrated into a bulletproof vest. Our group chose to design our prototype so it could be integrated into a commercially available plate carrier. Because of this, the thickness of the pad must be constrained as it needs to be placed into the same sleeve as the bulletproof vest. Geometries for the final vest were to be the same size as the inserts for the BPV, with a bit of slack in the instance of shrinkage or slight misprint on the Form 2.

American Engineering Group also requested our team to develop a biomarker to diagnose the severity and likelihood of injury after the product is impacted. Our team investigated thin metallic sheeting, force measurement tapes, and other measurement techniques and struggled to find a simple analog solution that was attainable within the term. We then decided that we would like to 'skin' or cover the exposed cells of our pad with an airtight seal and inject ink. These cells would be calibrated to burst with what is deemed a fatal force, allowing a medical professional to see where and how strong the impact was. To attain this, there would need to be a proper analog model of the human body, with numerical values of injury assigned to the complete profile. These values could then be correlated with the thickness of the cell walls, allowing them to burst when they reach injury values. This was investigated throughout the term and was not attainable with the available time and testing equipment.

Another thing that the team considered was the comfortability of the wearer. This product is in addition to an already designed vest, so ergonomically, with additive manufacturing, we would be able to scan the human body and use this model to create a pad that perfectly fits the curvature of the user. This pad also needs to be waterproof and not deteriorate when in contact with water. This is covered with the material of choice and manufacturing process used.

Finally, and most importantly, we want to reduce back force deformation by 50% at a minimum. Our pad needs to be effective, and if it does not achieve a significant energy reduction, there isn't much use in wearing it. With our target market being law enforcement officers, this product needs to be compelling enough for them to be willing to add weight to their already heavy belts and vest.

2.2.2 Embodiment Design

Our embodiment design was finding the proper lattice structure for our application. Our team had a general idea that we would assemble multiple printed parts together due to the restrictions of build size on the Form 2. We started by browsing the available lattice structures in nTopology and chose a few shapes. These shapes for the cells of our pad were strategically chosen based on their resistance to a force from one direction. Omnidirectional designs where the lattice structure behaves the same when struck from any direction were not appropriate due to the vest only being struck on one side. For this reason, we used 'honeycomb' structures with a uniform cross-section. Of our available options in nTopology, we chose a basic square, diamond, and a hexagonal shape pattern. We started by printing samples of one cell height and a cross-section with our planned testing apparatus in mind. These samples are simulated in the below section, and further testing analysis is found elsewhere in this report.

We found after testing the samples that the hexagonal shape was the best for our application and then set up the same testing protocol for the thickness of members. We found that the original thickness from test one was most appropriate. A hexagonal shape with a 1 mm member thickness was deemed our best configuration. This concluded our embodiment design period, and we then moved to the detailed design.

2.2.3 Detailed Design

Our detailed design was creating the final prototype. After looking at the print bed dimensions of the Form2, we were limited to having our final prototype be constructed with six separate panels. The team talked about how we were to adhere these panels together and explored options of using a liquid glue but ultimately chose a rubber adhesive tape to laminate the outer surfaces. When conducting verification testing, the pad stayed in one piece confirming this was the proper decision for our prototype. Along with using an adhesive, we purposefully left singular cells ‘overhanging’ on the sides of the panels that were to be placed together so they could lock together with similar geometry as seen in the figure below.

