Increasing The Emergency Capabilities of The Current Ballistic Vest

A Major Qualifying Project to the Faculty of

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Degree of Bachelor of Science

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Preface

The progress of this project was greatly affected by the COVID-19 global pandemic during D Term of 2020. In order to ensure the safety of its students, WPI closed all academic buildings and moved to continue projects and coursework remotely. Due to these unfortunate circumstances, our team was unable to complete the manufacturing and testing of this MQP or continue physical building that was planned for D-term. This pandemic negatively impacted the project’s progress and work schedule.

Abstract

The focus of this project was to make modifications to the Safariland Tactical Vest. Current protective vests only protect the front chest area of an officer, leaving areas throughout the body exposed with more opportunities for injury. The modifications included adding a hemostatic agent so that when punctured, the victim has more time before they bleed out, a GPS so that the victim can easily be located by a medic, shoulder guards that lighten or stop injuries to the shoulders, sensors that detect an impact, and sensors that read the vital signs of the individual wearing the vest, which can be sent directly to a dispatcher. All these modifications will save the lives of the people risking their own lives for our freedom and safety.

Keywords: protective vest, modifications, hemostatic agent, GPS location, shoulder guards, impact detection sensors

1.0 Introduction

The men and women in our Armed Forces and Police Force put their lives at risk every single day in order to protect and serve our country. Volunteering to go out in the field to defend this country exposes them to potential injuries from knives, bullets, grenades, bombs, and other weapons. Law enforcement officers and certain first responders wear bullet protective vests in the field in order to shield them from those weapons and their shrapnel[1]. Normally these vests are referred to as “Bullet Proof”, however, they are only bullet resistant, depending on the type of weapon that is fired at it or its force of impact. The ballistic vests can only help to minimize the severity of certain injuries, through absorbing and distributing the energy that encounters the vest.

Since these ballistic vests are not completely bullet proof, this still leaves chances for potential injuries. In these cases where the vest fails to fully resist the bullet, injuries can be extremely severe where a victim will not be able to call for help or backup. Other times, the injuries are fatal enough for the officer to bleed out and not have enough time to get to a hospital for medical assistance.

There have been several Major Qualifying Projects (MQP) completed by students from Worcester Polytechnic Institute (WPI) that are similar to this project. One team worked on a project that detects the impact of bullets on a vest and subsequently sends a signal to call for assistance (Santimore & Fairman, 2011). Most recently an MQP team created a system that would collect impact data on the test and sent it to a dispatcher to send help for the wearer (Keyes, Potvin, Richards, & Tolisano, 2016). Each of these teams assessed the current condition

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[1] Shrapnel: bomb, mine, or shell fragments (Shrapnel, (n.d.))

of the vest and found ways that it could be improved. The Body Armor Impact Map System project, (Keyes, Potvin, Richards, & Tolisano, 2016), were not only able to successfully incorporate these impact detection sensors into their vest, but their team was also able to add a Global Positioning System (GPS) device in order to track the wearer's location at all times. In the case where an officer is shot, a signal, along with their exact location, would be sent immediately to their base and the dispatchers would be able to send medical attention immediately to assist the inflicted officer. Our team believed that these ideas could save the lives of troops and first responders, but more work needed to be completed. In this project, we combined the ideas of these teams, along with additional modifications, which include hemostatic gel and an upgraded attachable shoulder pad for the vest.

Current protective vests in use only protect the front chest area of an officer. This design leaves other areas throughout the body exposed, leaving more opportunities for injury. Bullet-resistant vest manufacturers have had limitations with creating protection for the exposed body parts because it could create more restriction and limit the officer's range of motion, generating discomfort for the person wearing the vest as well as adding weight to the already heavy vest (Heath Grant, 2012). In most cases, these vests are not able to stop a bullet completely; they simply slow down a bullet, so the impact of the bullet is less detrimental to the human body. This slowed down impact, however, can still lead to injury in many severe cases. The current material of the common ballistic plate is a ceramic plate system that is capable of being inserted into the ballistic vests. If this plate material were to change to a material with a higher strength to withstand more stress, such as steel, it would likely increase the weight of the material and will consequently limit the mobility of the officer wearing it.

The focus of this project was to make modifications to the Safariland Tactical Vest (Titan Assult Vest, 2020).The five main modifications our team made to the Safariland Tactical Vest were

1. Adding a hemostatic agent so that when punctured, the hemostatic gel will bind with the wearer's blood to induce clotting, giving them more time before they bleed out
2. Incorporating a GPS location so that the wearer can easily be located by a medic in a time of need
3. Designing shoulder guards that will attach to the vest and lighten or stop injuries to the shoulders
4. Implementing impact detection sensors to determine where a person was shot and potential injuries that can be associated with that wound location
5. Developing sensors that read the vital signs such as heart rate and blood oxygen levels of the individual wearing the vest

The data from these sensors will be automatically transferred to someone who can dispatch the information to a medic. If the medics or other first responders are able to retrieve this information about the officer's injuries before arrival to the scene, they could prepare before dispatching out. This may include packing supplies that are more tailored to the specific injury so the medics can treat these officers as much as they can before arriving to a hospital. Our overall goal for this project is to successful incorporate these modifications to the vest to help save the lives of the people risking their own for our freedom and safety.

2.0 Background

The actions that an individual can take in order to protect themselves against a bullet or its shrapnel is extremely limited; the damage from one can be life altering or even fatal. When someone experiences this type of injury, they have minimal time to be treated for it, especially if they were to be hit in the torso where all the vital organs are located. The current ballistic vests can only sustain a small number of impacts, so when the vest is inevitably punctured through, it currently does not have the ability to assist the individual intreating themselves in the field or assisting an outside individual in accessing their current location in order to send proper medical attention.

2.1 Current Ballistic Technology

The current ballistic vests available to the military and police forces vary in their capabilities. There are different vests for different situations; lightweight vests are available when someone is operating in a low intensity area and heavyweight vests when the potential injury is increased. Overall, they generally consist of four plates in total, two Small Arms Protective Inserts (SAPI) plates in the front of the vest and two in the back. The plates fracture upon impact, making them only able to withstand one hit. The heavyweight vests also include a groin and neck guard in order to protect those parts of the body. Police officers also have different vests for different situations. At the Worcester Polytechnic Police Department, they wear the Safariland Tactical Vest. They generally wear these vests day to day, as they are lightweight, concealable under clothing, and have ceramic or composite plates. These composite plates are made from a polymer with extremely high tensile strength that is most effective in protecting an individual against stab wounds or low velocity gunshots. When there is a great possibility of encountering a high caliber bullet, they wear vests similarly found by military personnel, which carry ceramic plates. Both vests are shaped in order to give the wearer the most protection as well as freedom of mobility.

The shoulder clavicle area of the vest, as seen by the exposed grey of the mannequin under the vest in Figure 1, is one of the few areas where there are gaps in protection. The potential of having a lack of mobility in your shoulders is the reason why many service men and women refuse to wear shoulder pads, and why manufactures refuse to produce them. With any ballistic vest, although they are slowing down or maybe even stopping the bullet from penetrating the body beneath, there are still many cases where Behind Armor Blunt Trauma may occur, shown in Figure 2. Depending on where someone is shot, these secondary injuries then lead to broken ribs, bruising, internal bleeding or even death.

Figure 1: Vest Shown on Body with Shoulder Clavicle Circled

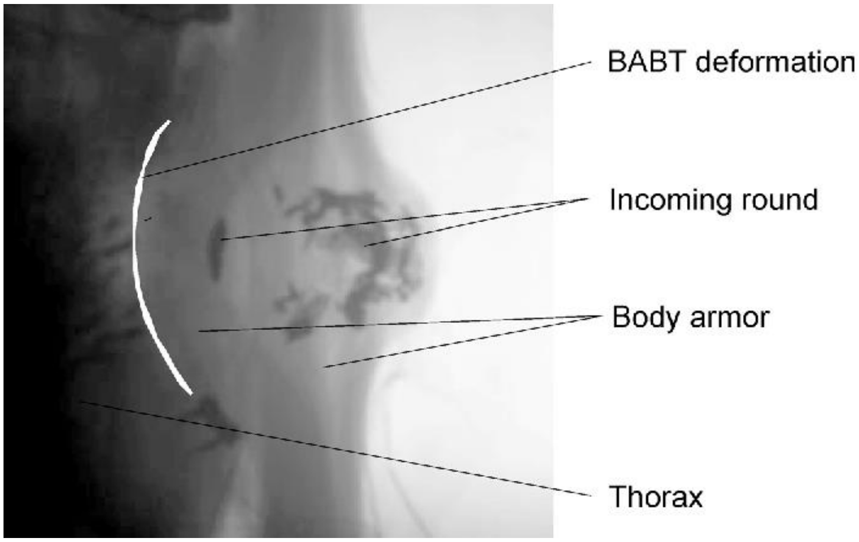

Figure 2: Impact of Behind Armor Blunt Trauma (BABT)

2.2 Bullet Wound Statistics

The System Sciences Laboratory of Defense Science and Technology conducted a study that summarized the gun and fragmentation wounds from multiple soldiers from past wars (Bradly, 2003). This group collected all the available data that was relevant to the location of these injuries on the victims' bodies. Most times, this information is not readily available for the public to view, so they were only able to collect data from five past conflicts (Vietnam War, Operation Desert Storm, Northern Ireland, Lebanon War and Croatia War). It was concluded that the three body parts that are most likely to be hit during combat is the Head, Torso and Upper Arms. Actions have already been taken to make the bullet proof helmets and vests more effective during combat. However, the upper arms and shoulders are still very exposed when they are on the field. According to this study, the percentage of gunshot wounds that were in the upper arm ranged between 20-30%, which accounts for wounds, shown in Figure 3.

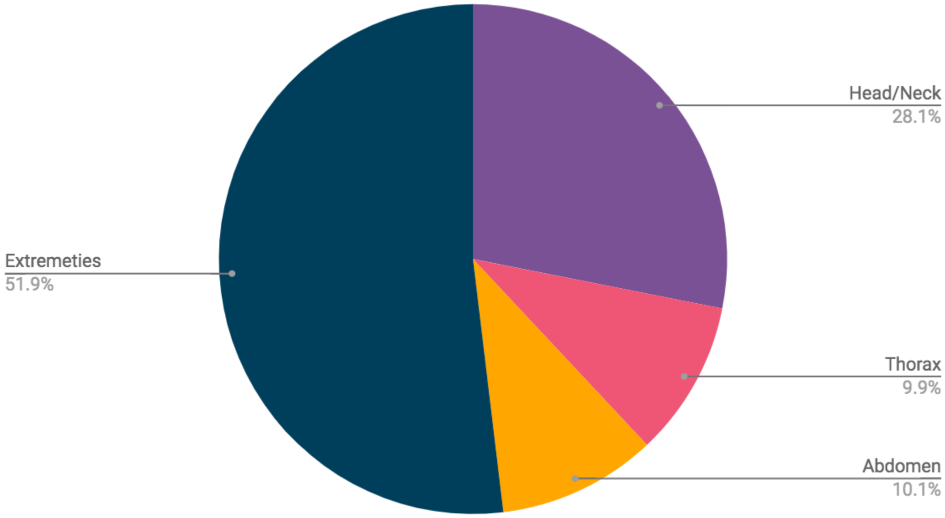

Figure 3: Distribution of Combat Wounds in Iraq and Afghanistan from 2005 to 2009

2.3 Shoulder Pad Protection

In order to address the excessive exposure to the upper arms in the current bullet proof vests, our team investigated the addition of shoulder pads. The goal was to add shoulder protection that does not restrict the person's range of mobility in their arm or add too much weight to the entire apparatus. Body armor created in the Medieval Times was very successful in allowing their knights to be able to experience a full range of mobility. With their armor, knights were able to run, jump and use their weapons while being covered head to toe in 80-120 pounds of steel. As circled in Figure 4, a layered fish scale technique was utilized around the torso to

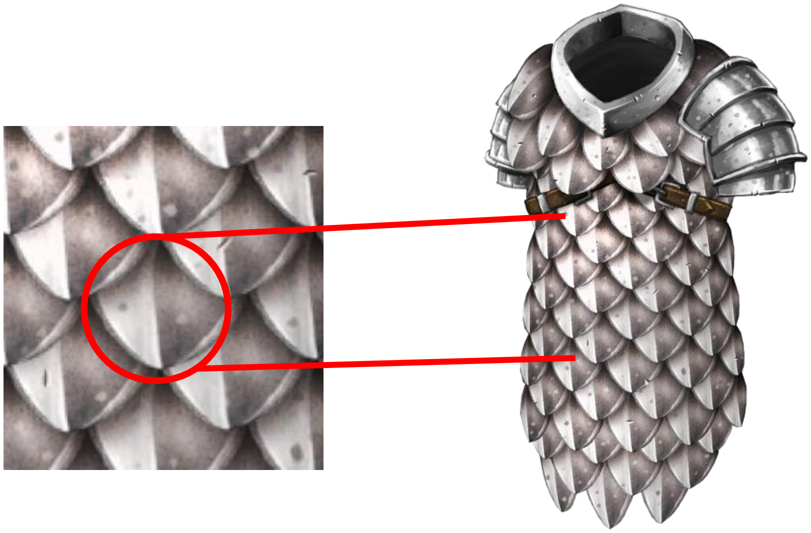

Figure 4: Knight Armor Used in Medieval Times Era

provide more protection. They also utilized a compressive armor technique that was used to protect the shoulders and allow the knight to use their shoulders freely.

Similar to the Kevlar plate that is placed over the chest and abdomen of a ballistic vest, the Kevlar shoulder plates that this project includes will distribute the shock of a bullet or other sharp object through a larger area. This helps to minimize the pressure experienced at the point of impact. Shoulder pads, such as those used for American Football players, work by absorbing the shock of impact through deformation. Shoulder pads will provide additional protection, prohibiting more upper body injuries.

2.4 Effects of Bullet Wounds

Military and police ammunition typically have a higher velocity than that of civilian ammunition. This greater velocity indicates a greater kinetic energy, and therefore, the potential to destroy tissue. When treating a gunshot wound, two of the highest priorities include hemorrhage control and infection prevention. The two most effective methods used in order to immediately control hemorrhaging include direct pressure and hemostatic dressings.

Additionally, the amount of tissue destruction is determined by the amount of time between when the person is wounded and their initial surgical treatment. The wound tract through human tissue can be force below in Figure 5. This pattern is formed by the direct shearing and cutting effect of the bullet forcing itself through tissue. (Penn-Barwell, Brown, & Fries, 2015)

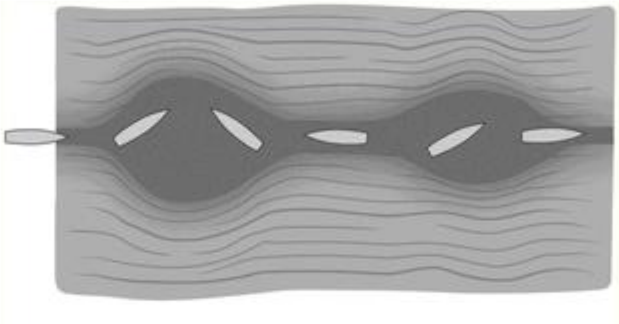

Figure 5: Bullet Wound Tract Through Human Tissue (Penn-Barwell, Brown, & Fries, 2015)

Due to the considerable damage that could be done, it is vital to provide immediate care to those with a gunshot wound (GSW). If immediate care is not available, one must take necessary precautions to ensure exsanguination[2] does not occur. To keep the person alive when excess bleeding occurs, direct pressure is required, which is not always attainable on the battlefield.

2.5 Typical Recovery Period

The matter in which battlefield injuries are managed is very different than that of a civilian circumstance. However, a ballfield injury is managed very similarly to that of a mass-casualty event. In this case, all initial measures are focused on a concept known as “tactical abbreviated surgical care” (Franke & Güsgen, 2017). This type of care includes a shortened initial care procedure followed by successive correction prioritized life-threatening conditions, including penetrating wounds or hemodynamic instability, subsequently followed by definitive repair. This abbreviated care is the most efficient method to save a maximum number of patients

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[2] Exsanguination: the action or process of draining or losing blood (Exsanguination, n.d.)

in a hostile environment with limited resources. Later, a definitive surgery will take place in a more equipped hospital. Using this procedural care, survival rates have risen, along with extending the life of precious resources (Rao & Singh, 2017). After the individualized treatment, it will be determined how this person will recover and whether they will be able to go back to the service.

Overall, there is a benefit in wearing a ballistic vest when it is needed, yet there is still the risk of injury that the vest cannot prevent. The team saw this as an issue, and therefore came up with design implementations that will likely increase the survival rate and lower the injury rate for the wearer. The following section will demonstrate the design and ideation of the protective vest modifications.

3.0 Design and Implementation

Our team used the problem decomposition outlined in Figure 6, to narrow down what our problem was and how we could solve it. This project hoped to add further equipment and modifications to a ballistic vest in order to increase safety of the person wearing it. This project is further broken down into two categories: utilizing more technology on the vest and mitigating injury risk. The first improvement was to add a sensor array that will provide information on the vital signs (heart rate), GPS location, and general health of the person that is wearing the vest. The second improvement was to add a hemostatic gel to the vest with the goal of releasing it when the vest has been pierced in order to lower the chances of exsanguination. The final improvement was to add shoulder pads to offer more protection to the wearer including lowering the chances of shoulder injury.

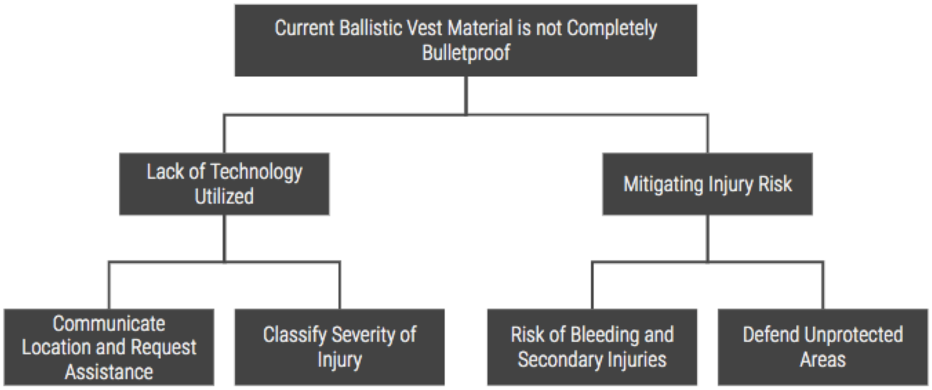

Figure 6: Problem Decomposition

3.1 Specific Sensors

A variety of sensors can be used to collect data on the wearer, which can be crucial for proper response to injuries in the field. These sensors have the goal of monitoring vital health statistics, the location of a soldier, and impact information from the plate.