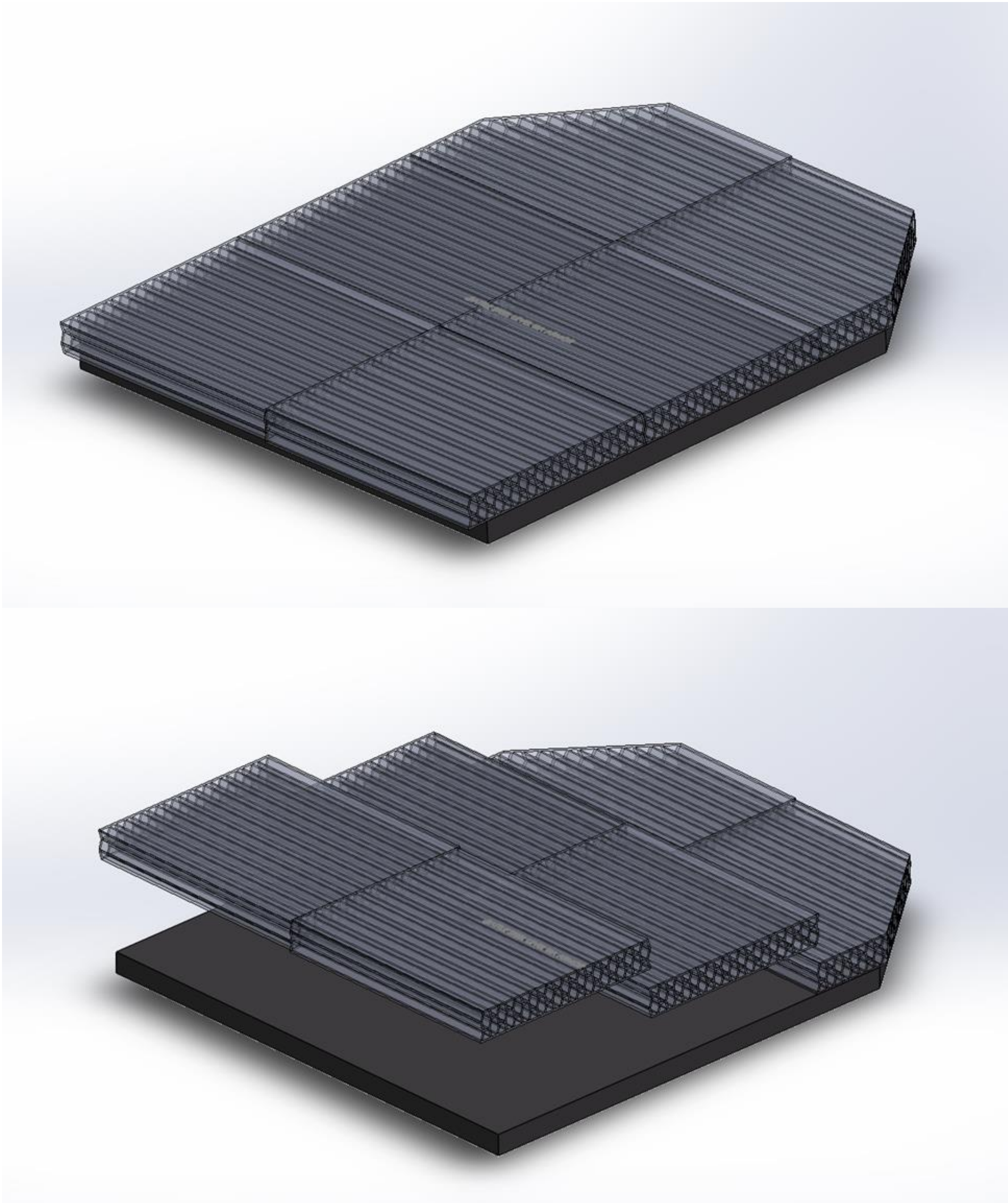


Figure 2: Vest CAD Design

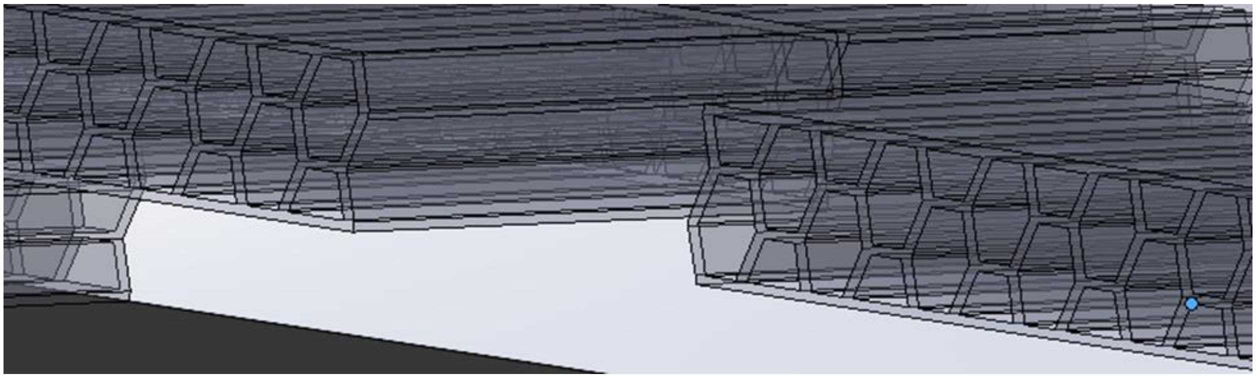


Figure 3: Honeycomb CAD Detailed View

2.3 3D Printing

To fully understand the attached summary of our team's printing process, it is necessary first to overview the additive manufacturing process used for our design. The process used for our design was vat photopolymerization. Vat photopolymerization (VP) is a process that results in the formation of a light-cured thermoset polymer. In other words, a VP machine uses a light source to build a 3-dimensional part. The specific type of VP machine used for this project is a stereolithography (SLA) machine. An SLA machine contains many parts, but the most important are the build surface, the resin tank, and the laser source. The build surface controls the Z-axis movement of the machine and is programmed to move in discrete steps so that the part can have consistent layer heights. The resin tank contains the photopolymer that is cured into the final part. And the laser source projects the light of a specific wavelength to cause the curing of the photopolymer [3].

The process of manufacturing a part on an SLS machine is relatively straightforward. The first step is to save your desired part geometry as a standard triangle language file (STL). Once a file is saved in this format, it can be imported into slicer software. A slicer is a software that turns an STL file into a language the machine can understand by "cutting" the model into discrete layers. Once a file is sliced into discreet steps, the file can be imported into the machine. Once in the machine, the printing process can begin. While much faster than other processes, SLS prints still take several hours to finish. For example, our final designed print took over 24 hours to print. Upon the conclusion of the printing process, the finished part must be removed from the printer promptly. Once removed, the parts must be post-processed. This means the removal of support material and excess resin. After a part is cleaned, it should be post-cured to ensure optimal material properties. However, this was not something available to our group [3].

In order to complete the design of our project, our group needed to obtain access to a printer capable of printing a shear-thickening rubber-like material. This was necessary because we intended to combine shear thickening properties and a compressible lattice structure. We contacted Dr. Choi, and he recommended using the Formlabs Form 2 vat polymerization printer. Our group had originally intended to use a material manufactured by Carbon 3D called EPU-41. However, the Formlabs printer that was available to us only allowed for the use of proprietary materials. With this in mind, our group selected the resin Flexible 80a from the Formlabs material catalog. The material Flexible 80a has similar properties to the EPU-41 we intended to use, with the materials having shore harnesses of 80 and 71, respectively [1] [2].

With a chosen material and a preliminary design in place, our group made necessary modifications to our design to ensure accuracy and printability. The Flexible 80a resin has parameters that must be considered when designing a part to ensure accurate printing. Failure to abide by the printing parameters will result in printing failure. The parameters are reported in the table below [4].

Print Feature	**Minimum Feature Size**	**Recommended Feature Size**
Supported Wall Thickness	400 microns	600 microns
Unsupported Wall Thickness	600 microns	800 microns

Shallow angles	19 degrees	45 degrees
Vertical Wire Diameter	300 microns	1500 microns
Clearance between Adjacent Parts	1000 microns	
Hole Diameter	800 microns	
Horizontal Span/Bridge	600 microns	

Table 2: Printing Parameters

The material also has a tensile strength of 8.9 MPa and a tear strength of 24kN/m. Additionally, Formlabs states that this material is suitable for applications involving impact [4].

Upon receiving the material, our group decided to conduct some test prints. These prints followed the above-stated metrics but still failed due to over-curing. This was valuable data because it showed the limitations of our available printer. These failed prints were an attempt to create scale models of the final vest we wanted to build; however, modifications had to be made because the print failed. Our design for testing had to be scaled up to ensure reliable printing. Because of the printing limitations, our group decided to test one layer of our chosen lattice structures to ensure the minimum feature sizes were met.

Figure 4: Print Samples

With our designs optimized for printability, our group began printing our initial round of samples. Our first round of samples for testing were printed without error. The samples are shown below.

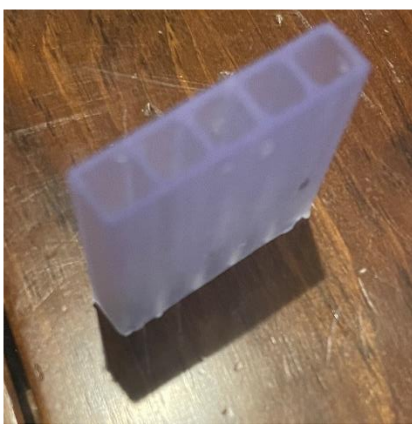


Figure 5: Sample B-1

Figure 6: Sample A-1

Figure 7: Sample C-1

When our group attempted to print the samples for our 2nd round of printing, our group began experiencing printing failures. The prints were failing to adhere to the printer's build plate. Our group set up the machine, loaded our files for printing, and started the printer. When our group returned, the printer was full of partially filled resin. Our group then cleared the tank of the partially cured material, cleaned resin spills, cleared the build plate, and manually reset the printer's software. After restarting the printer, our group left and then returned after several hours to check on the success of the prints. The prints were adhering to the build plate, and the process appeared to be proceeding without error. However, returning to pick up the prints in the morning, the printer had failed differently than it did previously. This presented an issue because testing was scheduled for later that day. One of the four samples that our group put on the printer failed. Therefore, our testing data only contains a D-1 sample and no D-2 sample. The failed D-2 sample, and the successful E samples are shown below.

Figure 8: Sample D-2 Failure

Figure 9: Sample E-2 Failure

Our group reached out to Dr. Choi to remedy this problem to seek advice. Dr. Choi and Rui Huang, a Ph.D. candidate of his, assisted us in repairing the machine. The process involved filtering the resin and further cleaning the machine.

After our scale testing was completed, our group designed our final prototype according to our design criteria. The process of printing our final prototype was successful, and our group did not encounter any additional printing issues. An example of the finished pad is shown in the image below.