The first sensor was an optical heart rate sensor, which can provide the heart rhythms of the wearer to tell if they are injured and if there is any unnatural heart rhythm that could be indicative of major health issues. This sensor operates by taking the reading from the body and putting it through amplifiers in order to increase the signal. Then it puts this signal through both a low pass and high pass filter in order to remove any electronic noise that could interfere with the heart rate signal. Figure 7 below shows the circuit that was used for this sensor.

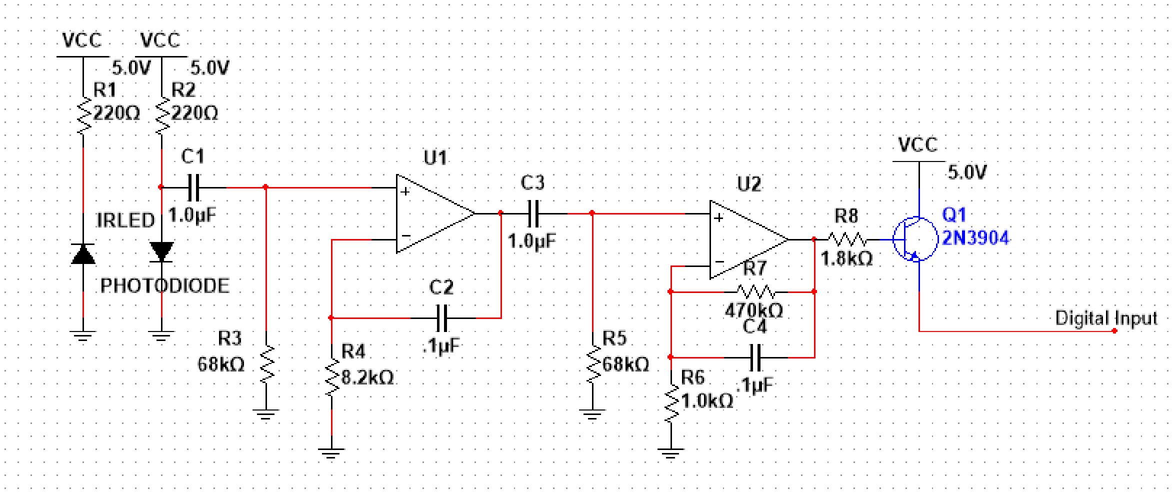

Figure 7: Optical Heart Rate Sensor Circuit

The location monitoring system relies on a GPS module that can be used to give the exact coordinates of the vest. This is useful for locating a serviceperson in the field, especially when that person is injured. This can allow for the dispatchers receiving this data to react in a timely manner and could be the difference between a life saved and a life lost. An inertial measurement unit (IMU) will also be used to track the person's movement and help correct GPS errors.

The final sensor is located on the plate of the vest in order to indicate if the plate has been pierced. One prototype design used was a matrix of wires that ran both vertically and horizontally in order to pinpoint the exact location of the impact with a robust design. It was later found that this design was overly complex and gave unnecessary information. It was then decided to proceed with a simpler final design in which once it is pierced, a signal will be sent back to the microcontroller. The weave that will be used for the final sensor is shown in Figure 8. We will divide the plate into seven quadrants, shown in Figure 9, so the sensor will be able to detect where on the body the officer was shot and the potentially injuries that are associated with that GSW. This information would be able for medics to prepare for those injuries before they are able to arrive to the scene and assess the officer. We chose these seven quadrants based on quadrant locations known to the medical community.

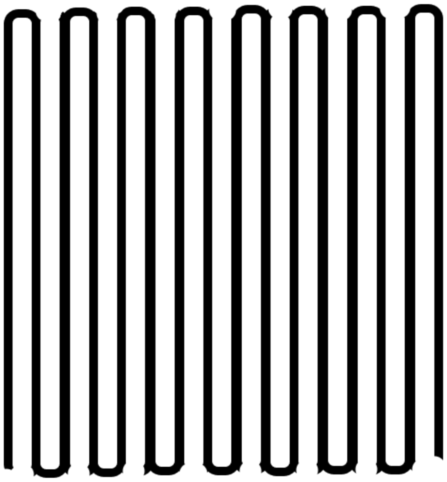

Figure 8: Sensor Weave Pattern

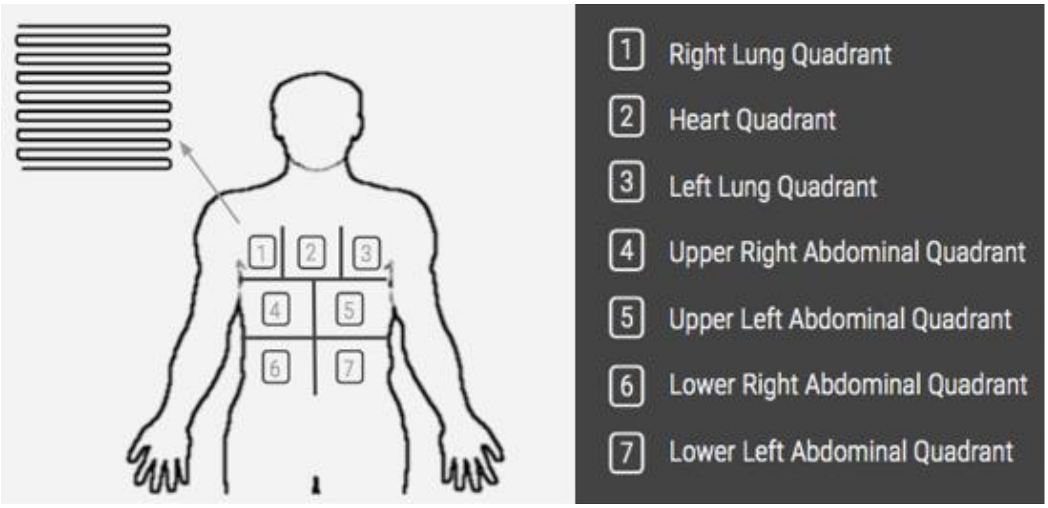

Figure 9: Seven Impact Detection Sensor Segments

Some of these sensors are located on the vest and others are placed on the body of the person wearing the vest. The heart rate sensor will be attached to the body using adhesive stickers so that it can read heart rate, while the other sensors will be located on the vest. The GPS and IMU will be placed along with the microcontroller on the top of the plate so that it can easily be replaced if there is an issue with the vest. The other sensors will be located on both the front and back of the plate in order to sense the impact. The functional requirements of these sensors are summarized in Table 1.

Table 1: Functional Requirements of Sensor Design

Ability to Sense Imminent Danger

- Be able to detect specific heart rate patterns
- Accurate sensor dectection of vest impact

Accurate Communication of Vest Location

- Acquire a GPS location once an injury detection is triggered
- GPS within a range of 10 meters of actual location

Ability to Work in Non-Ideal Conditions

- Able to withstand environmental changes
- Withstand stress of wearer's body weight
- Withstand impact that doesn't pierce through the vest

3.2 Hemostatic Gel

Immediately controlling hemorrhaging is the main priority when treating a GSW because hemorrhagic shock is the main cause of battlefield mortality. To ensure proper trauma management, prompt hemostatic measures must be applied. In the application of this novel protective vest, a hemostatic gel will be placed between the Kevlar plate and the material of the protective vest. The hemostatic gel will be placed in this location so that it will be released if the protective vest is pierced by a bullet or another sharp object that can lead to internal and external injuries to the person wearing the vest. When directly applied to bleeding surfaces, this hemostatic gel provides a plant-based mechanical matrix that facilitates clotting factors, which begins the healing process and slows the bleeding (Khoshmohabat, Paydar, Kazemi, & Dalfardi, 2016). The functional requirements of the Hemostatic Gel are summarized in Table 2.

Table 2: Functional Requirements of the Hemostatic Gel

Stress Analysis

- Withstand stress of wearer's body weight
- Withstand impact that does not pierce the vest

Proper Application of Hemostatic Gel

- Gel is applied to wounds within 30 seconds
- Enough gel is applied to stop or slow down the bleeding

Praticality of Hemostatic Gel

- Must be able to reach all outlined sections of bullet-proof vest
- If one section is pierced, the others will remain intact

In adding this gel layer, it is important to make sure that once the layer is pierced the gel can reach the wound on the surface of the body. However, it is very likely that if you are shot you have been shot in more than one location. With a single layer of gel, once punctured, all the gel will flow to the wound. If the officer were to be shot multiple times, there would be no gel left for the other areas after the gel is released. To solve this problem. our team has designed a multi-pocket silicon container to store the gel within the vest, shown in Figure 10. Since this feature will be located on the chest of the wearer, there is the possibility that the wearer could fall forward, and their entire body weight would be acted on the silicon contraption. Therefore, this container unit must be strong enough to withstand normal stress and forces, but delicate enough to break from a bullet. Using liquid silicon, we aimed to mold this feature to store the gel without releasing it unless a bullet is inflicted.

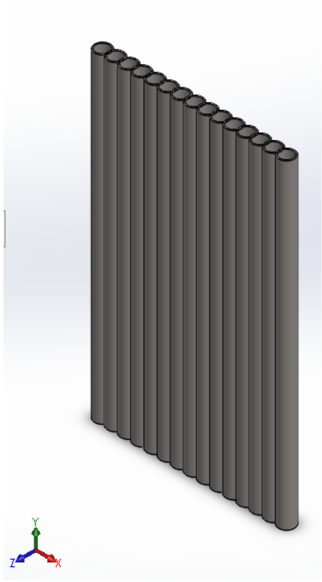

Figure 10: Multi-pocket Gel Layer Design

3.3 Shoulder Pads

When a unit loses an individual due to a casualty[3] it interrupts their mission readiness as well as the morale. The idea of adding the protective shoulder pad is to allow the troops or police forces to remain in combat. The current ballistic vests do a good job at protecting the torso of the wearer but leaves the shoulder exposed. The shoulder is a very exposed area of the body that frequently gets hit in any form of combat. By adding this, as well as the hemostatic gel, we could increase the overall safety of the wearer, as well as, the unit's mission readiness. The functional requirements of the Shoulder Pads are summarized in Table 3.

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[3] Casualty: a military person lost through death, wound, injury, sickness, internment, or capture or through being missing in action (Casualty, n.d.)

Table 3: Functional Requirements for Shoulder Pad Design

Full Range of Motion

- Must allow the wearer to experience a full range of motion in all three degrees of freedom that the shoulder exhibits

Weight

- Shoulder pads cannot exceed a combined five pounds of total weight

Lifetime and Stress Analysis

- Must last for the entire duration of the bullet proof vest's expiration date

In this section, our group described the design requirements taken into consideration that stemmed from both the ideation process as well as feedback from the Worcester Polytechnic Institute Police Department. For each modification included in this project, there is a specific set of functional requirements including the modification’s ability to effectively protect the wearer. Using the specified requirements, the team was able to then design each modification, ensuring each addition would improve the tactical vest while continuing to keep the wearer protected. Once the design process previously stated was completed, the group then began to manufacture, assemble, and test the overall product, which will be explained in the following section.

4.0 Methodology

This chapter will discuss the process the team took in order to assemble our improved Bullet Proof vest with the modifications discussed in the previous chapter.

4.1 Sensors

This section of the paper will discuss the individual sensor design for the improvements. The sensor discussion will start with that of the GPS, then the heart rate monitoring and finally the bullet impact detection sensor.

4.1.1 GPS Sensor

After discussing the use of GPS with the WPI police department, this idea seemed unfavorable because it has the potential to be intrusive on an officer's privacy. In order to still incorporate a GPS sensor into our design, our team determined a series of cases that must happen for the GPS sensor to send an officer's location to their base. This includes a layer of sensors that can sense if the vest has been pierced, which would assume a gunshot or stab wound. Another case that could set off the location is if the wearer is experiencing heart rates that indicate blood loss or excessive activity, to indicate the wearer is running away or engaged in combat. The GPS sensor was designed using a GPS Mouse GP-808G sensor. This sensor will send information through the Arduino TX and RX ports when any of the other sensors notifies of potential danger (SparkFun, 2020). This method is most optimal because using anything other than a pre-built GPS sensor could cause potential for inaccuracy with very little saved on cost. Once this sensor was complete, its output data was compared to the GPS data of a cell phone to ensure that it received an accurate location that was within 10 meters. We used a cellphone’s GPS to compare the GPS values because it was easily accessible to our team and is considered a highly accurate form of GPS technology.

4.1.2 Heart Rate Sensor

The heart rate sensor design that we have chosen is a double filtered optical heart rate sensor. This signal is AC coupled and filtered to remove frequencies outside of the expected operating band. It is then put through a gain-controlled integrator op amp to give this signal uniform peaks at the heart beats. This design was built using an infrared LED and a photodiode to change the voltage passing through the circuit based on the flow of blood. This design was chosen because it can eliminate much of the potential interference that can arise from excess movement. This heart rate sensor was then compared to a cell phone optical heart rate sensor to ensure that it operated to our standards.

4.1.3 Bullet Impact Detection Sensor

The bullet impact detection sensor used a wire matrix design. This matrix has individual weaves over the seven segments of the chest: right lung, heart, left lung, right upper abdominal quadrant, left upper abdominal quadrant, right lower abdominal quadrant, and left lower abdominal quadrant. Each segment has a weave matching the pattern shown in Figure 7 made with a thin layer of copper between two layers of polypropylene plastic. This design was chosen in order to minimalize issues with potential short circuits and make sure there will be no breakage caused by outside sources. This design was shot with simulation rounds in order to determine whether it could accurately detect when a segment of the vest was pierced.

4.2 Hemostatic Gel Container

The layer of hemostatic gel will be compromised of liquid silicon that is hardened to a specific mold best suit for this application. In order to create the mold, we 3-D printed our design. This method was chosen because it is more cost efficient and is easier then machining a stock of metal material. When this print was complete, we poured liquid silicon into the structure and allowed it to set in that shape. Once our gel container was completely solid, we planned to run tests, outlined in section 5.3 to ensure our model met our preset functional requirements as described in Table 2. If it failed to meet our requirements, we planned to test other materials to create this mold and determine which material is most suitable for this application.

4.3 Shoulder Pads

To perfect the design of the shoulder pad, prototypes were made with wood. For the portion that covers the shoulder, we used kerf bending. Kerf bending is the process of cutting slots into a material allowing it to bend. This strategy makes the material thinner, allowing it to be flexed to follow a curve. Multiple kerf bending patterns were cut and tested to determine which pattern would best fit this application. The pattern shown in Figure 11 shows the specific pattern used for the finalized shoulder pad. This pattern allows for movement in the Pitch and Yaw arm motions (What is Pitch, Roll and Yaw?, 2017). Once the shoulder pad was tested as explained in Section 5.1 and the pattern was deemed to satisfy its testing requirements, the

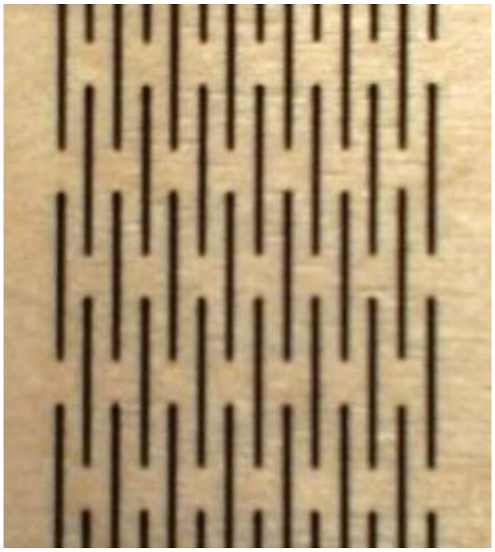


Figure 11: Kerf Bending Pattern

finalized prototype was intended to be made using Aluminum Alloy, based on analysis ran on ANSYS Workbench shown in Section 7.

In this section, we discussed the modifications that our team made throughout the project. Through prototyping and testing we were able to create modifications that could save the lives of those on our frontlines and first responders. In the next section we will be talking about the design iterations that we went through.

5.0 Design Iterations

This section will go through the ideation and design process of the different components of the project. After in person ideation sessions, the group created SolidWorks models for each manufactured component, in many cases 3-D printed the product, then evaluated and adapted the design. This section will explain the design challenges and failures the group encountered and how the components were changed to meet the team's needs.

5.1 Shoulder Pad Design

Our team decided to incorporate an idea similar to the Medieval Armor we discussed in Section 2.3 to satisfy our design requirements of a shoulder pad that could protect currently exposed areas, allow the wearer flexibility, as well as made by a material that can slow down or even stop a bullet's penetration to the body. One view of our SolidWorks model is displayed in Figure 12, where the shoulder pad is shown in its compressed form. This will be exhibited when the wearer raises their arm, so their shoulder is not restricted. The image displayed in Figure 13 is the shoulder pad shown in its expanded form. This form will be exhibited when the wearer's arm is lowered and in a relaxed position. In this shoulder pad design, we performed multiple extrude cuts in a specific pattern. This strategy is referred to as kerf bending, which will ideally allow flexibility in material. Incorporating this technique onto the material aided the shoulder pads in being less restrictive on the wearer.

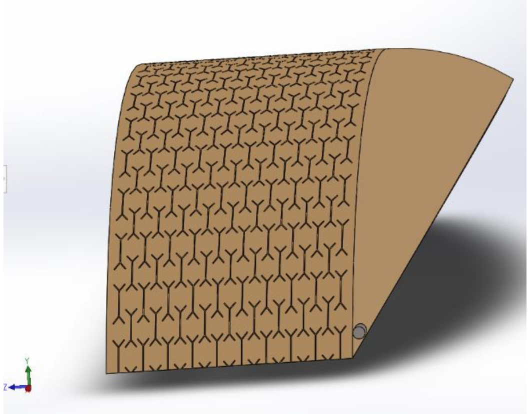


Figure 12: SolidWorks Model of Shoulder Pad in its compressed form

After prototyping this initial design, our team discovered how this design might be more restrictive to the wearer then we expected. The left portion of the kerf bended material intended to protect the shoulder clavicula; however, the shoulder clavicula of the tactical vest we were modifying had enough Kevlar protection and made this portion of our design unnecessary and would make the vest bulkier. The next iteration of our design removed this protection and we decided to add more compressible layers to the shoulder pads so that the whole design is compressible; The compressible layers also have the kerf bending technique to ensure the most flexibility for the shoulder pad. This updated design is shown in Figure 14.

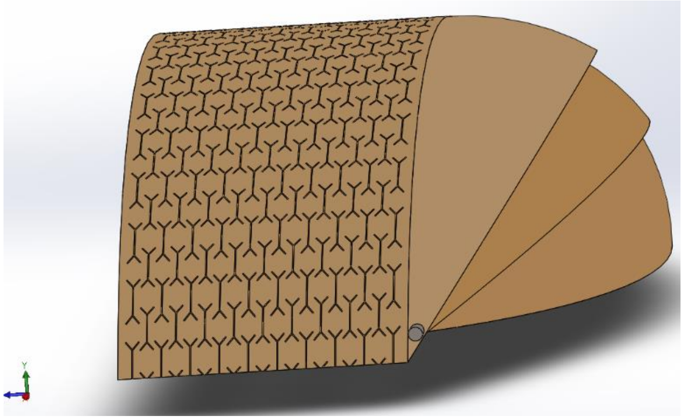


Figure 13: SolidWorks Model of Shoulder Pad in its expanded form

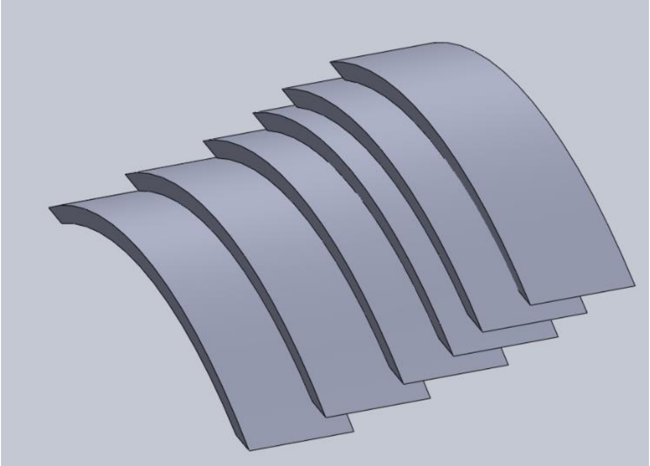


Figure 14: Final SolidWorks Model for Shoulder Pad Design

5.2 Hemostatic Gel Holder

The goal for designing our hemostatic gel holder was to create a container to hold the gel that can withstand the impacts of daily life and work. Originally, we based our design on cylindrical bubble wrap, shown in Figure 15. However, if someone were to get shot, it is possible that they would get shot more than once, and in different locations on their body. We designed the hemostatic gel tubes to be replaced individually and capable of fitting in the area on the vest designed for on the vest designed for on the vest designed for the ballistic plates. Our team also recognized that if someone were shot while wearing their vest, it would not puncture through every single tube, which is critical so the get in the other pouches can be directed to other wounded areas. An individual tube design is shown in Figure 16.

Figure 15: Ten-Inch-Long Bubble Wrap Tubes

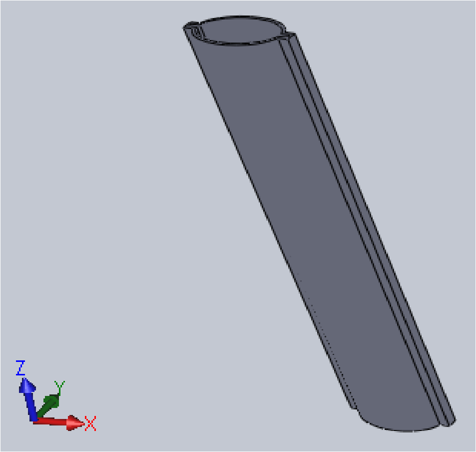


Figure 16: Hemostatic Gel Individual Tube Design

The next step is to prototype this design by creating a mold that can replicate this model out of the material we choose. Our team chose to use silicon because many MQP groups can mold this material using Polylactic Acid (PLA), which is the material typically using to make 3-D printed parts. We initially designed a mold, shown in Figure 17, where we are placing a material into the tube and inserting another block to mold an opening for this model. Figure 18 shows the 3-D printed parts of this mold.

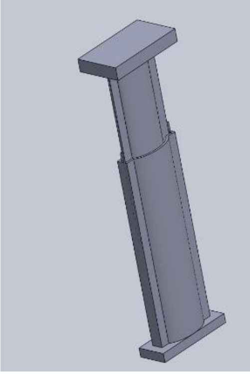


Figure 17: SolidWorks Model of First Iteration of Gel Mold

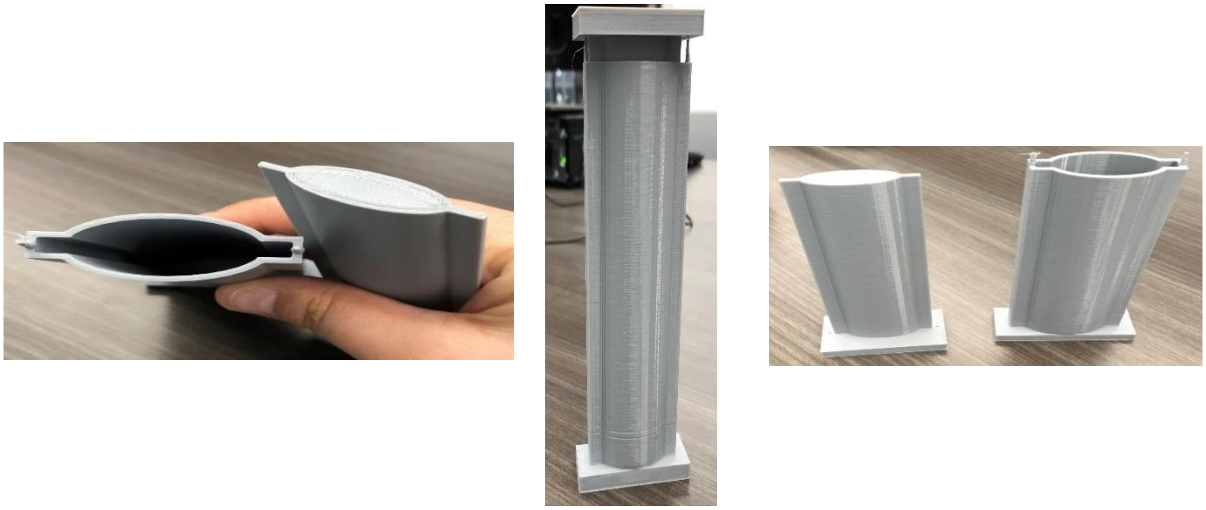


Figure 18: 3-D Printed Parts of First Iteration of Gel Mold

After attempting to mold silicon using our 3-D printed parts, the mold was harden shut and we were unable to open it and retrieve the silicon molded material. After talking to other MQP teams that had success with molding their parts using PLA parts, we decided to make some alterations to the design. Another suggestion was to create a two-part mold that snaps into place, eliminating air gaps that can defect the mold. Additionally, it was suggested to extrude a hole placed the top of the mold where we would use a syringe to insert the material we are attempting to mold. This method of material insertion would also help eliminate air gaps. Our final suggestion was to extrude small holes on the side on the mold to also aid in reducing air bubbles. Figure 19 shows a second iteration of this gel mold with the alterations suggested to our team.

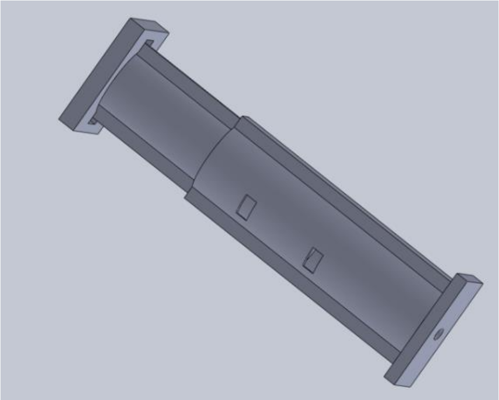


Figure 19: Second Iteration of Gel Mold

Once our team attempted to mold the silicon with the new printed mold, we noticed other flaws in the design. Although the silicon successfully hardened, it stuck to 3-D printed mold and we were unable to retrieve it without breaking the part and ultimately puncturing the silicon mold. After analyzing both design iterations, we felt the extra suction that caused the mold to stick together was due to extra friction between the mold chamber and the silicon. To reduce the friction within the mold, we increased the surface area where the two pieces came together in the mold. Instead of having a vertical two-part mold, we created a horizontal two-part mold, shown in Figure 20. Our team also removed the extruded holes on the side of the mold because too much of the silicon material seeped out of the mold. We also added small handles so we could easily remove the molded silicon without breaking the mold itself.

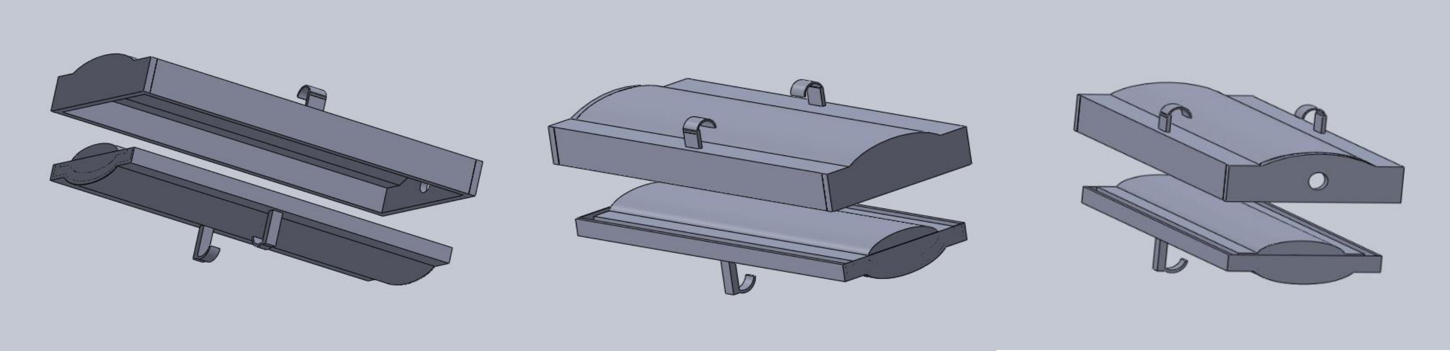


Figure 20: Third Iteration of Gel Mold

As mentioned in Section 2.2, over 60% of injuries are found at the extremities and abdomen. With the additions of the shoulder guards and hemostatic gel, the level of protection in those high-risk areas of the body is increased. The main functional requirements for these components was to add protection while not adding additional weight to the vest, which would inhibit the wearer's mobility. Our team believes a compressible shoulder guard design along with a kerf bending manufacturing technique, will allow zero limitations to an officer's range of mobility. The material we will use for the shoulder pads will add an additional layer of bullet prevention, or a layer to absorb most of the impact of the bullet. When selecting materials to use for our hemostatic gel container, we choose silicon because it is light weight, yet has a yield strength that will not allow fractures under normal stresses. We decided to mold the silicon with 3-D printed parts because of the accessibility our team had to the prototyping lab and the expense of printing and re-printing parts. Although the hemostatic gel does not prevent a GSW, it does prevent further complications such as extreme blood loss, which in major cases leads to death. Our team's Solidworks Models and dimensions for all iterations of our shoulder guards, hemostatic gel holder and gel mold can be found in Appendix D.

6.0 Testing Plan

To ensure the modifications made to the vest are beneficial, and not detrimental to the wearer, each modification was tested based on specific testing requirements outlined in their specific appendices. We ensured each aspect of the project satisfies their specific functional requirements. If for any reason the functional requirements were not met, we planned to make further adjustments until each of the requirements were satisfied.

6.1 Shoulder Pads

To determine if the shoulder pads created by the team have better design and functionality than the shoulder pads currently included on the Safariland ballistic vest, we performed tests to complete the weighted decision matrix in Appendix A. Collaborating with the WPI Police Department, we were able to determine which factors in the matrix they valued the most, and weighted the matrix accordingly. Because the ballistic vest and materials associated with it and other forms of protection are extremely heavy as it is, the shoulder pads should not add too much weight. One of the design criteria is that the shoulder pad should not exceed 5 pounds, and the lower this weight is, the more desired it will be for the purposes of this project. An effective shoulder pads allows for mobility of the arm in all three degrees of freedom that the shoulder exhibits; these motions are referred to as the Pitch, Yaw and Roll. A member of the team performed a workout designed by the team, which can be found in Appendix B. This workout includes stretches and other opportunities allowing the wearer to determine the mobility of each shoulder pad. The wearer then ranked the shoulder pads as they deemed fit. To test the strength, we planned both the Safariland shoulder pad and the team's created shoulder pad to undergo projectile testing. This was to help the team determine which shoulder pad could withstand the most direct force. The last test required is the durability testing. Durability in this case includes determining how long the shoulder pads will last. We planned to run a series of Tensile tests, to determine the strain of the product as the pressure is increased. We also wanted to run a corrosion tests, to determine if our product could fail from potential corrosion and how long it will take to fail. Additionally, we aimed to use fatigue tests to analyze how the product will degrade over time. The comfortability of the shoulder pads was determined by the wearer based on if they would feel comfortable wearing these shoulder pads for long term periods of five hours or more at a time. Due to the COVID-19 pandemic, the group was unable to perform the durability, tensile, fatigue, or corrosion tests for the shoulder pad design.

6.2 Hemostatic Gel

The purpose of hemostatic gel is to control external traumatic bleeding that cannot be treated with pressure or tourniquet application. With a severe injury, such as an arterial bleed, someone can bleed out as fast as twenty seconds after the injury. Because of this, it is important that the hemostatic gel can flow to the source of injury and engage with the wound to stop bleeding or slow it down within that twenty-second-time period. Hemostatic gel can only be sold to medical professionals and is extremely expensive to buy, selling at approximately $26 per 30 mL of gel. Due to its heavy expense, rather than buying and performing testing on hemostatic gel, we planned to complete our testing with hair gel, due to its similar consistency**.** To test how fast it will take the hemostatic gel to flow from its pouch in the vest to the surface of the human body, we must test a gel that has a similar viscosity. The Quick-Stat hemostatic gel is a hemostatic gel company widely used across the globe with a product that is highly viscous yet granular, allowing it to flow out of a syringe (ABOUT QUICKSTAT, (n.d)). We assumed that after someone gets shot, they will be lying down. To mimic this situation, we wanted to penetrate the silicon pouch that holds the hemostatic gel while held in a horizontal position, and test how long it would take to flow from the pouch to the surface of the human body. Due to the COVID-19 Pandemic, the group was unable to complete the hemostatic gel testing, but recommends future groups working on this project complete this testing to determine whether this feature is effective.

6.3 Silicon Hemostatic Gel Holder

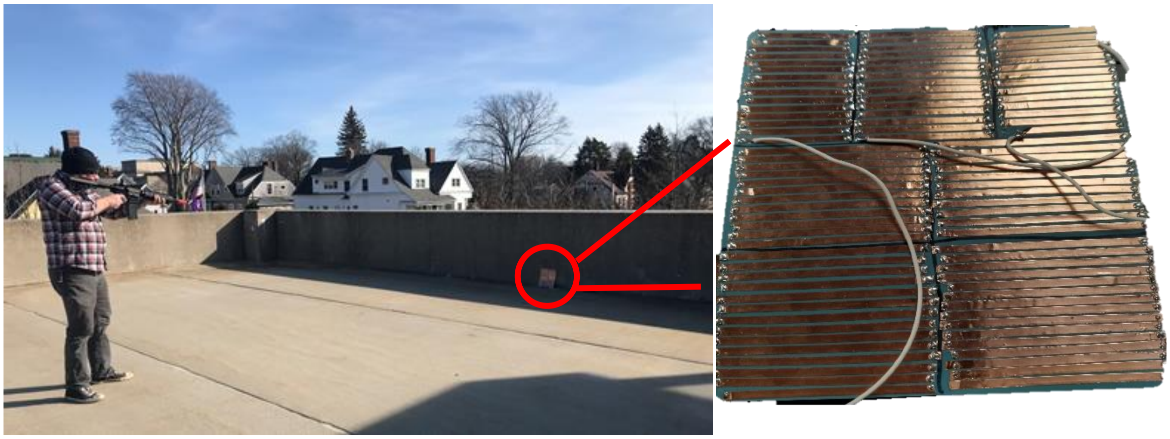
To ensure that the gel will only be released during a bullet impact, we tested the strength of gel holder. The gel holder should be strong enough that it does not break from mild impacts such as if you were punched or if you fell on the ground. However, a bullet should be able to puncture the holder, allowing the gel to flow into a wound. Once our silicon mold was formed, we ran a series of tests to ensure that our functional requirements listed in Table 2 were met for this product. After confirming that the mold could withstand a normal amount of stress, using ANSYS Workbench software, we planned to run rounds from handgun and rifles in order to test how the mold will act once shot with an actual bullet. We aimed to run the three rounds of simulation bullets: the first round from 20 yards, the second from 40 yards and the last from 60 yards.

6.4 Sensors

The first sensor that was tested was the impact detection sensor. With the help of the WPI Police Department, we planned to use both simulation airsoft bullets as well as real bullets from a shotgun. This sensor was tested first with 10 simulation rounds to each segment of the sensor at varying ranges in order to ensure that each portion of the sheet is working successfully, shown in

Figure 21. The first round of simulation bullets was taken from 20 yards from the vest, the next from 40 yards, and the last from 60 yards.