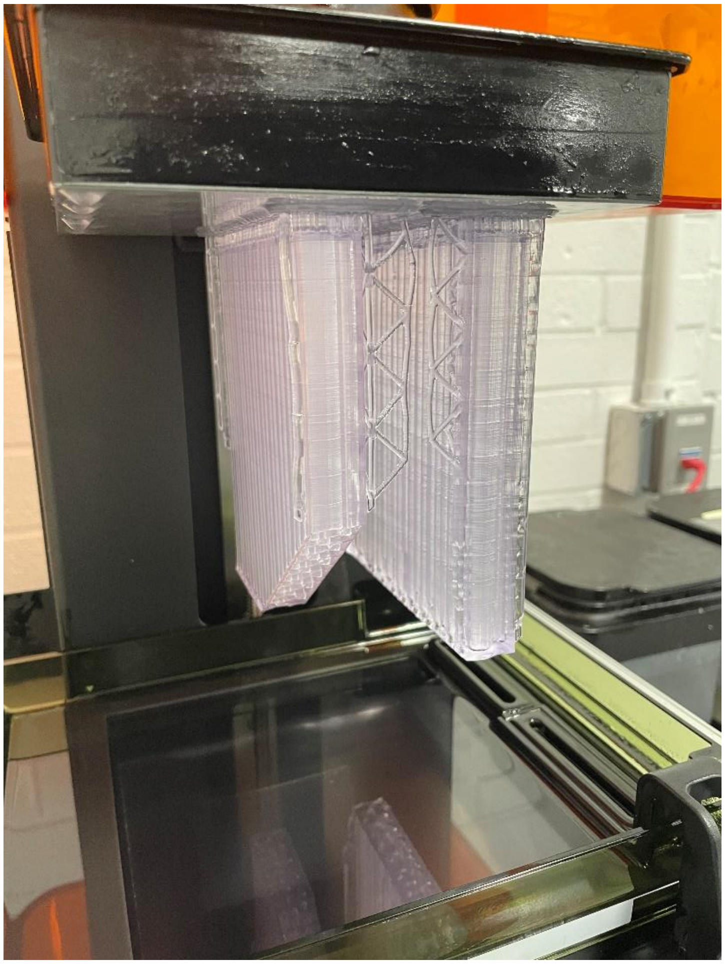


Figure 10: Final Parts

2.4 Testing

In order to continue the design process for our project, our team needed to conduct testing on the chosen Flexible 80A resin. The chosen testing procedure had to be able to determine energy reduction in our samples. Our team carefully compared both Ball Drop testing and High Velocity Impact testing to determine which method was more applicable to our requirements.

The original testing process that we planned on using was a ball drop test owned by the Civil Engineering Department at the University of Akron. This test consisted of dropping a ball bearing onto each sample and measuring the rebound during each test. Measuring the rebound would then allow us to determine the amount of kinetic energy absorbed by each sample. We met with Dr. Tan in the Civil Engineering Department to speak more about using the ball drop method to test for our application. During our meeting, Dr. Tan gave more insight on the testing method and explained its application and use in the field of Civil Engineering. Dr. Tan also expressed his interest in the High Velocity Impact testing versus Ball Drop testing as it would better replicate the kinetic energy that is given by a firearm.

The High Velocity Impact testing was first recommended by Dr. Mani Kannan. Dr. Kannan has used this testing method in the past for applications similar to ours. He pointed us in the direction of Dr. Morscher who is the University faculty member that is most involved with High Velocity Impact testing. Our team scheduled a meeting with Dr. Morscher to learn more about the method and its availability. During the meeting, Dr. Morscher showed pictures and research documents while explaining the testing procedure. The method consists of a 150 psi air gun that has the ability to shoot 1/16” or ⅛” diameter bearings at velocities around 300 m/s. The testing setup also has a high-speed camera to capture the video of the projectile’s entry and reflection off of the tested material. Using the video from the high-speed camera, we can then use the Tracker software to determine the velocity of the projectile in the moments before and after contact with the samples. With these velocities we can finally determine the kinetic energy at each point which then allows us to determine the amount of kinetic energy reduced by each sample. This would allow us to effectively compare the energy reduction capabilities in any two samples. The testing setup is located in the Gas Turbine Testing Facility on the University's Campus. This meeting allowed us to decide on using this method to test our samples.

In our testing we used a 1/16" Chrome Hardened steel bearing. We originally planned on using a ⅛" Tungsten bearing to increase the kinetic energy, but unfortunately the bearing that we bought did not fit the tolerances of the ⅛" tube on the pressure gun. We also purchased ultra-high-density polyethylene to replicate the use of a bullet proof vest in front of our tested samples. We scaled this down by using three sheets of the polyethylene in front of each sample. We decided to use three sheets by testing the polyethylene sheets without a sample behind them. In the test, the projectile broke through the first two layers of the fabric but was stopped by the third layer. In the end, our setup consisted of three layers of polyethylene fabric taped to each sample which was all taped to a steel plate which had an open backing.

Figure 11: Testing Apparatus

In the first round of testing, we wanted to compare the ability to reduce kinetic energy in three different lattice geometries. We chose to use square, diamond, and hexagonal honeycomb structures because they are optimized for one-directional force. We tested two samples of each lattice geometry which made for six samples in total. The two hexagonal samples were each 2”x 2” while the square and diamond sections were each 1.5” x 1.5”. The results of this section were documented in excel graphs which can be seen in the figures below. The results show that while each lattice geometry reduced the kinetic energy by quite a significant amount, the hexagonal honeycomb structure performed the best out of the three.