Figure 21: Simulation Rounds by WPI Police Department with the Impact Detection Sensor Highlighted on Right



To determine that the sensors were working properly, the group ensured the detected signal would go from a logic high value to a logic low value when the segment was hit with a round. Once the sensor design passed this test, the intention was to then move to test it with handgun and rifle rounds again with a test to each segment of the sheet from the varying ranges previously stated. The goal of this testing was to ensure that the sensor can determine when the vest has been pierced and that it would be able to detect a second impact to another segment after the initial impact. Unfortunately, due to the COVID-19 outbreak, the group was unable to complete the handgun and rifle rounds of testing for the sensors.

The GPS sensor testing was completed by comparing the created sensors to the GPS found by a cell phone and ensuring that they are within a predetermined range of each other. The heart rate sensor was tested with the comparison of the heart rate sensor to an electrode-based ECG in order to assure that there was no error between the electrical and optical signals. The sensors were then attached to a person at rest and while working out**.** Testing at both times ensured that the sensor was able to read normal and stressed heart rates and determined that the signal is detected only with an abnormal heart rate as desired. An abnormal heart rate includes one that is too fast (tachycardia), too slow (bradycardia), or has abnormal peaks. The procedures to obtain the recorded signals are documented in Appendix C**.**

Although the group ran into many setbacks in testing the final product due to COVID-19, the group was able to create a successful testing plan. Before the pandemic, the group was able to test the impact detection sensors using simulation rounds with the help of the WPI Police Department; testing of the GPS and heart rate sensors was also successful. Additionally, the group completed testing of the hemostatic gel holder and shoulder pads using an online analysis tool called ANSYS. With more time and resources, the group could have completed testing of the impact detection sensors as well as the shoulder pads with projectile testing, which would have allowed us to make improvements with the modifications as deemed necessary. Next, we will discuss the results and analysis of the testing the group was able to complete.

7.0 Results and Analysis

As previously mentioned, there were several tests that our team was unable to complete due to the COVID-19 pandemic. However, we were still able to produce efficient test results through our simulation and ANSYS testing. All ANSYS boundary conditions for testing and those results can be found in Appendix E.

7.1 Silicon Hemostatic Gel Holder

One of the functional requirements for the hemostatic gel holder was to be able to withstand a certain amount of stress. The only case where these silicon tubes should be broken, is when the vest is pierced and resulted in a flesh wound. These tubes should not break from small stressed such as, dropping the vest on the floor or falling while wearing the vest. In order to replicate this and to prove it can withstand those stresses, we needed to perform an impact drop test. It is important to represent the force acting onto the tube as a uniform load in order to replicate this test accurately. To represent a uniform distribution of force onto the tube, we fixed two solid plates onto the tube. Then we added a force of 1000N to act on each plate in opposite directions of one another. We assumed that 1000N would be the maximum force the vest would experience if it were dropped or if the officer fell while wearing the vest because 1000N is about the weight of an average male times the force of gravity. Then we measured the equivalent stress our design can withstand, which is $1.6326 \times 10^3\ psi$, and the total deformation it can experience, which is $2.6801 \times 10^{-3}\ in$.

7.2 Shoulder Pads

As mentioned in previous sections, kerf bending is the manufacturing process that consists of laser cutting a specific pattern into a material that will add flexible properties to that material. However, the flexibility properties of a kerf bending pattern can be different depending on the distance between each individual cuts. For this project, it was important to determine the optimal distance of our kerf bending pattern, Figure 22 shows our kerf bending pattern, indicating the distance we will be modifying Δx. We analyzed the maximum deformation and stress at four different Δx values. Figure 23 shows the relationship of each case between Δx and

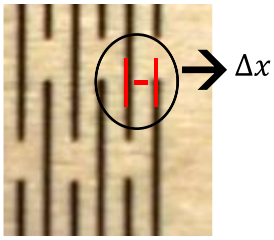


Figure 22: Kerf Bending Pattern labeling the distance we will be modifying

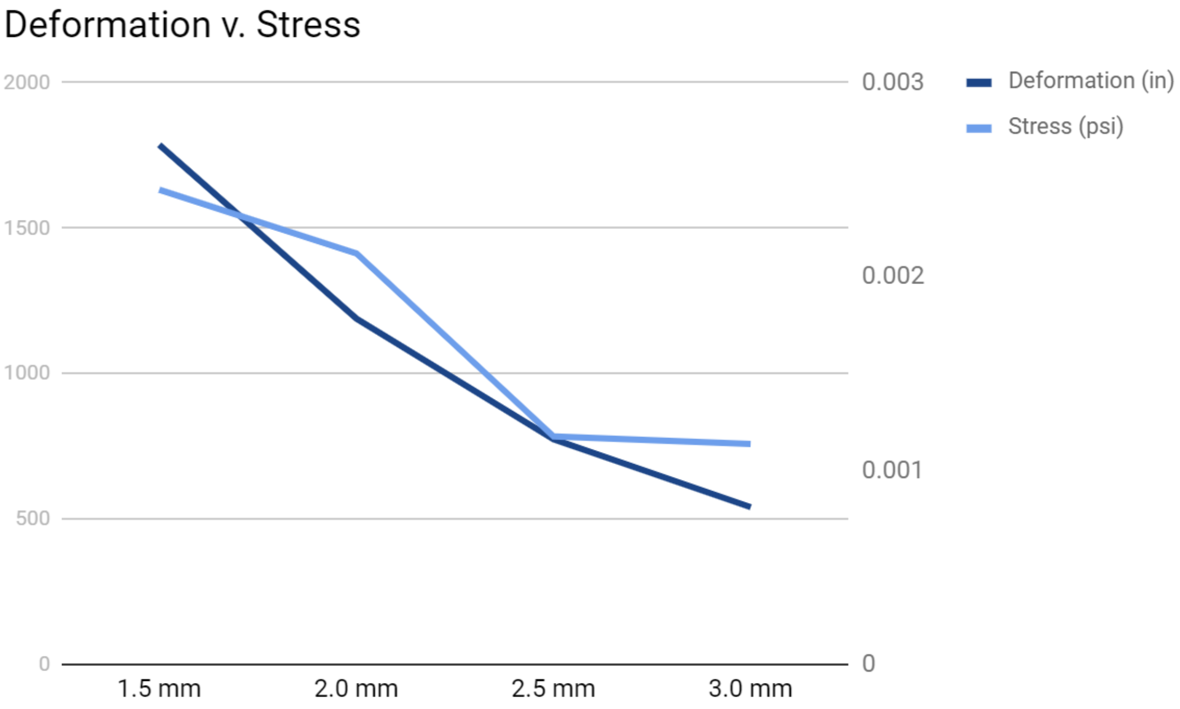


Figure 23: Relationship between the Deformation and Stress at Each Kerf Bending Distance

the deformation and stress. For these simulation rounds, Birch Tree Wood was the selected material because that was the material used for initial prototyping.

After analyzing our results, our team discovered that as the distance between two lines of the pattern decreased, the maximum deformation of the material increased. However, before we can declare the smallest distance as the optimal one, we needed to analyze the trend of maximum stress. As the distance between the two lines decreased, the maximum stress that the material can withstand increased. Hence, the optimal distance for this kerf bending pattern is 1.5mm, shown in Case 4.

Next, we needed to determine the optimal material for this application that can withstand the most deformation and stress. Our team analyzed three materials, Titanium, Aluminum and Stainless Steel. We selected these materials based on the applicability of the laser cutter that WPI has in its facilities. Then we tested the deformation and stress of each case, the results shown in Figure 24.

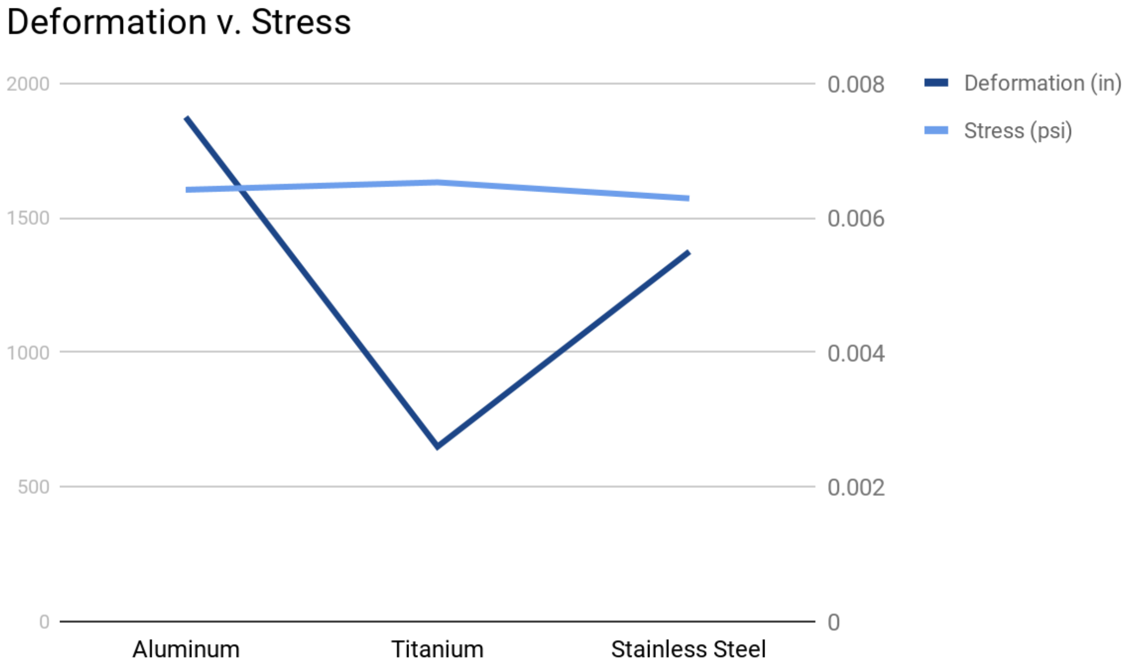


Figure 24: Relationship between the Deformation and Stress of Different Materials

From the ANSYS Workbench Analysis, our team found that the aluminum alloy would experience the most deformation with this kerf bending pattern cut into it. However, the stainless-steel material would experience the most amount of stress before fracture at 1,632.5 psi. Due to the similarity between the stress results of the stainless steel and aluminum alloy, our team decided that aluminum alloy would be the ideal material to use for this situation. Due to the COVID-19 outbreak, our team was unable to prototype the shoulder pads with this optimal material.

7.3 Sensors

While they did not receive all the expected testing, most of the sensor designs were tested to the point where reasonable results could be taken from the testing. Both the GPS and heart rate sensor received full testing individually but not applied with the rest of the system and the impact detection sensor only received simulation testing.

7.3.1 GPS Sensor

The main functional requirement of the GPS sensor was to acquire a location with an accuracy of 10 meters. This testing was done by making comparisons with a phone GPS with approximately 3-meter accuracy. Table 4, shown below, shows some of the data points. The total distance was calculated by calculation the difference of the latitude and longitude and then using these numbers to calculate the total difference in distance.

Table 4: GPS Data

Location Name	GPS Lat	GPS Long	Phone Lat	Phone Long	Distance Difference (Meters)
East Hall Garage	42.273659	-71.804389	42.273605	-71.804407	6.19128248
AK 219	42.275479	-71.807169	42.275473	-71.807153	1.477029653
CC Hagglund Room	42.274592	-71.808372	42.274651	-71.808355	6.715375186
Foisie Makerspace	42.274211	-71.808791	42.274207	-71.808837	3.813562912

The requirement for difference in distance is below in all these locations and the highest it reaches is even below 7.0 meters making it meet the functional requirements set out for the sensor.

7.3.2 Heart Rate Sensor

The main requirement of the heart rate sensor was that it was able to accurately able to detect heart signals. Unfortunately, there are only results for the filtered signal and no results for the unfiltered signal so its cannot be seen if it correctly collects any signal other than heart rate. The heart rate data was collected in 3 different situations and the results are featured in Table 5.

Table 5: Heart Rate Data

	Phone (BPM)	Sensor (BPM)	%
Resting	96	89	7.8652
15 Jumping Jacks	124	119	4.2017
Running 1/2 Mile	162	156	3.8462

This sensor data turned out to average at around 5.0 % less than the data that was found on the phone. Through analysis of the sampled data it was found that this was because the sensor would fail to detect some heart beats because the voltage peak did not reach the threshold. This could be fixed with some small changes to voltage applied to the sensor and how it is attached to the body. This sensor is still within an acceptable range for heart rate detection even with this issue. There was also an issue with the fact that the sensor overheated which could have been fixed by a change in LEDs and resistors in the optical sensor.

7.3.3 Bullet Impact Detection Sensor

This sensor's main functional requirement was to accurately detect when the vest has been pierced. While this function was not fully tested, it was found that after being shot with the simulation rounds, all the zones that had been pierced by the bullet were reported back to the microcontroller as pierce, shown in Figure 25. This testing was done without live data, so it is unclear if the data was communicated immediately when the matrix was broken but highly likely. These results did yield a small issue with the matrix wiring bending which was fixed in the next iteration under real fire or with live data.

Figure 25: Bullet Impact Detection Sensor After Tested with Air Bullets

This section described the results and analysis of the testing the group was able to complete this academic year before the COVID-19 pandemic. After testing per the group's recorded testing plan, each modification was analyzed keeping its specific functional requirements in mind. The group used ANSYS testing for many of the project components; the boundary conditions and results for this method of online testing can be found in Appendix E. After online modeling and in person testing was completed to the group's best ability in the given conditions, we were able to generate conclusions using our results. In the next section, the group will define the outcome of this project, the changes and improvements that were made to the Safariland tactical vest, and improvements that could be made in the future to continue on this project.

8.0 Conclusion

Every solider and officer that steps out of their door to go to work is signing up to risk their lives to protect someone else. Tremendous strength and bravery can’t even describe what their sacrifice means. They risk so much to protect this country and yet when they do so, they are not properly protected. For all that these men and women do for us, it is our duty that we give back to them and keep them safe too. Because of this, our group aimed to improve the safety and overall effectiveness of the current protective vest used by officers on the field, such as the Worcester Polytechnic Institute Police Department. To do so, we created modifications to the current vest that included covering previously unprotected areas, adding sensors to track the officer’s location and vital signs, and a hemostatic gel to slow down or event prevent the officer from bleeding out from an external injury.

This project has shown that there are multiple ways that we can adjust the current ballistic vests, to increase the level of protection it can offer. As mentioned in previous sections, most ballistic vests are only bullet resist which means that the vest lessens the impact of a bullet but cannot prevent the bullet from piercing through a person. You could always add a thick layer of steel, or other strong metal, to prevent the impact of a bullet, but you cannot expect the wearer to experience their maximum level of mobility, strength, and endurance. Our goal was to find ways to protect these heroes without increasing the current weight of the vest and without decreasing their mobility.

The first major improvement to the vest was the addition of smart technology. The use of smart technology can increase the survival rate of these officers by being able to locate the officer and send help if necessary. After discussing the use of GPS with the WPI police department, this idea seemed unfavorable because it has the potential to be intrusive on an officer's privacy. In order to still incorporate a GPS sensor into our design, our team determined a series of cases that must happen for the GPS sensor to send an officer's location to their base. This includes a layer of sensors that can sense if the vest has been pierced, which would assume a gunshot or stab wound. Another case that could set off the location is if the wearer is experiencing heart rates that indicate blood loss or excessive activity, to indicate the wearer is running away or engaged in combat. Our testing concluded that our GPS sensor displayed an accurate location with a tolerance of +/- 10 meters, which is accurate enough to still locate someone at the scene. Unfortunately, we were unable to test this sensor design with real bullets, however we were able to test this design using air bullets and were able to successfully determine if the vest had been pierced. Lastly, our team developed a heart rate sensor that was able to sense the heart rate of the wearer. This sensor successfully sensed an accurate heart rate; however, it had some complications because the sensor would heat up. Unfortunately, our team could not figure out why this complication occurred.

Another important part of our project was to add a layer of hemostatic gel to the vest. The function of this gel is to enter and cauterize a wound. This decreases the chances of a gunshot victim from bleeding out and allows more time to get medical attention. Our team found that the best way to store this gel on the vest was to create small, individual pouches that are a few inches long. Silicon was chosen has the best material for this function due to it being light weight and able to withstand normal stresses without fracture. We chose to create this silicon piece by molding liquid silicon with a 3D printed part. Several iterations were made to this mold with intentions to allow the silicone to harden without sticking to the 3D part. Although our team was unable to test the final iteration of the gel mold part, we believed it was the best way to create the silicon mold.

And lastly, our team wanted to the increase the area of protection about the vest wearer’s body. Our goal was to add a lightweight set of shoulder pads that would not limit the movement of one’s shoulders. Our final shoulder pad design was composed of multiple pieces that was able to compress and expand as the wearer moved their shoulder up and down. This design also included a manufacturing technique called kerf bending to increase the flexibility of these shoulder pads. After proper analysis, we determined the ideal kerf bending pattern for maximum flexibility and the optimal material based on the capabilities of current WPI technology.

Overall, the team was able to add improvements to the current ballistic vest, making it safer and smarter for those risking their lives on the front lines. Although the team was unable to complete manufacturing and testing due to the COVID-19 outbreak, they have provided future improvements that could make this protective vest even more secure. With further materials and manufacturing research and investigation, this protective vest can be enhanced for more protection and smarter technologies. While this project was intended to help police officers on the front lines, this technology can be further implemented with all first responders, servicemen and servicewomen across the globe.

9.0 Future Recommendations

This project had the opportunity to become an extremely vital tool in our defense operations. We were successful in adding several components to the bullet proof vest to make it more efficient in emergency situations. Because of the COVID-19 outbreak, classes at WPI were adapted remotely for the final term of the year from March to May. Due to this unexpected change, the team was unable to complete the manufacturing and testing of the components of the entire project. While reflecting upon the components of the project that remained unfinished, the group has identified further work that can be completely to increase the validity of this project

First, the team was able to create a prototype of the shoulder pads using kerf bending machinery and wood material as seen below. The team recommends using a very similar design as to this one, however using a material with more durability and bullet resistance, yet can also be manipulated to this shape, such as steel. Because the design created for the shoulder pads includes kerf bending to obtain the desired flexibility, it is important to test different materials with kerf bending analysis to determine the best material for this application. Additionally, our group discovered that when attaching the separate pieces, the material was too brittle, and would therefore crack during the manufacturing of the part. Because of this, the manufacturability should be discussed and improved upon to determine the best method to create the pieces that make up the final shoulder pads, shown in Figure 26.

Figure 26: Completed Shoulder Pad Manufactured with Wood

Additionally, the team was unable to model the flow of hemostatic gel within its hemostatic gel pouch. By using ANSYS modeling technologies and effectively modeling the gel within the pouch, future groups will be able to better understand the stresses the hemostatic gel pouches can withstand before bursting. With this modeling, future groups can best model the material to use for the hemostatic gel holder in order to pick the material that can withstand great forces while releasing hemostatic gel, allowing it to flow from the vest to the body, and hopefully save the wearer. Also, because the team struggled greatly with choosing the correct material and design to mold the hemostatic gel holder, it could be very beneficial to future teams to do further research to determine the best practices for molding the hemostatic gel pouches. Lastly, because our group was extremely focused on the beneficial additions to be made to the protective vest, we ignored the feasibility of adding additional weight to the vest. With each component added weight to an already labor-intensive job. Because of this, the team recommends future iterations of this project research the feasibility of both making lighter weight additions as well as the feasibility of using a lighter weight vest. If this is possible, not only will the men and women that serve our country be better protected, but also better equipped for the intense situations they will inevitably face.

Appendix A
Shoulder Pad Weighted Design Matrix

Evaluation Criteria	Safariland Shoulder Pad		MQP Design	
5 – high 1 – low	Ranking	Weighted	Ranking	Weighted
Light Weight	3	3	5	5
Range of Motion	4	12	3	9
Strength	4	8	2	4
Durability	4	8	3	6
Comfortability	3	2	1	1
Total Score		33		25

Appendix B
Shoulder Mobility Workout

1. **Posterior Capsule Pails and Rails:** Improves internal rotation
2. **Prone Lift Offs:** Provides significant stimulus to build upper back strength while increasing flexibility
3. **Crab Sliders:** Improves shoulder extension
4. **Scapula Cars While Hanging:** Improves mobility and muscle control
5. **Supine Raises:** Improves shoulder flexion and extern rotation
6. **Overhead Opener:** Improves overhead mobility and maximizes thoracic extension
7. **Downward Dog:** Activates the serratus anterior to work on this scapula motion as well as mobilize the thoracic spine
8. **Bench Thoracic Spine Mobilization:** Stretches shoulders and thoracic spine

For a demonstration of each of these workouts: https://thebarbellphysio.com/8-best-drills-unlock-shoulder-mobility/

Appendix C
GPS and Heart Rate Sensor Testing Procedures

GPS Testing procedure:

1. Turn location services "on" phone
2. Attach GPS sensor on to power source to turn it on
3. Compare signal from phone with signal on vest and note results below:

   ____

   ____

   ____

   ____

HEART RATE:

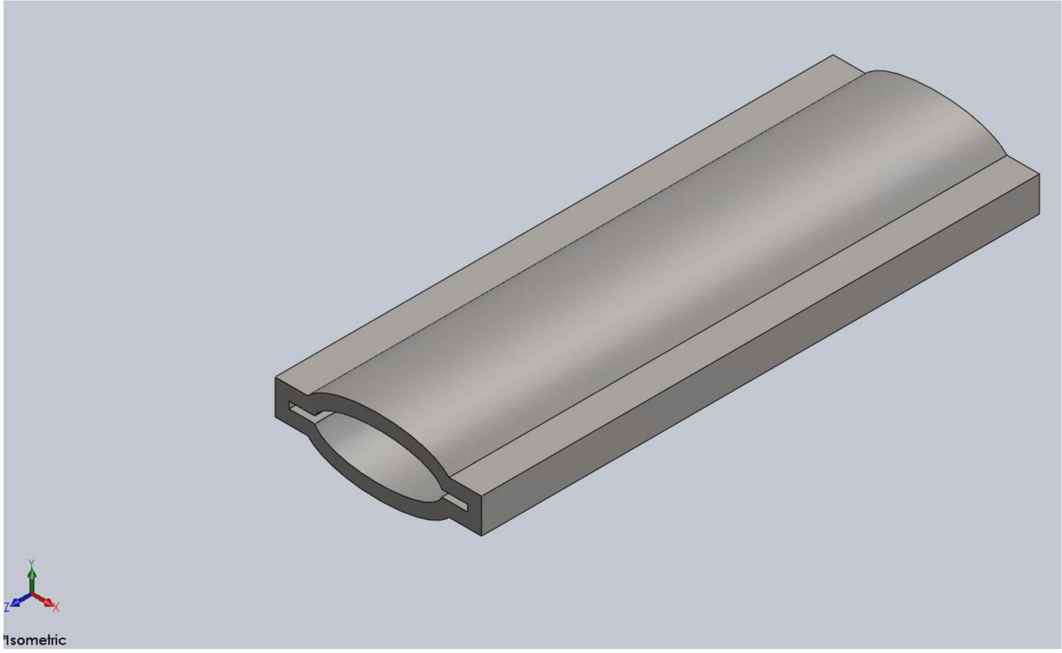
1. At Rest:
   a. Is there a signal sent to command? ______________________
      (Anticipated response is no signal)
   b. Include picture of signal:

2. Working Out:
   a. Is there a signal sent to command? ______________________
      (Anticipated response is stress signal from tachycardia)
   b. Include picture of signal:

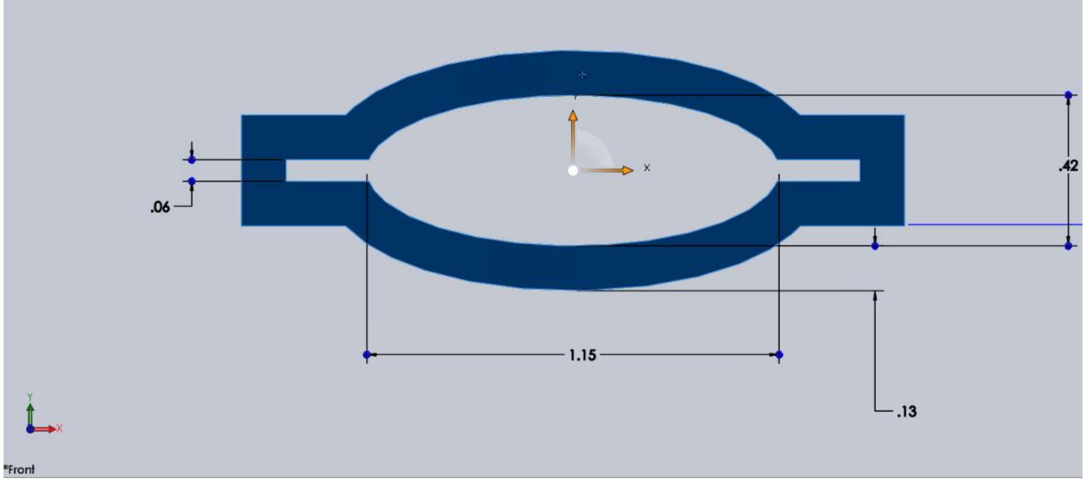
Appendix D
SolidWorks CAD Models

Hemostatic Gel Holder

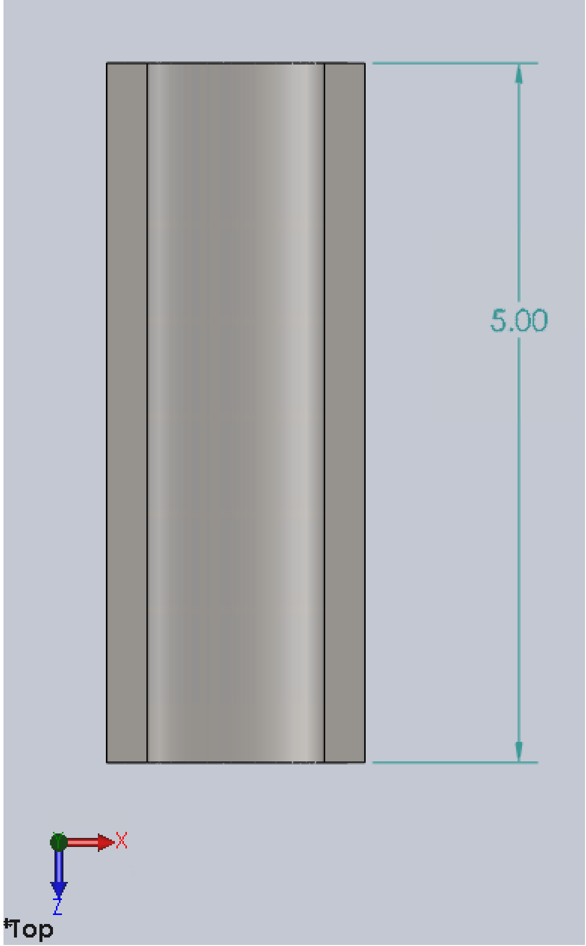
The figure below shows the individual hemostatic gel tube in the Isometric view.



This figure below shows the individual hemostatic gel tube in the Front view with its dimensions displayed.



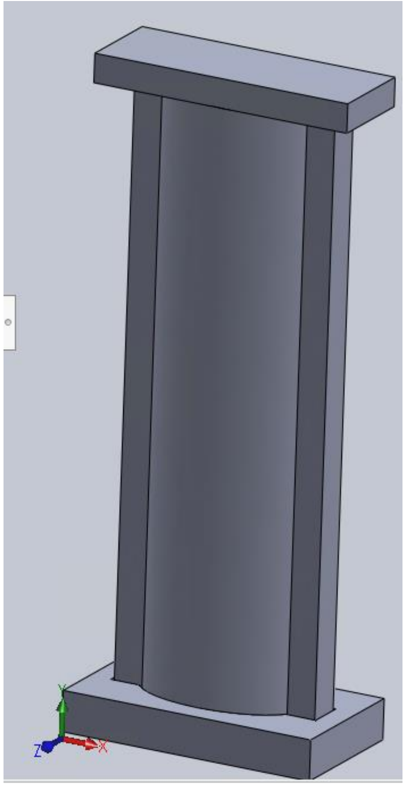
The figure below shows the individual hemostatic gel tube in the Top view with its dimensions displayed.



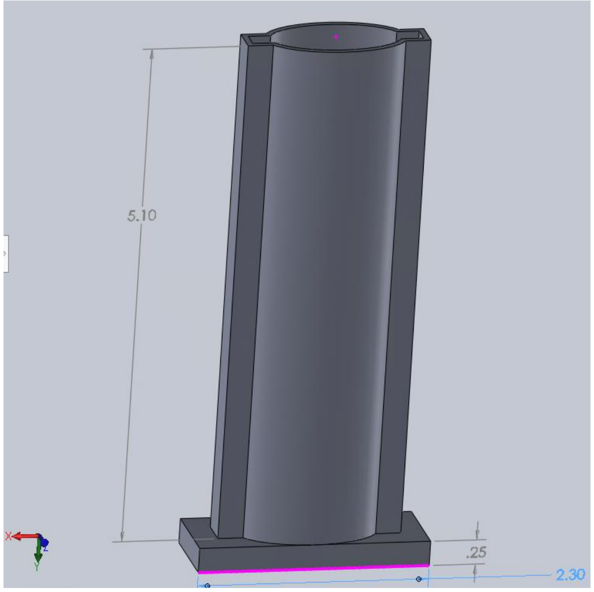
Hemostatic Gel Mold Iterations

Iteration 1

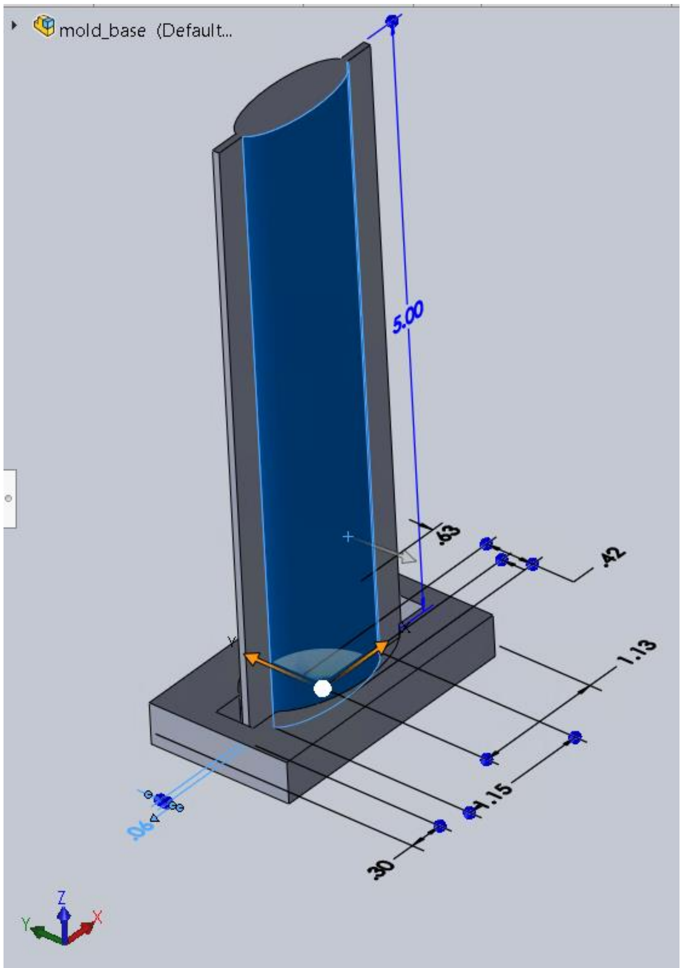
The figure below shows the first iteration of the hemostatic gel mold in the Isometric View.



The figure below shows the bottom part of the mold with its dimensions displayed.

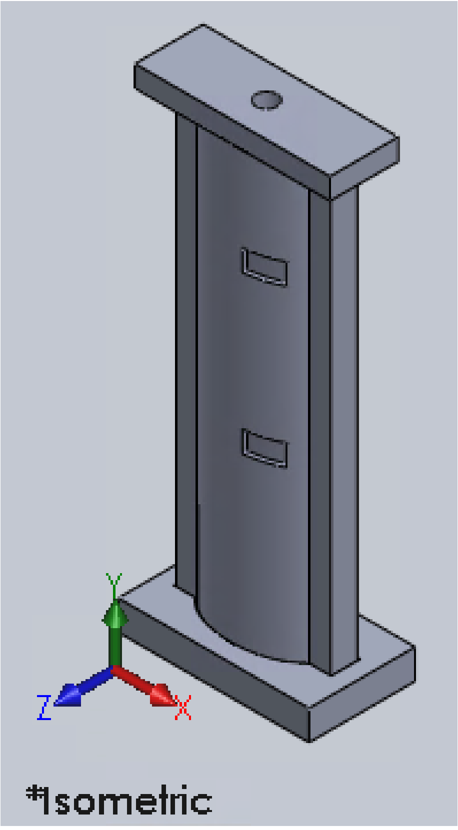


The figure below shows the top part of the mold with its dimensions displayed.

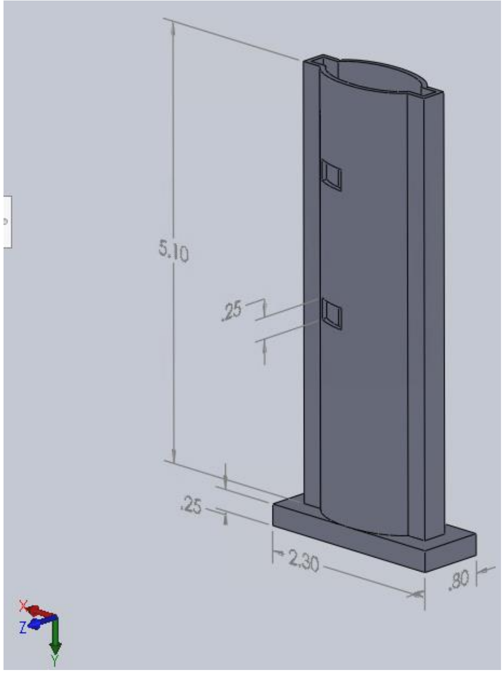


Iteration 2

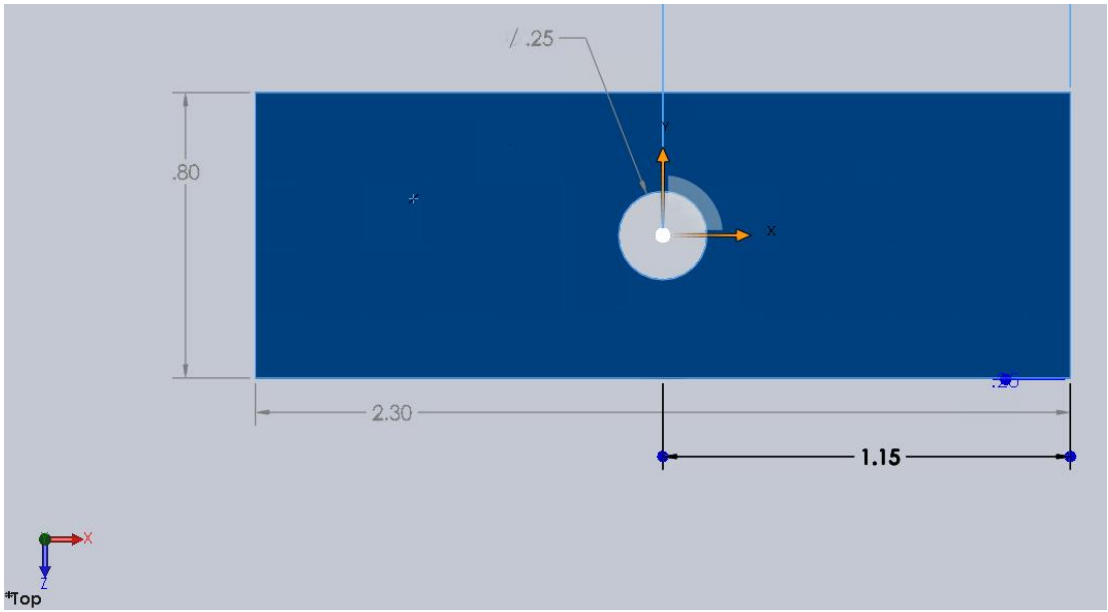
The figure below shows the second iteration of the hemostatic gel mold in the Isometric View.