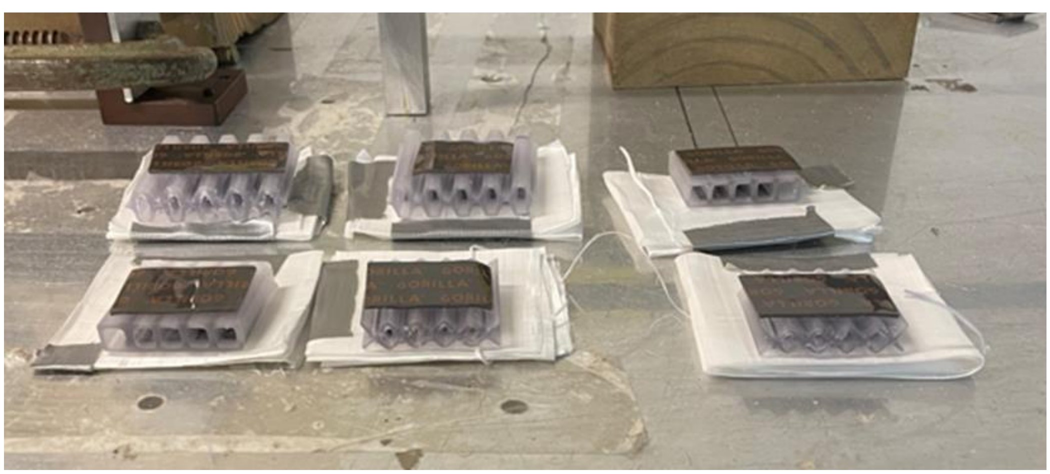


Figure 12: Test 1 Specimen

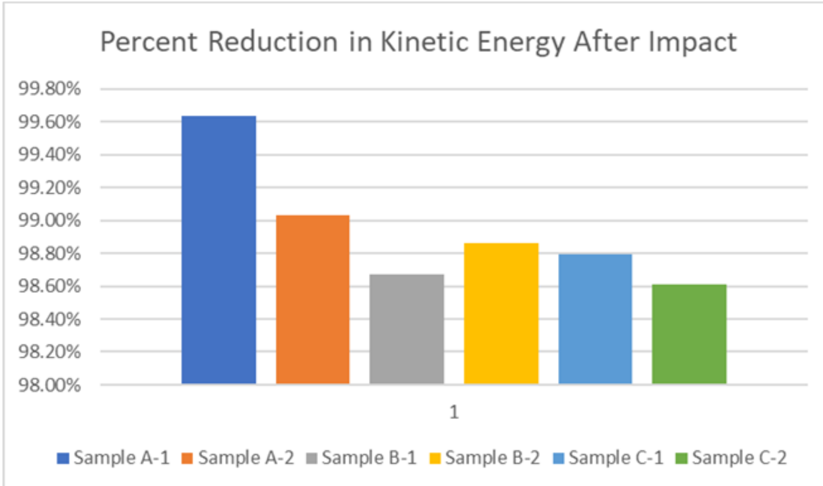


Figure 23: Kinetic Energy Reduction Data

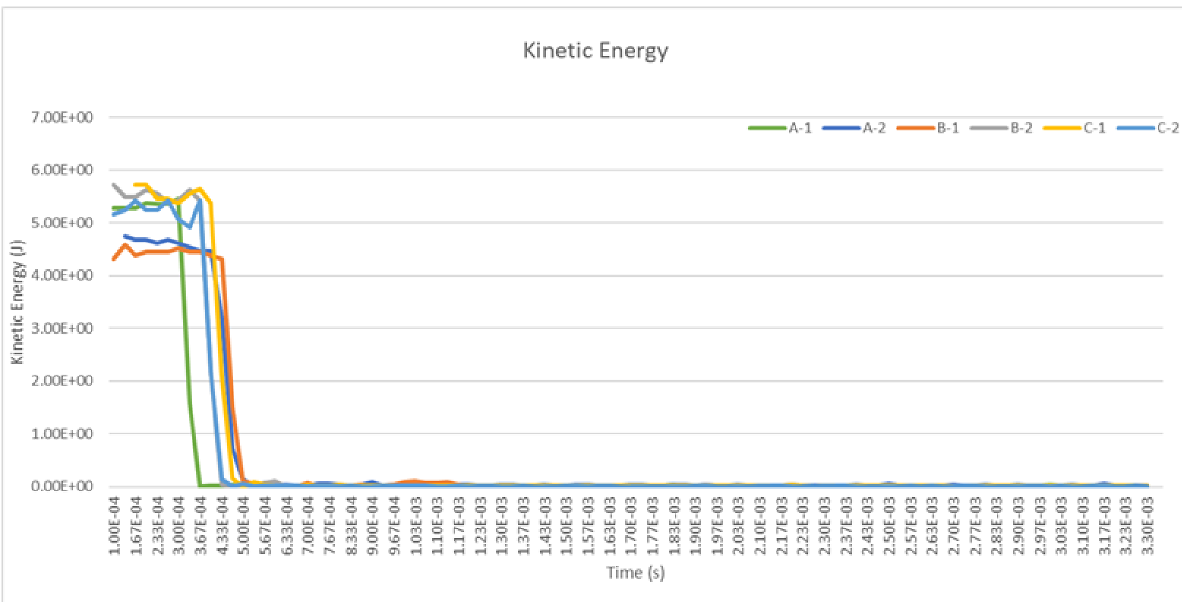


Figure 34: Kinetic Energy Reduction Over Time

After conducting the first round of testing and finding that the hexagonal honeycomb structure showed the largest reduction in kinetic energy, we immediately moved into the second round of testing. In the second round of testing, we studied the effects of the lattice member thickness on the reduction of kinetic energy. For this testing we only used the hexagonal honeycomb structure. This round of testing consisted of three samples. Two of the samples had 50% of the member thickness that was used in the first round while the other sample had 200% of the original member thickness. Unfortunately, we could not test two of each because the second sample of the enlarged member thickness failed during the print. In the results, of this second round of testing we found that the smaller member thickness showed the most reduction in kinetic energy during this test.