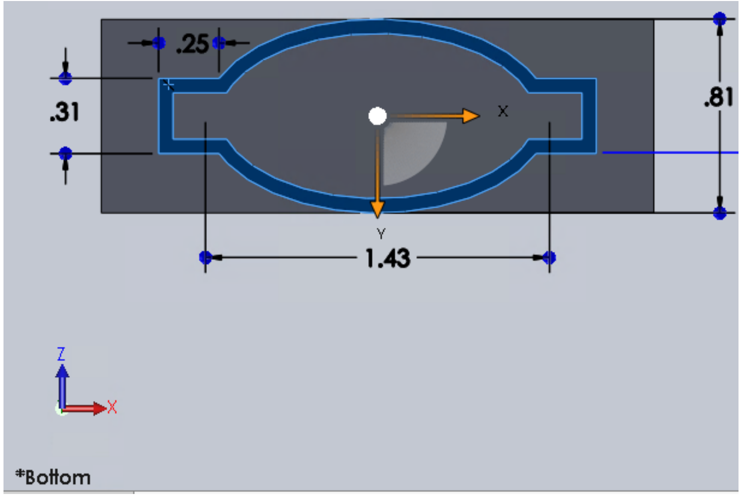
The figure below shows the bottom part of the mold with its dimensions displayed.



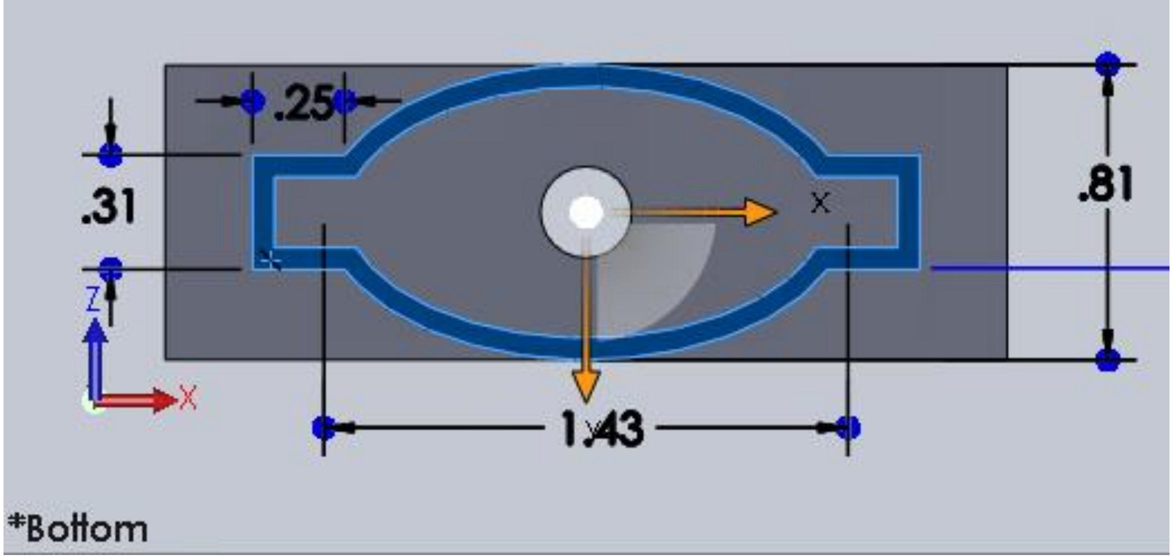
The figure below shows the bottom part of the mold with its dimensions displayed in the Bottom View.



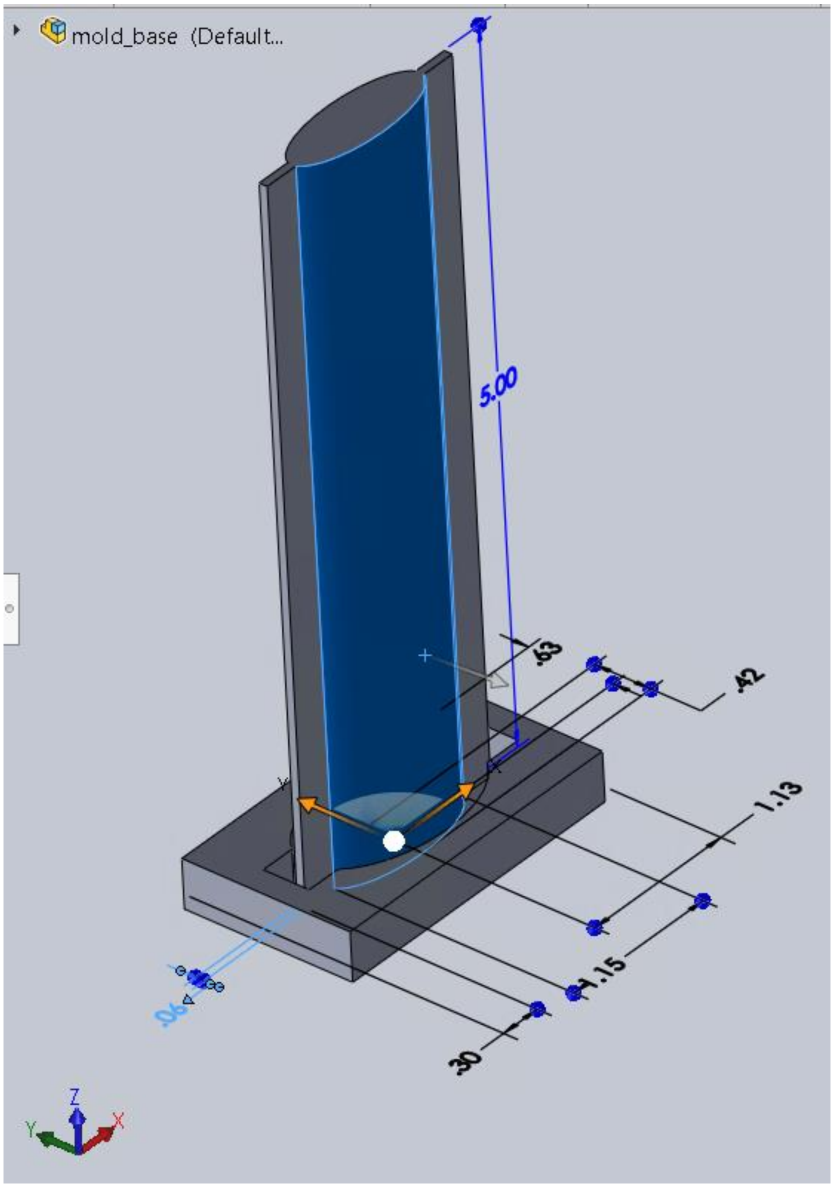
The figure below shows the top part of the mold with its dimensions displayed in the Top View.



The figure below shows the Bottom View of the top part of the mold with its dimensions displayed.

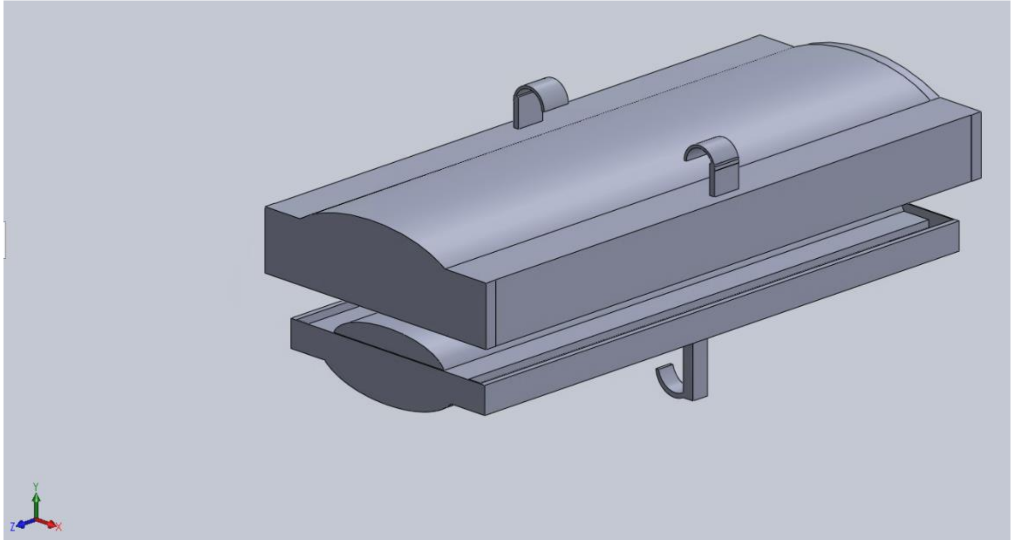


The figure below shows the Top part of the mold with its dimensions displayed.

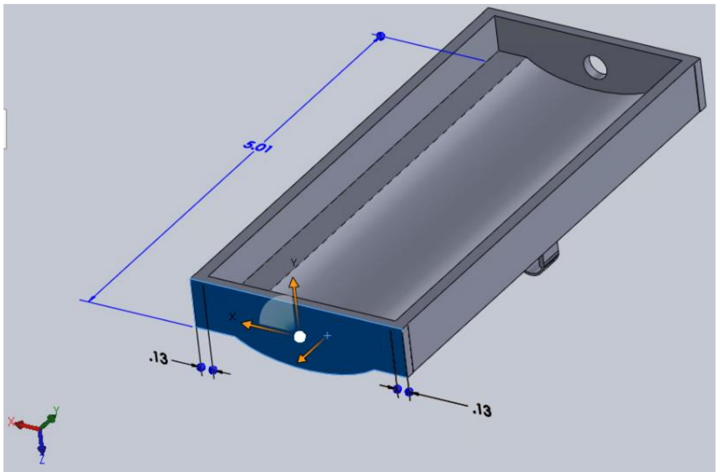


Iteration 3

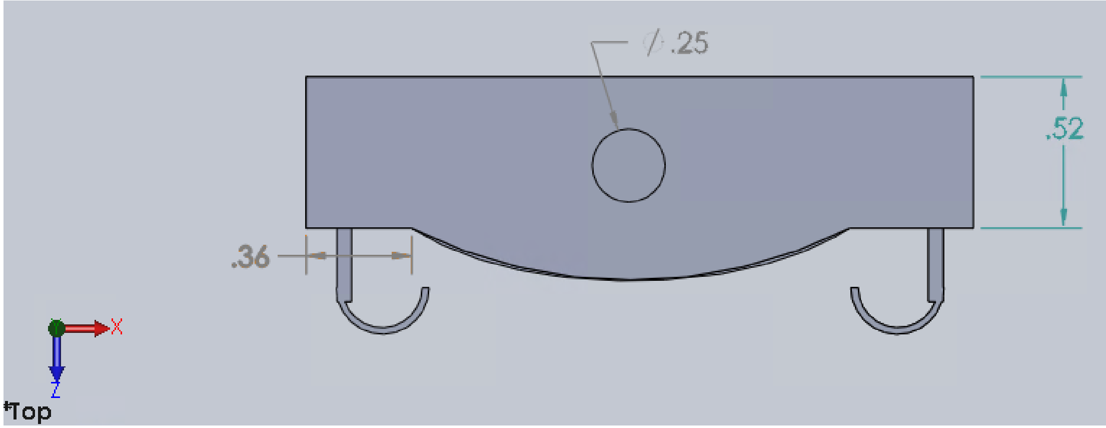
The figure below shows the third iteration of the hemostatic gel mold in the Isometric view.



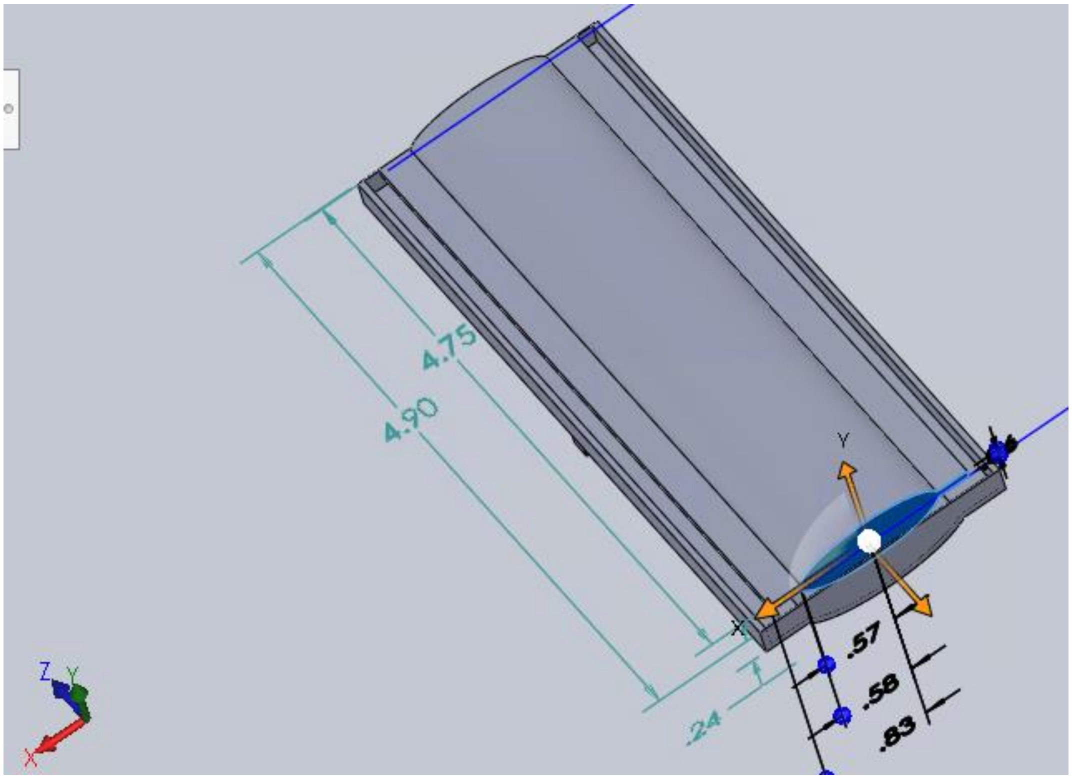
The figure below shows the top part of this mold with its dimensions displayed.



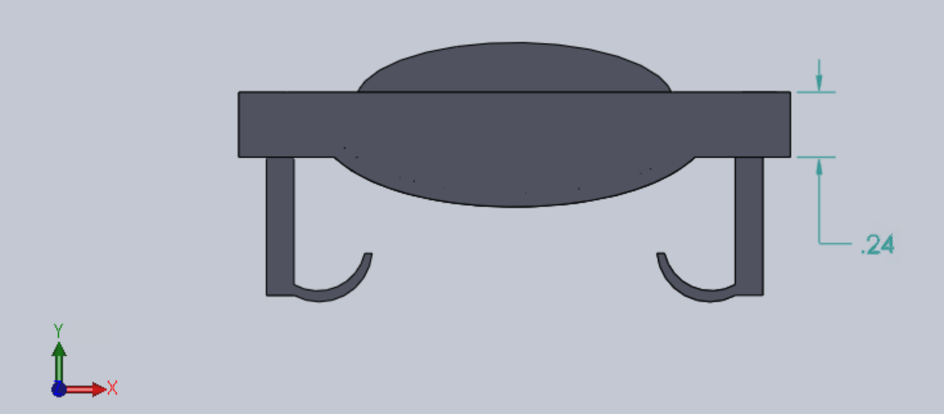
The figure below shows the top part of this mold in the Front view with its dimensions displayed.



The figure below shows the bottom part of this mold with its dimensions displayed.

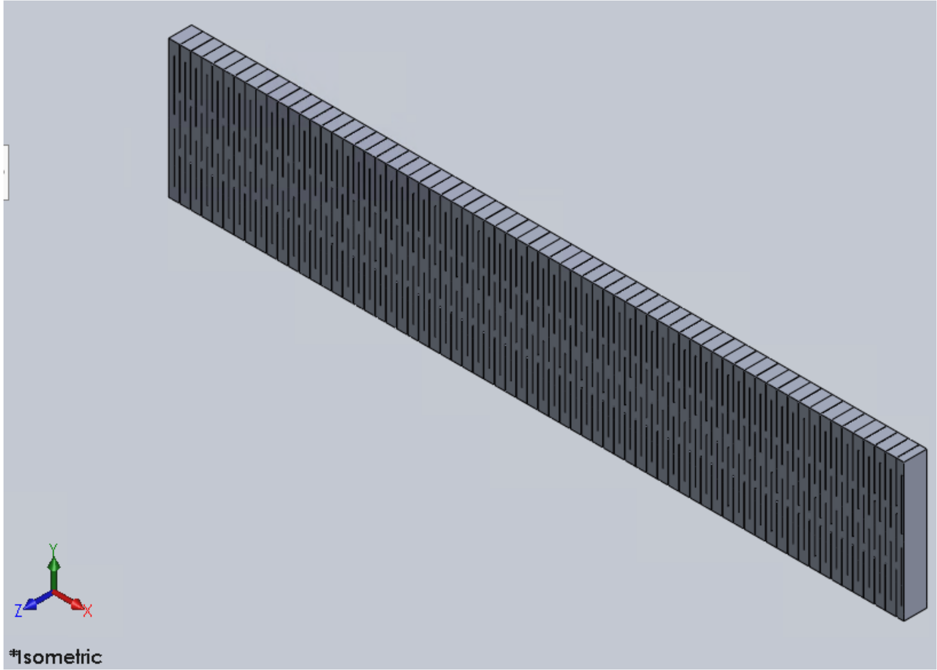


The figure below shows the bottom part of this mold in the Top view with its dimensions displayed.

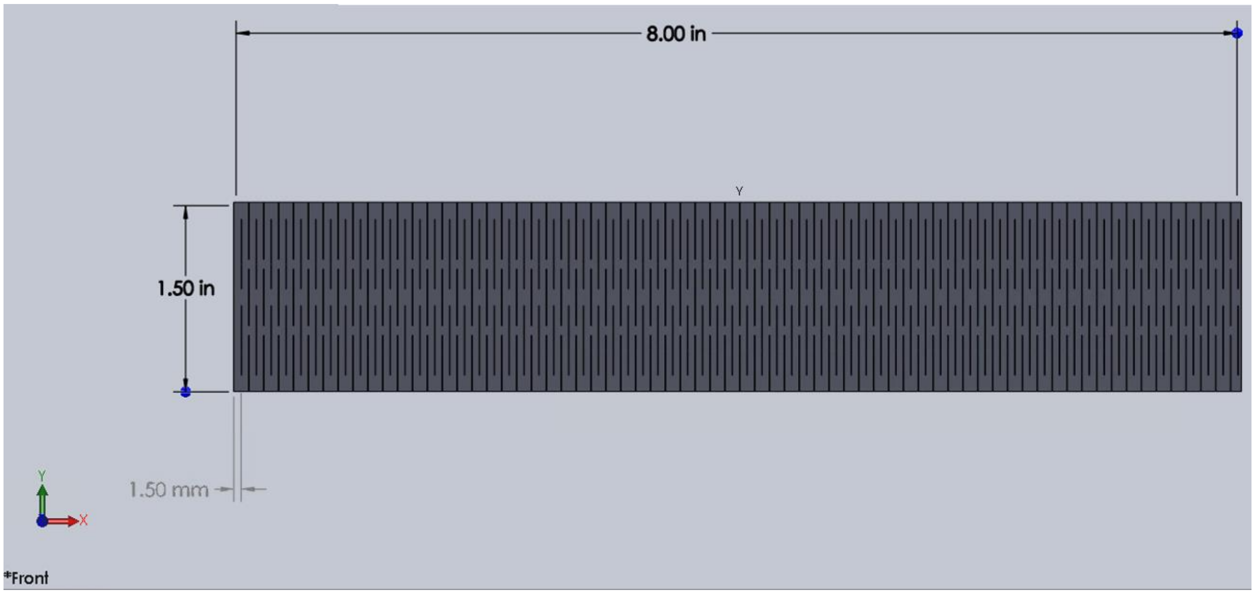


Kerf Bended Parts

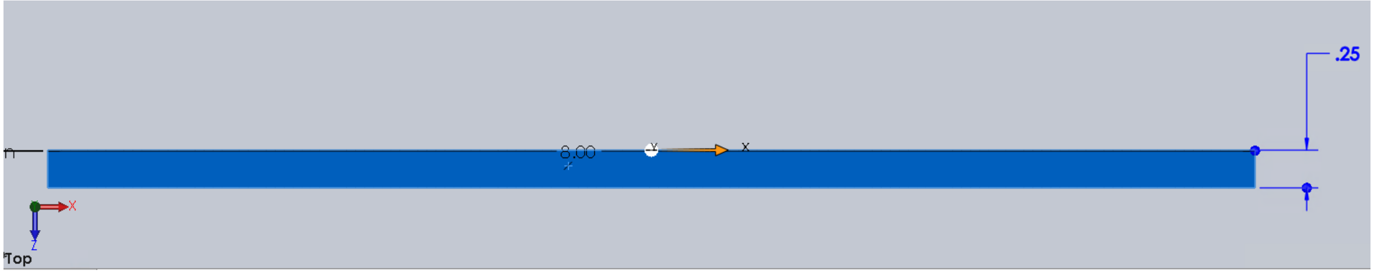
The figure below shows the optimal kerf bended piece in the Isometric View.



The figure below shows the kerf bended piece in the Front View with its dimensions displayed.



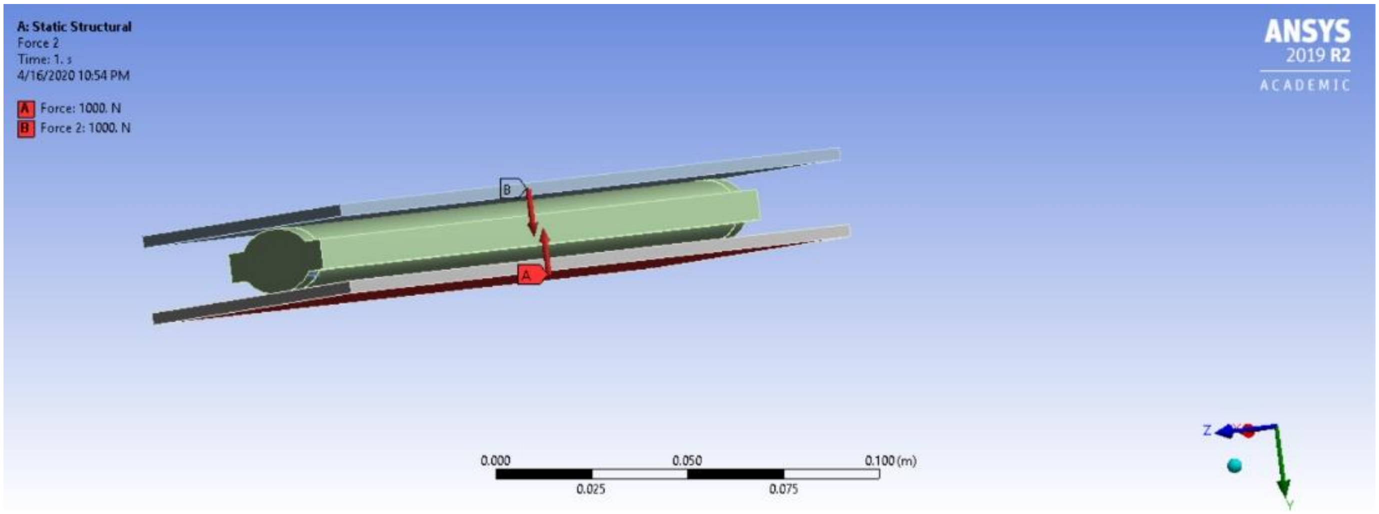
The figure below shows the kerf bended piece in the Top View with its dimensions displayed.



Appendix E
ANSYS Workbench Boundary Conditions and Results

Impact Drop Test Simulation

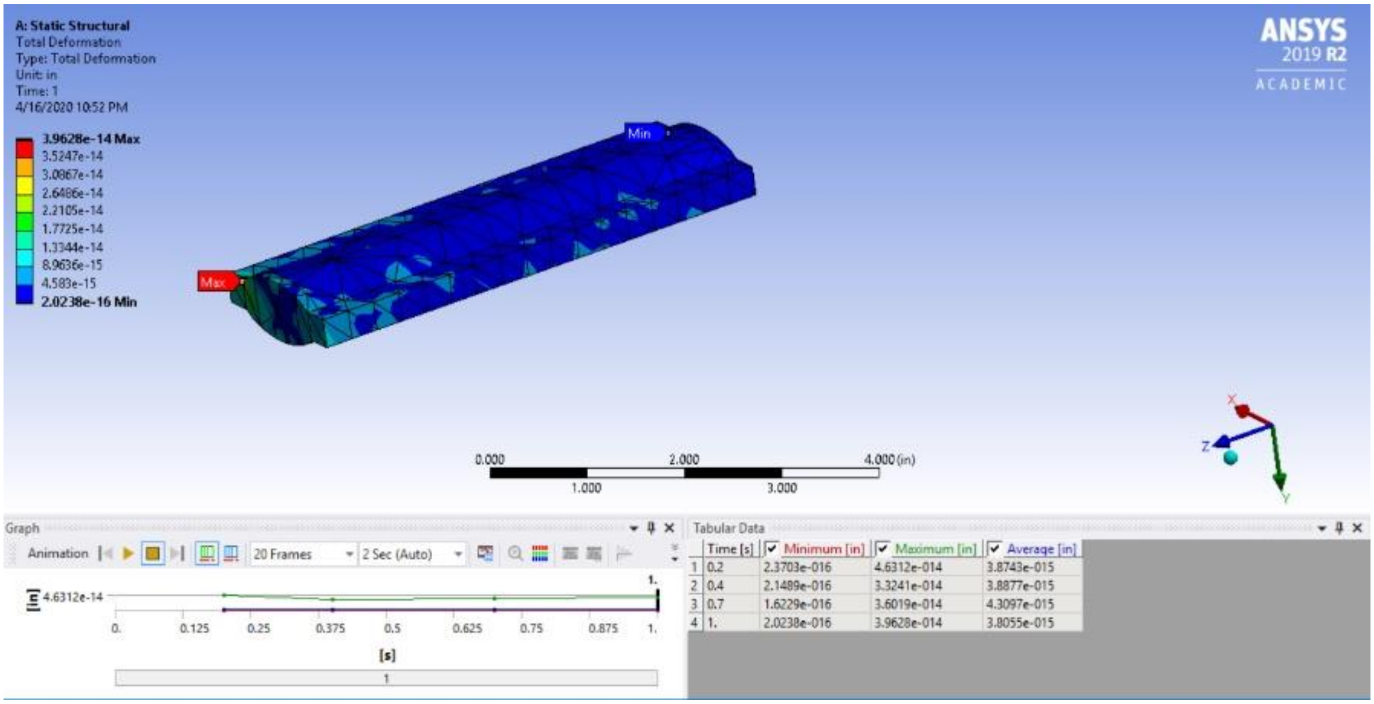
Physical ANSYS Representation of how the Impact Drop Test was Simulated. The figures\ below show the boundary conditions that our team set for these simulations. Two steel plates are fixed in place to represent the officer’s body and the ground. This ensures that there is a uniformly distributed force along the tube. Two forces are also shown in the figure acting on the tube where $F_1 = 1000\ N\ and\ F_2 = 1000\ N$.



A: Static Structural
Force 2
Time: 1. s
4/16/2020 10:54 PM

A Force: 1000. N
B Force 2: 1000. N

This figure shows the total deformation that the silicone gel tube experiences during the impact drop test. The locations where the tube experiences the maximum and minimum deformation is indicated from the figure.

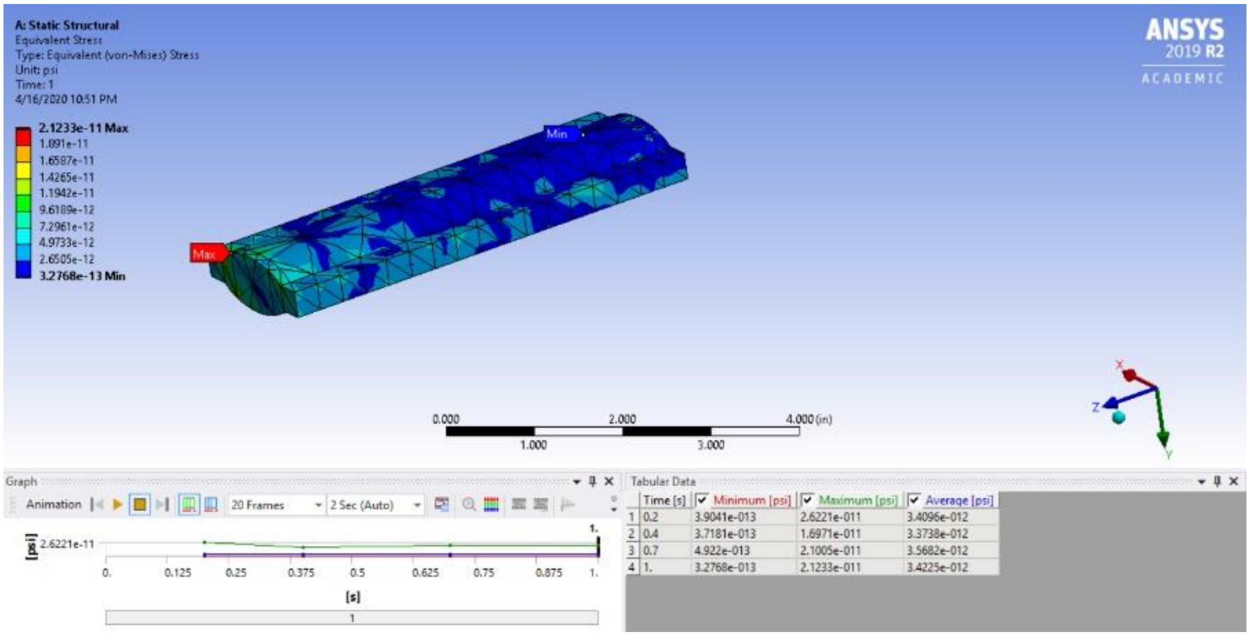


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: in
Time: 1
4/16/2020 10:52 PM

Tabular Data

	Time [s]	☑ Minimum [in]	☑ Maximum [in]	☑ Average [in]
1	0.2	2.3703e-016	4.6312e-014	3.8743e-015
2	0.4	2.1489e-016	3.3241e-014	3.8877e-015
3	0.7	1.6229e-016	3.6019e-014	4.3097e-015
4	1.	2.0238e-016	3.9628e-014	3.8055e-015

This figure shows the total stress that the silicone gel tube experiences during the impact drop test. The locations where the tube experiences the maximum and minimum stress is indicated from the figure.



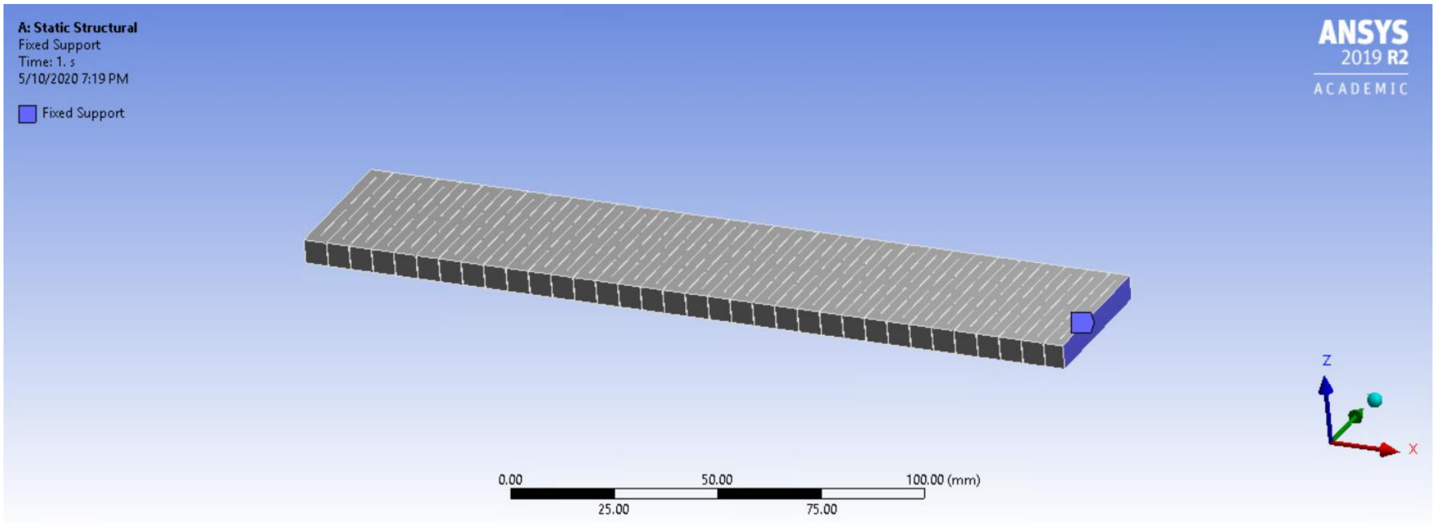
A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
4/16/2020 10:51 PM

Tabular Data

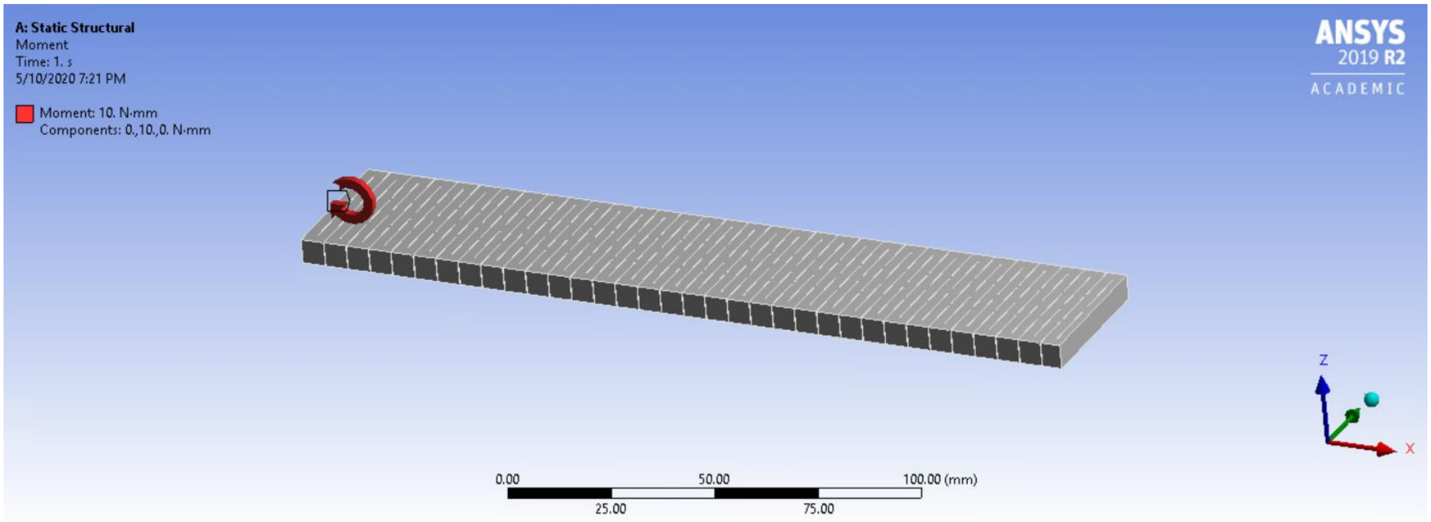
	Time [s]	☑ Minimum [psi]	☑ Maximum [psi]	☑ Average [psi]
1	0.2	3.9041e-013	2.6221e-011	3.4096e-012
2	0.4	3.7181e-013	1.6971e-011	3.3738e-012
3	0.7	4.922e-013	2.1005e-011	3.5682e-012
4	1.	3.2768e-013	2.1233e-011	3.4225e-012

Kerf Bending Simulations

This round of simulations measures the deformation and stress that the individual kerf bended should pad part experiences. The figures below show the boundary conditions that our team set for these simulations. This figure highlights the part of the kerf bended part that we fixed in place.