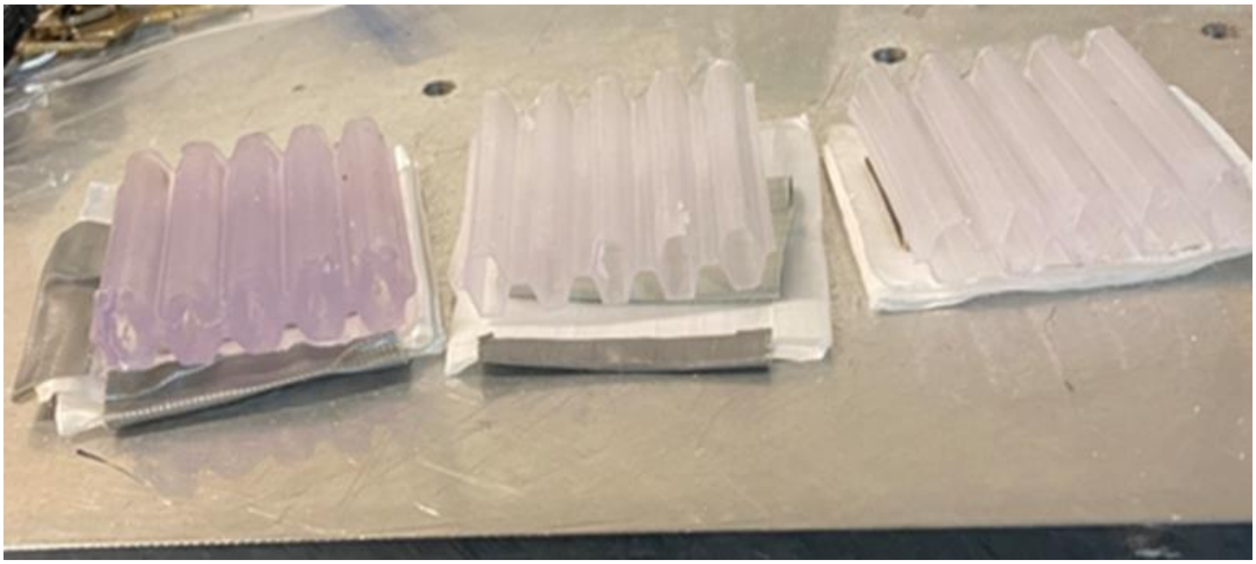


Figure 45: Test 2 Specimen

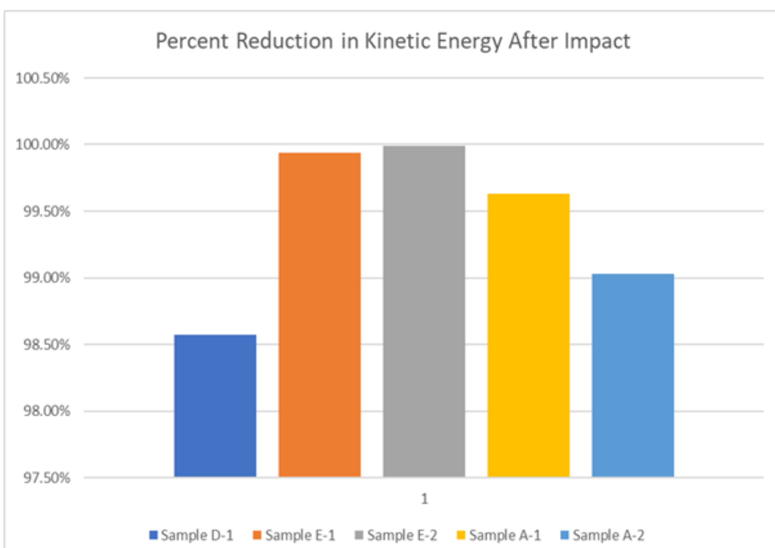


Figure 56: % Kinetic Energy Reduction

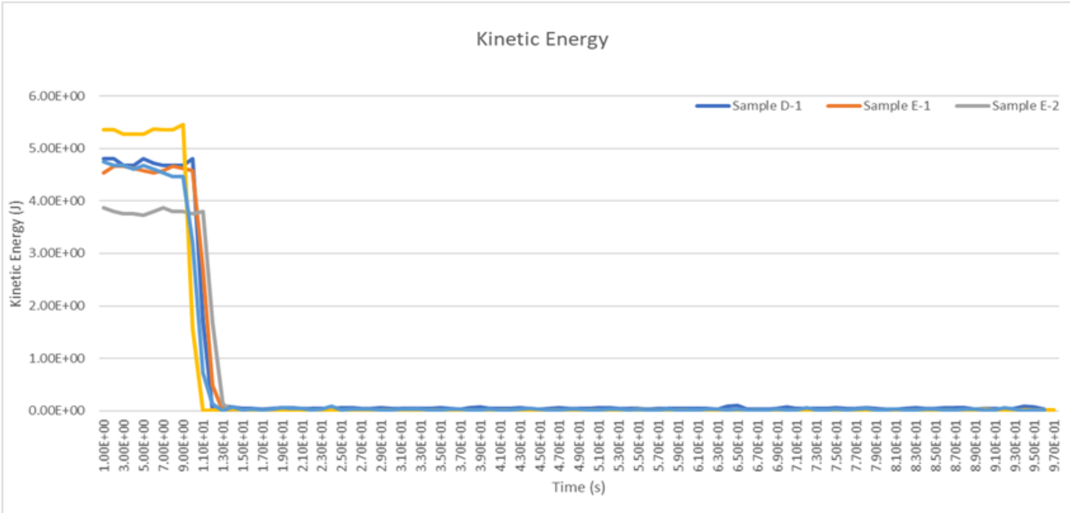


Figure 67: Kinetic Energy Reduction Over Time

After the second round of testing, we decided to use the original thickness of the hexagonal honeycomb structure to form our prototype. Even though the smaller member thickness had better results for reducing energy, we chose to use the original thickness for two main reasons. The first reason was due to the durability of the different sizes. When we decreased the member thickness to 50% of the original, the samples became extremely flimsy and fragile. We immediately noticed how easily they ripped apart which wouldn't be allowable in our application. The second reason is due to the kinetic energy in testing versus that of a real-world scenario. The kinetic energy that we were able to generate in testing was a few orders of magnitude smaller than what we calculated would be applied by a real firearm. With these two reasons in mind, we decided to keep a larger member thickness.

2.5 Software Used

2.5.1 nTopology

The use of nTopology for this project was critical to its success. This software allows light weighting of defined objects with specific internal lattice structures. We had the flexibility in this software to take our generic shapes for the panels of the final vest and use experimental data to automatically generate a lightweight part or define the desired lattice structure, using the defined geometry as a shell. Due to the way that we conducted testing, we defined our lattice patterns with the final pad geometries as the bounds.

nTopology allowed our team to create and alter our parts for testing also quickly. The parts for testing were of a smaller thickness and cross section, so instead of having to manually alter the files in Solidworks and deal with the hassle of manually changing various parameters, we simply had the ability to open the .ntop file and change parameters as needed. This was especially useful for the second round of testing that we did where we changed the member thickness. A manual change of thickness of a geometry like these would require much time and this was reduced to a matter of a few minutes.

Finally, this program allowed our team to understand the available structures that have been used professionally to lightweight parts. When the team was researching different lattices to fill a defined geometry for light weighting purposes, we were overwhelmed with the number of options and nTopology allowed us to see all available options in the software and choose a few of interest for our application. Furthermore, we were able to really understand file types and how CAD modeling is developed in a more specific sense by manually meshing the components to our own specifications and exporting them to be optimized for additive manufacturing.

2.5.2 ANSYS Workbench

ANSYS Workbench was used to simulate our first round of testing in order to validate that our selection of samples was justified. Due to the lack of material data for Flexible 80A, we really did not have a reference as to how thick the samples needed to be in order to conduct effective testing. Having this tool had the potential to save our team weeks of valuable time if the samples chosen couldn't withstand the testing apparatus designed. If these simulations showed complete material failure, then we would have time to adjust the samples and not waste a scheduled time slot in the laboratory.

For ANSYS, we used explicit dynamic modeling with accurate material properties of the intended projectile to be fired. This modeling allowed us to directly see plots of velocity and kinetic energy before and after impact. More importantly for our model, we were able to see if the projectile could be retained by the geometries and not go completely through the assembly. This gave us a good understanding of the rigidity of the geometries chosen before going into the laboratory, with accurate hypotheses made.

2.5.4 Tracker

Tracker was used to analyze our testing data recorded by a high-speed camera in order to get numerical data. We manually selected the object at different frames in order to have the program output data for velocity and kinetic energy. The ability to use this software to obtain these values made it so the team did not have to manually measure the distance of the object at different frames, giving a more scientific analysis. This software also was the software used to record the different samples in order to see perfectly accurate timestamps and manipulate different parameters for the capturing of video.

Basic operation of this software is calibrating a measurement of actual distance by placing an accurate ruler size on the screen. This will allow the program to be able to use the pixels of your screen as measurement and convert that distance to actual measured distance. A user would then click on the moving object at each frame until their desired end of analysis: For our testing we wanted to see before and after impact, so about 100 points. As you place points, the plots update to the inputted data, and you are able to see the kinetic energy and velocity profiles in real time.

3. Design Verification

3.1.1 Testing Verification

After completing two rounds of testing, we settled on a final design that utilized the hexagonal honeycomb lattice structure with the original member thickness of 1mm. The prototype consisted of six panels that were adhered in order to create one pad to be placed behind a BPV. In order to verify our prototype's effectiveness, we decided on comparative testing with an existing product that had already been tested to NIJ standards. The reasoning behind this decision was due to cost and lack of resources. The clay that NIJ standards call for, Roma Plastilina No. 1, is extremely expensive in the quantity that is required by the NIJ. To save cost, we instead used clay that the University already had in storage which was previously used for impact resistance testing. This clay was also an oil-based clay but denser than the Roma Plastilina No. 1 clay. With this in mind, we expected less deformation to be shown in the clay than that of normal NIJ standard testing. We formed the clay into a 11"x11"x5.5" block to be used for testing.

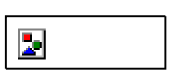
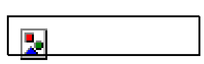
During verification testing we used the University of Akron ROTC Program's shooting range in the basement of South Schrank Hall. The testing setup consisted of a BPV with the market pad or our prototype behind it and the clay block behind the pads. The three layers were then adhered together using tape. A .44 magnum with a 20" barrel was used during the testing. The first pad that was tested was the market pad. The deformation in the clay after testing the market pad was about 6.93 millimeters. Next, we tested our prototype in the same format as the market pad. The results of this test were excellent, and no deformation was detected in the clay. Finally, we tested the bulletproof vest without a trauma pad placed behind it. The results of this test showed a deformation in the clay of 16.71 millimeters.

The verification testing for our prototype went as we planned. The results proved that our design is even more effective than a market pad in mitigating blunt force behind a bulletproof vest. Although we were not able to test in exact accordance with NIJ standards, we believe that the comparative testing with a market pad is more than sufficient to prove the effectiveness of our design. With this being said, there are many things that need to be improved upon in our design, including weight, comfortability, and uniformity. These improvements are explained more in the conclusion section of this report.

3.1.2 FEM Verification

For emulation of Flexible 80A resin, Ogden 3rd Order mathematical model is used due to this material being a nonlinear material. This hyperelastic model is used for rubbers and polymers and is used for our material estimation of using ‘Rubber 1’. We chose to use Rubber 1 due to its similar elastic trends and behavior; the team would have to do rigorous testing in order to model the Formlabs resin in ANSYS, because of this we used Rubber 1 as it is a similar material. This is appropriate because our group intends to do comparative testing for our senior project. The testing involved the comparison of three distinct shapes made of the same material. Because the material was the same in all samples the substitution of material in ansys is valid.

Ogden Model: $W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}(\underline{\lambda_1}^{\alpha_i} + \underline{\lambda_1}^{\alpha_i} + \underline{\lambda_1}^{\alpha_i} - 3) + \sum_{k=1}^{N} \frac{1}{D_k}(J-1)^{2k}$

Reduced Principle Stretches: , 

Values for this model are shown below in the attached ANSYS table.

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	1000	kg m^-3
4	Ogden 3rd Order		
5	Material Constant MU1	6.1803E+05	Pa
6	Material Constant A1	1.3	
7	Material Constant MU2	1180	Pa
8	Material Constant A2	5	
9	Material Constant MU3	-9810	Pa
10	Material Constant A3	-2	
11	Incompressibility Parameter D1	4.825E-09	Pa^-1
12	Incompressibility Parameter D2	0	Pa^-1
13	Incompressibility Parameter D3	0	Pa^-1

Figure 78: ANSYS Table

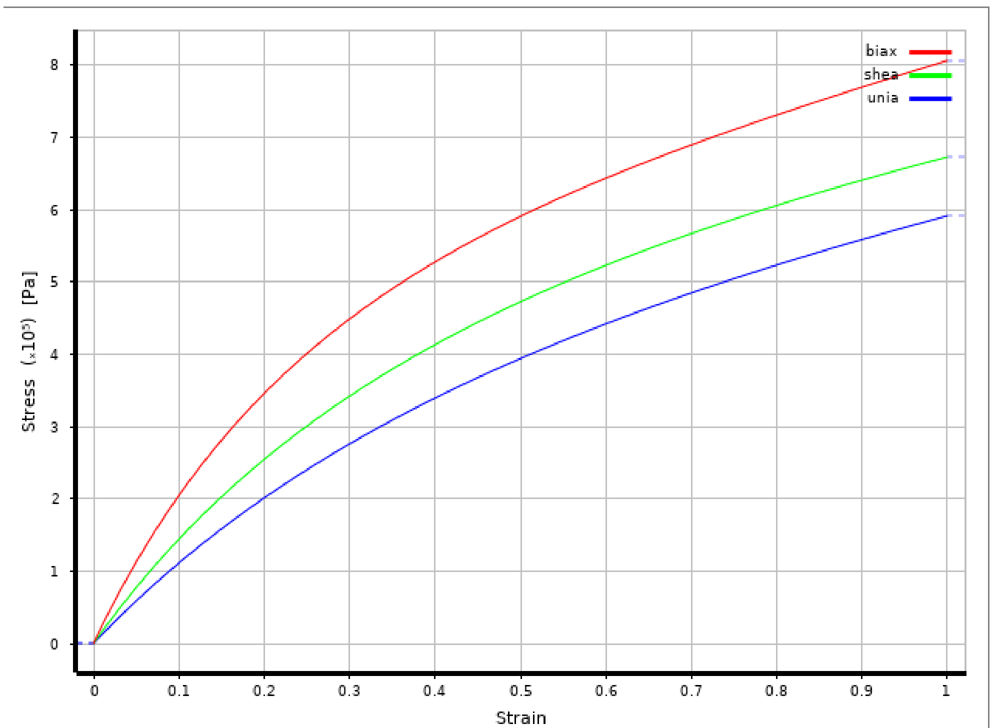


Figure 89: ANSYS Stress-Strain Graph

For emulation of high-density polyethylene sheeting, the Shock EOS Linear model (also known as Mie-Grüneisen EOS model) is used. This model is used to determine the pressure in a shock-compressed solid and due to our explicit dynamics model of a high-speed projectile impact, this is the appropriate model. This sheeting is used to emulate our bulletproof vest for the full-scale testing model, and so the variability of internal pressure due to a shock-compression is of the highest concern to demonstrate its deformation and absorbed force when struck. Due to lack of engineering data on the physical sheeting that we are using to perform these experiments, we chose 'POLYETHYL.' as a substitute material for the same reason as the choice of material for the pad. Experimental data must be taken in order to have a perfect model and for our analyses this is unnecessary.

Mie-Grüneisen EOS

<u>Hugoniot Shock-Particle Velocity Curve</u>

Values for this model are shown below in the attached ANSYS table.

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	915	kg m^-3
4	Shock EOS Linear		
5	Gruneisen Coefficient	1.64	
6	Parameter C1	2901	m s^-1
7	Parameter S1	1.481	
8	Parameter Quadratic S2	0	s m^-1

Figure 20: Kinetic Energy Reduction Over Time

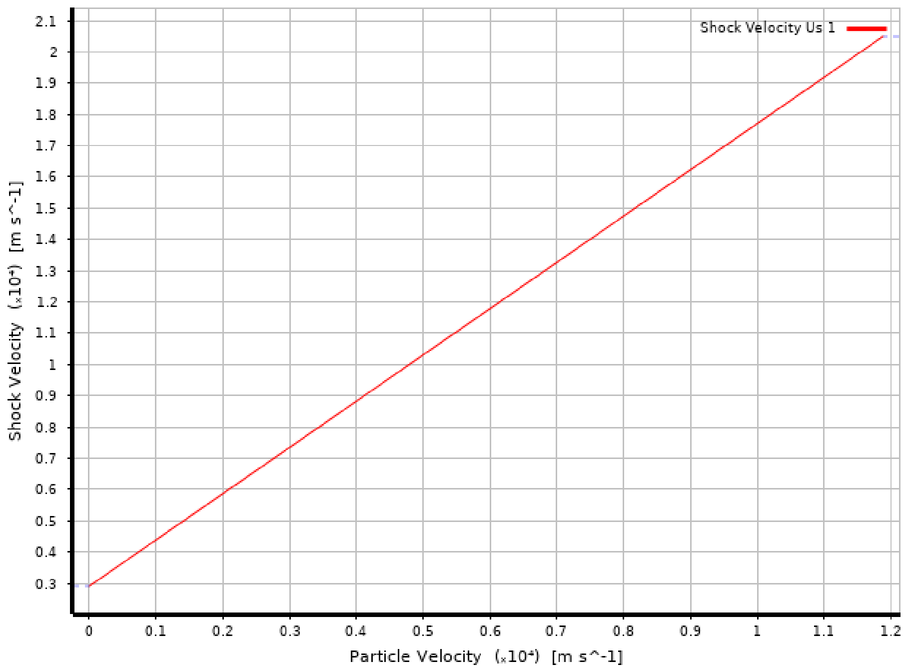
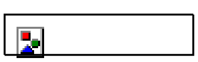


Figure 21: ANSYS Stress-Strain Graph

For emulation of Tungsten Alloy, the Shock EOS Linear model (also known as Mie-Grüneisen EOS model) is used. The theory behind using this model is the same as it is for polyethylene where we are concerned about the rigidity of the bearing as it is impacting, for explicit dynamics this is of great concern.

Mie-Grüneisen EOS

Hugoniot Shock-Particle Velocity Curve



Values for this model are shown below in the attached ANSYS table.

	A	B	C
1	Property	Value	Unit
2	Material Field Variables	Table	
3	Density	17000	kg m^-3
4	Specific Heat Constant Pressure, C_p	134	J kg^-1 C^-1
5	Johnson Cook Strength		
14	Shear Modulus	1.6E+11	Pa
15	Shock EOS Linear		
16	Gruneisen Coefficient	1.54	
17	Parameter C1	4029	m s^-1
18	Parameter S1	1.237	
19	Parameter Quadratic S2	0	s m^-1

Figure 22: ANSYS Table

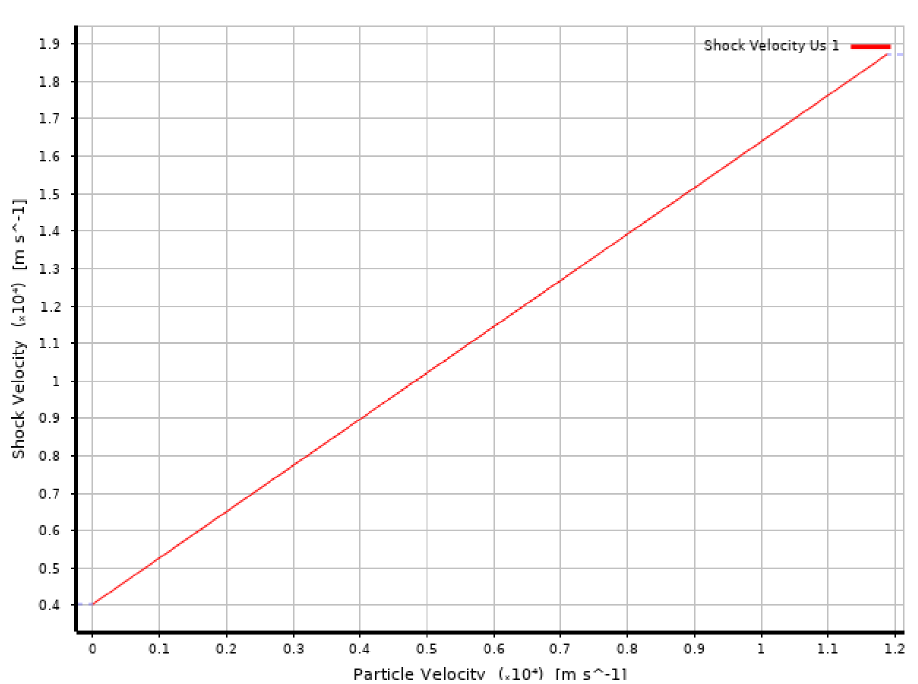


Figure 23: ANSYS Stress-Strain Graph

*After speaking with Dr. Dong about the complexity of importing material properties of this 3D printed resin, we decided to go with the most similar material that ANSYS has built into the software. Using a similar material will not hinder our desired results as we are conducting a comparative test between samples, and it is not a scaled model of our final testing.

Geometry

Assembly shown in the below figure was created in ANSYS SpaceClaim. The individual components of the assembly were imported and placed together. The square honeycomb pad was created in nTopology, while the bearing and sheet of material were constructed in Solidworks. We used the 'Tangent' feature to constrain the bearing to the sheet and the sheet is constrained to the pad using 'Align' on two different surfaces as they have the same cross-sectional profile along the z axis.

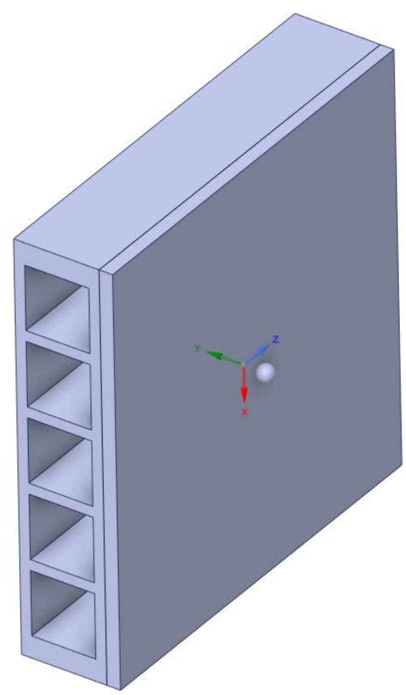


Figure 24: ANSYS Assembly

Mesh

The generated mesh for our assembly is shown in the figure below. Our team used the default mesh settings due to the basic geometry at hand. Flat surfaces that are being impacted so as long as the individual cells are of acceptable size, we are able to obtain our desired result. To reiterate, our team is looking at the deformation in order to deem these samples worthy of projectile testing, so the numerical solution is less of concern as the stress profiles and total deformation seen.

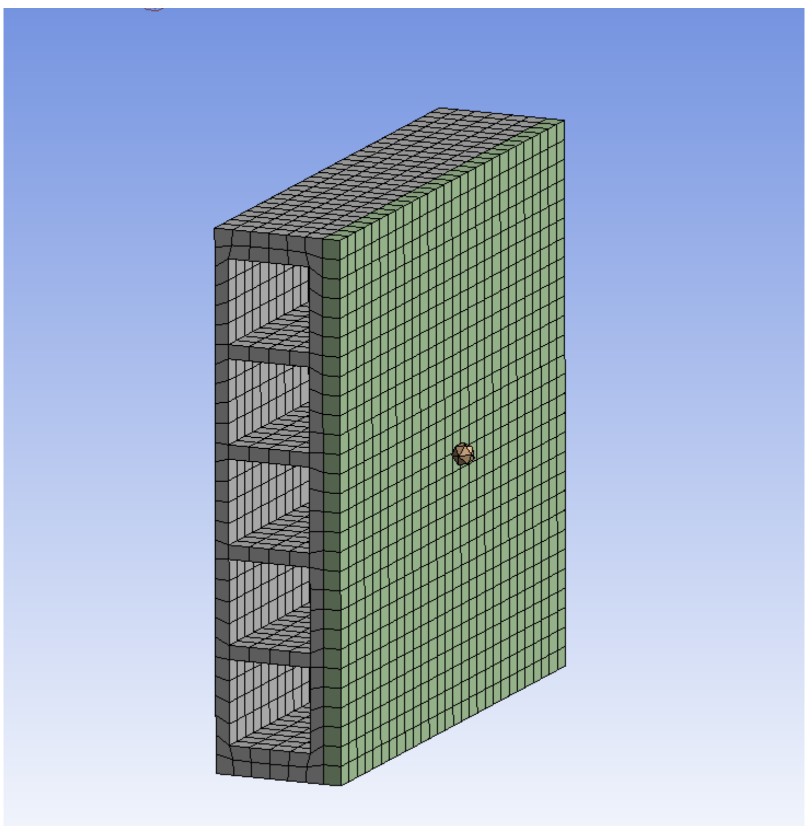


Figure 25: ANSYS Mesh

Initial Conditions

Our team used explicit dynamics for these samples, so the initial conditions that are recommended by ANSYS are to have a fixed support region, an initial velocity and of course an end time. For a fixed support we chose the face of the samples that is to be mounted on the apparatus for actual testing and set the initial velocity to 300 m/s as this is what the testing apparatus is designed to produce. End time was established by the initial velocity of 300 m/s and chosen as an arbitrary value to show the impact and resultant of impact, we used a value of .003 seconds. Finally, for Explicit Dynamic modeling in Workbench, we are by default given the option to change the 'Pre-Stress' which may have been of influence depending on how the team is to mount the testing subjects to the testing apparatus. Due to our team planning to simply tape everything together, this stays at a value of zero because this stress is negligible.

Our results were somewhat as per expectation for our first round of testing. We chose to emulate the system without the apparatus that holds the pad and high-density polyethylene sheeting to examine if there was a possibility of the projectile to go through our samples. As seen in the figure below this was the case for the triangle lattice structure. The tricky part of our simulation is choosing a material that accurately describes our high-density polyethylene due to the flexibility but also stiffness when impacted. This led to choosing polyethylene that is softer but still gave us similar deformation as seen in our testing methods. The numerical results given to us with these simulations is not desired, but more the behavior of the spreading of stresses along the object and its behavior in a compressive state. Too little deformation is not something that is desired due to us looking to disperse force across the surface but also cannot allow too much deformation as to be an effective part of energy dispersion. In the figure below one can see the Von-Mises Strain at the peak of impact and visually see the deformation of various materials.

Von-Mises Strain

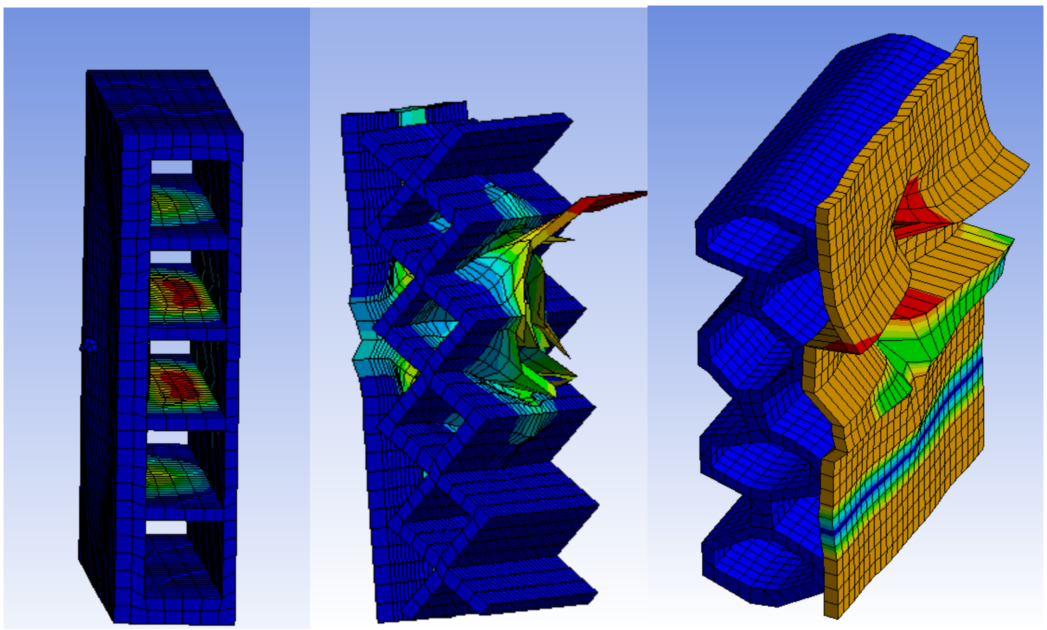


Figure 26: ANSYS Simulation

With this simulation, our team expects the hexagonal sample to perform the best for our application due to slight deformation and retention of the projectile. The square sample appears too rigid, while the diamond sample failed, and the projectile went through the sample. Due to the materials not being perfectly accurate to our testing details, we are going to use this to hypothesize the honeycomb lattice to be the best sample and still test all of them. Seeing these strains on our samples allows the team to adjust design accordingly to optimize the part if necessary and can be reused if physical testing is not deemed successful.

4. Costs

The following sections outline the costs for this project. We were given a budget of $500 by American Engineering Group for our project.

4.1 Parts

Item	Qty	Description	Manufacturer	Cost $
AR500 Armor Trauma Pad	1	Used for comparative testing	AR500 Armor	$45
High Density UHMWPE Bulletproof Fabric	1	Same material used in purchased BPV	Skarr Armor	$49.35
Flexible Ballistic Armor Level IIIA	1	Standard vest for our application	Battle Steel	$64.03
Flexible 80A Resin 1 L	1	Resin selected for 3D Printing of pad material	Formlabs	$224.97
Total:				**$383.35**

Table 3: Project Parts and Cost Overview

4.2 Estimated Labor

Labor cost is only to be accounted for by team members hourly wage throughout the term, no specialized help was necessary for our project.

$$5\ team\ members * \left(4\frac{hours}{week}\right) * 30\ weeks * \frac{\$40}{hour} = \$24{,}000$$

5. Conclusion

5.1 Accomplishments

Our most significant accomplishment for this design is that we successfully reduced the back deformation to unmeasurable levels. Our team was delighted with this result as we did not expect it to mitigate that point force completely. Another thing seen in the testing videos shot on an iPhone was that the testing setup didn't rock after being shot as it did when it was hit with the market pad or no pad. By inspection, we can loosely infer that the force was better dissipated throughout the body and was not concentrated enough to allow the testing setup to move.

Other accomplishments for our design criteria were done by choosing to use additive manufacturing over different manufacturing types. These accomplishments were the pad being waterproof, easily manufacturable, and able to fit to anybody when scanned with a 3D scanner. The customizability and manufacturability make it so that the system can be adapted to any bulletproof vest or user. In conclusion, all major goals for this product were successful.

5.2 Uncertainties

While our vest met all of our design requirements, certain aspects cannot be verified. The NIJ standard states that level IIIA vests can stop eight impacts from a rated round of ammunition [7]. We shot our vest three times, so according to the standard, our vest is acceptable. However, it is unclear if the vest degrades slightly between consecutive shots. The rounds fired into the vest also have a level of variability from round to round. The rounds used for the project were 240 grain (15.6 g) projectiles traveling at 1270 ft/s (387 m/s) [12]. However, rounds of ammunition have a small variability from round to round in both velocity and mass. This would result in a small difference in kinetic energy between shots that we could not account for.

Additional uncertainty is the types of injury that can result from ballistic impacts. Injuries can occur from both back face deformation and propagation of a shockwave. However, with the testing methods available to our group, we could not verify this aspect.

Another thing that needs to be considered is the shape and size of the individual pads that were developed. There are minor differences in every pad manufactured due to the nature of additively manufactured parts. With only one round fired at the final design, it is impossible to verify whether or not all pads would provide the same level of protection.

The clay used was also not of the type specified in the NIJ testing instructions. Our group believes that this would not be an issue because comparative testing was conducted for our purposes. However, the clay used for our testing has different properties than that specified in the NIJ standard, so it would be necessary to verify the acceptability of this clay.

5.3 Ethical considerations

When creating a product that is used in the space of firearms, we must be careful to properly understand the problem and challenges ethically that result. Our product is designed to be used by law-enforcement officers and is not intended to be used for the wrong purposes. This could be resolved by distributing only to law enforcement officers, but the product's nature could result in poor usage.

Another ethical consideration could be the proper inspection of parts due to inconsistencies from print-to-print with the chosen manufacturing process. Even a single layer of misprinting can make the product behave differently than the ideal, so there would have to be a testing protocol for individual pieces to ensure they perform as expected.

Finally, as discussed in 'Uncertainties,' we could not follow the exact testing protocol per NIJ standards. This is necessary before it is marketed because this verification deems it safe and is also used as a marketing point to use this product over untested ones.

5.4 Future work

As discussed throughout this report, if given more time and resources we would implement a biomarker system and a system for 3D scanning to create specialty parts per each user. The biomarker system would require extensive testing to develop. An accurate model of the human body as well as a calibration system would be needed for these purposes. A 3D scanning tool could be implemented more easily to ensure customization of the pads. These plans would take another entire term to implement properly.

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