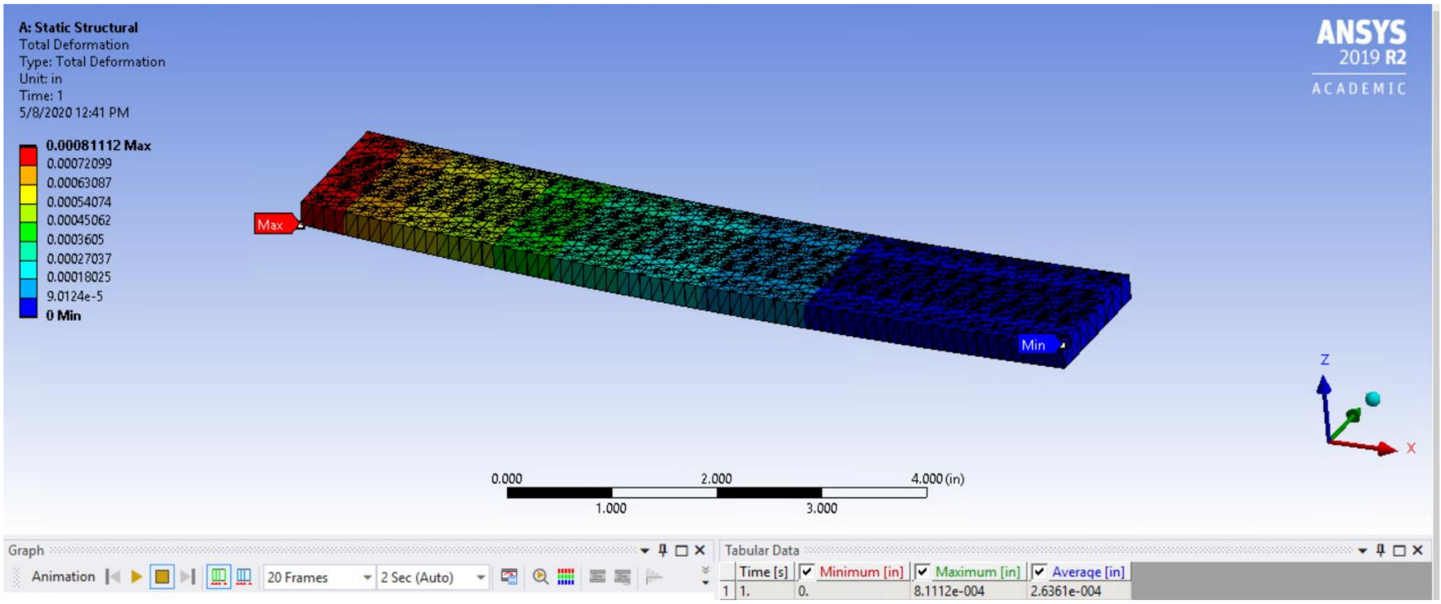
This figure shows where the moment acts on the shoulder pad part, where $M = 10\ N \cdot mm$



Testing Different Distances

Case 1

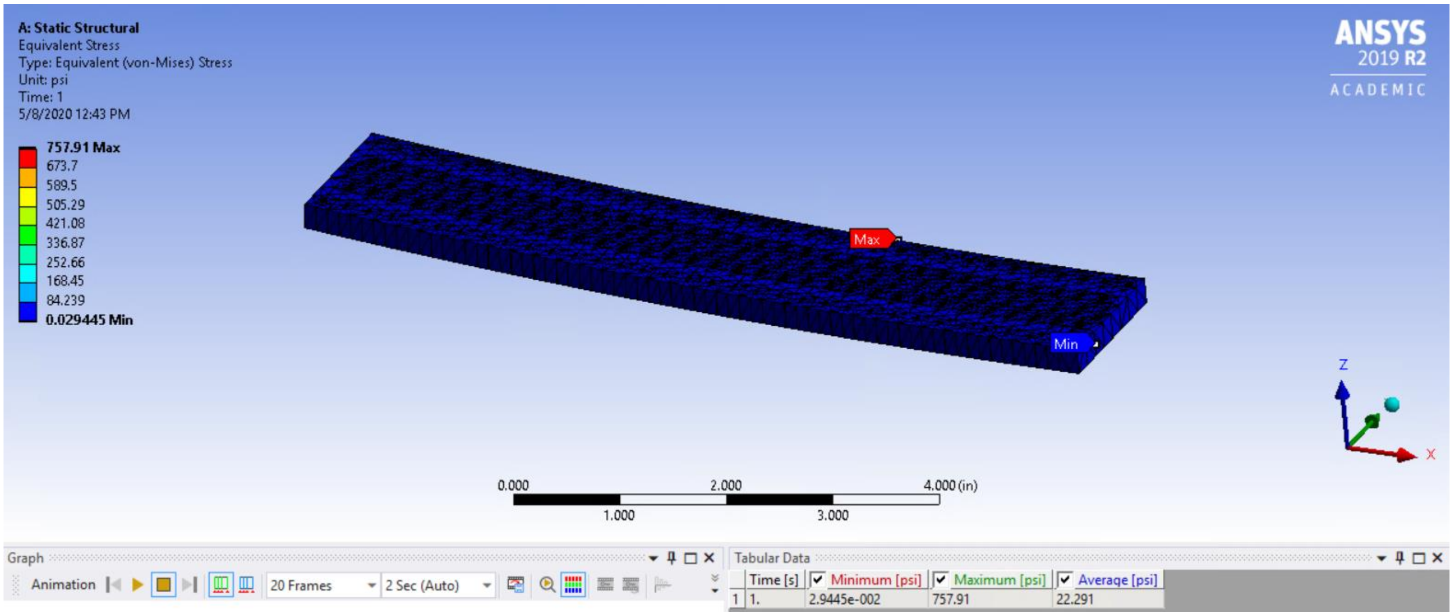
The first case of these simulations is when $\Delta x = 3.0mm$. This figure shows the total deformation the material experiences in Case 1. The locations where the material experiences the maximum and minimum deformation is indicated in the figure.



A: Static Structural
Total Deformation
Type: Total Deformation
Unit: in
Time: 1
5/8/2020 12:41 PM

Time [s]	☑ Minimum [in]	☑ Maximum [in]	☑ Average [in]
1.	0.	8.1112e-004	2.6361e-004

This figure shows the total stress the material experiences in Case 1. The locations where the material experiences the maximum and minimum stress is indicated in the figure.

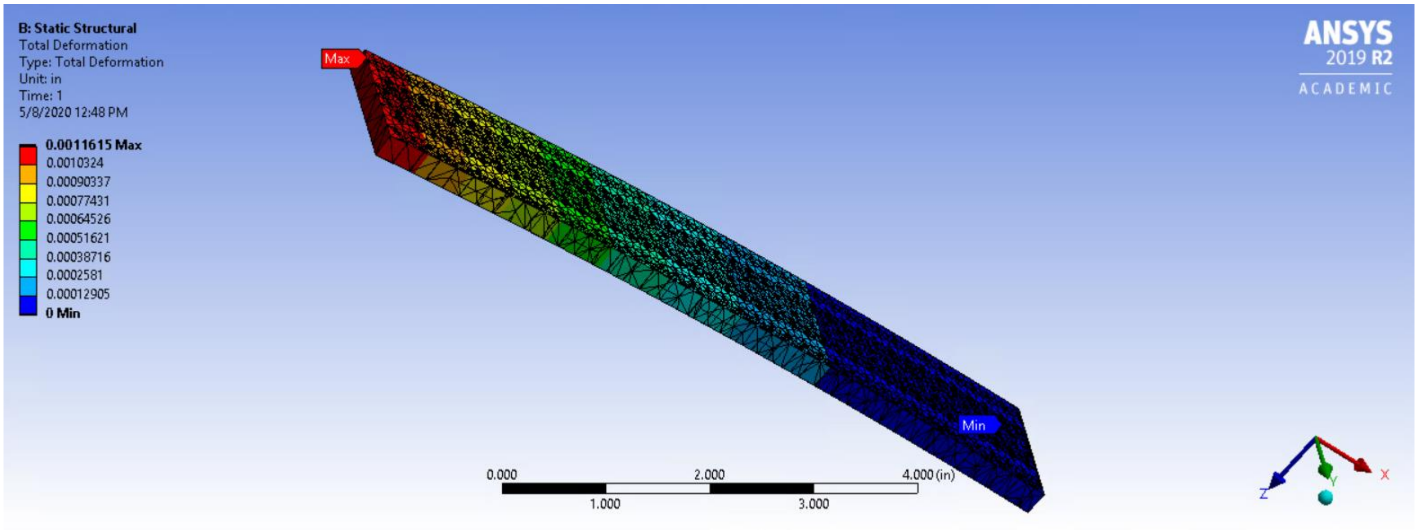


A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
5/8/2020 12:43 PM

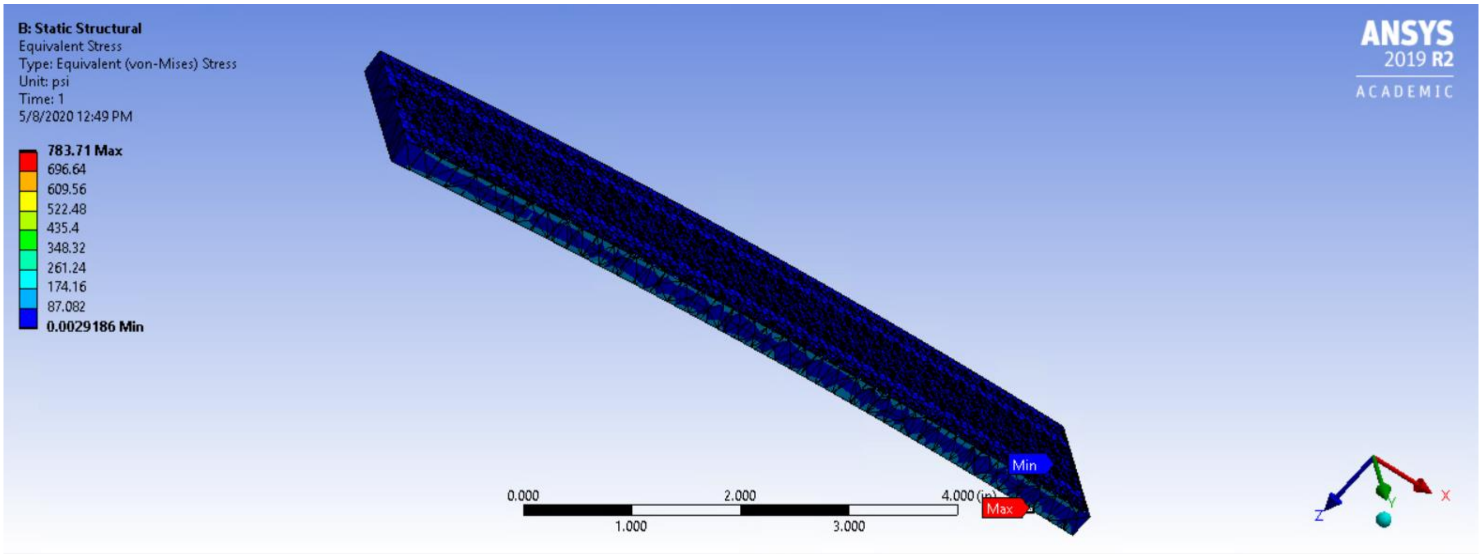
Time [s]	☑ Minimum [psi]	☑ Maximum [psi]	☑ Average [psi]
1.	2.9445e-002	757.91	22.291

Case 2

The second case of these simulations is when $\Delta x = 2.5mm$. This figure shows the total deformation the material experiences in Case 2. The locations where the material experiences the maximum and minimum deformation is indicated in the figure.

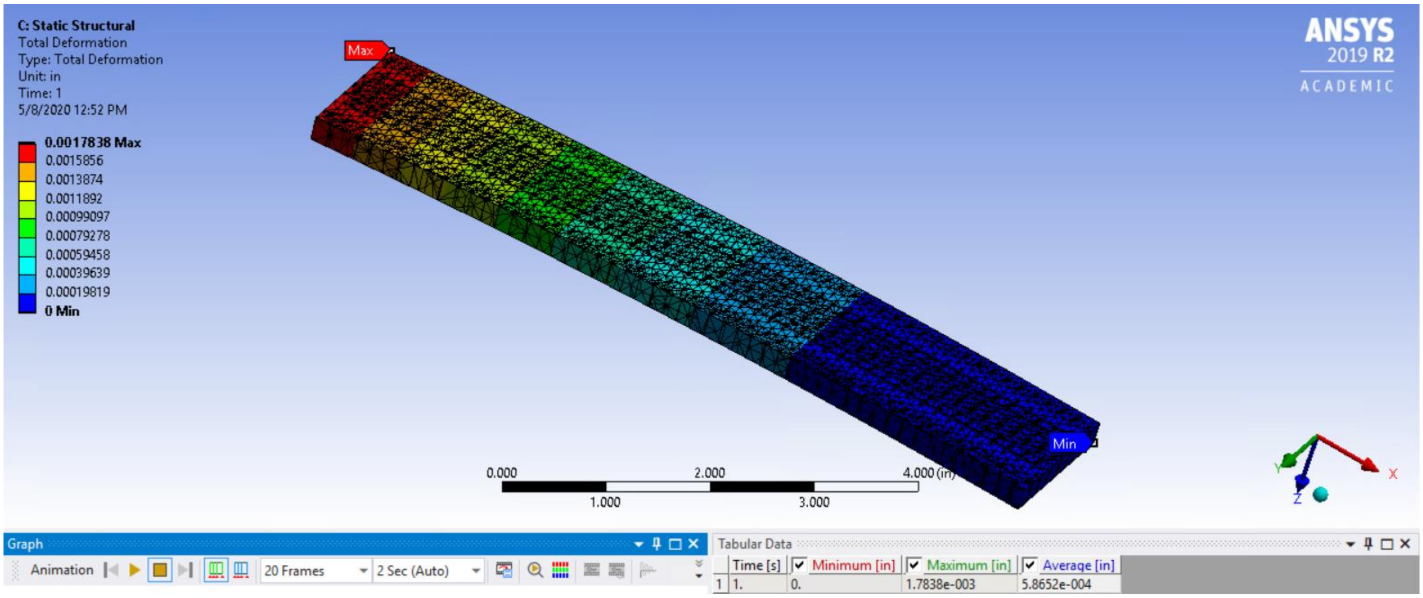


This figure shows the total stress the material experiences in Case 2. The locations where the material experiences the maximum and minimum stress is indicated in the figure.



Case 3

The third case of these simulations is when $\Delta x = 2.0mm$. This figure shows the total deformation the material experiences in Case 3. The locations where the material experiences the maximum and minimum deformation is indicated in the figure.

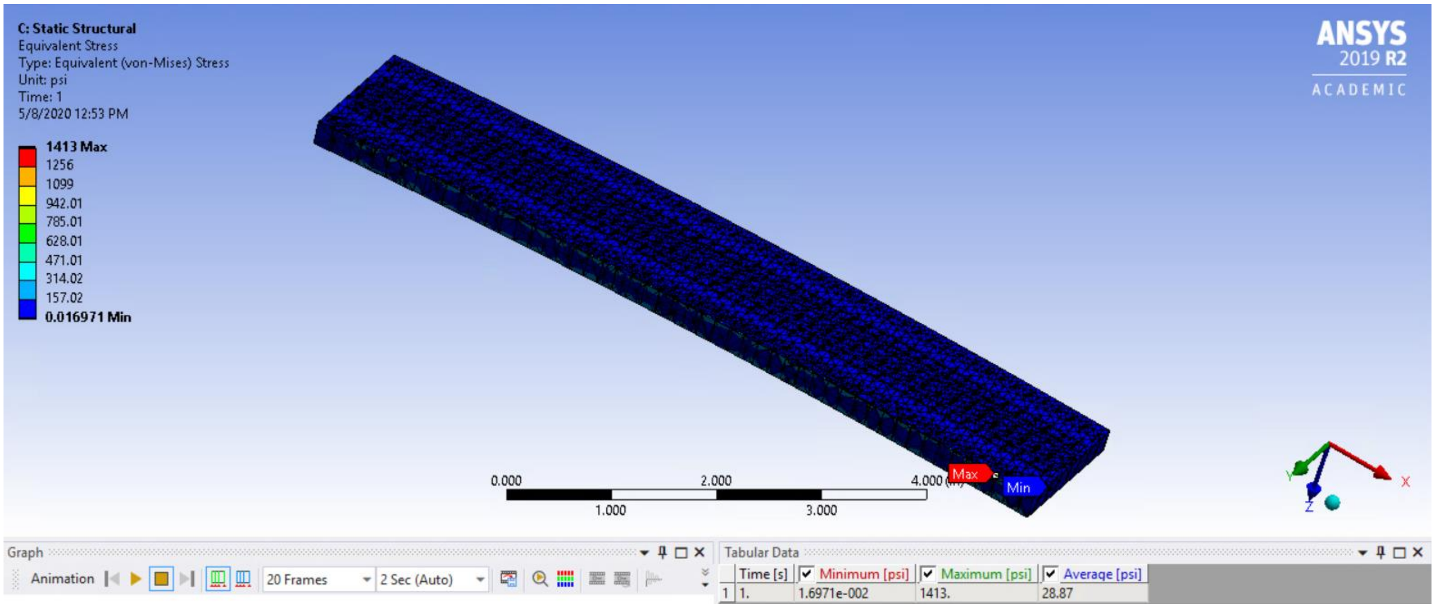


C: Static Structural
Total Deformation
Type: Total Deformation
Unit: in
Time: 1
5/8/2020 12:52 PM

0.0017838 Max
0.0015856
0.0013874
0.0011892
0.00099097
0.00079278
0.00059458
0.00039639
0.00019819
0 Min

	Time [s]	☑ Minimum [in]	☑ Maximum [in]	☑ Average [in]
1	1.	0.	1.7838e-003	5.8652e-004

This figure shows the total stress the material experiences in Case 3. The locations where the material experiences the maximum and minimum stress is indicated in the figure.



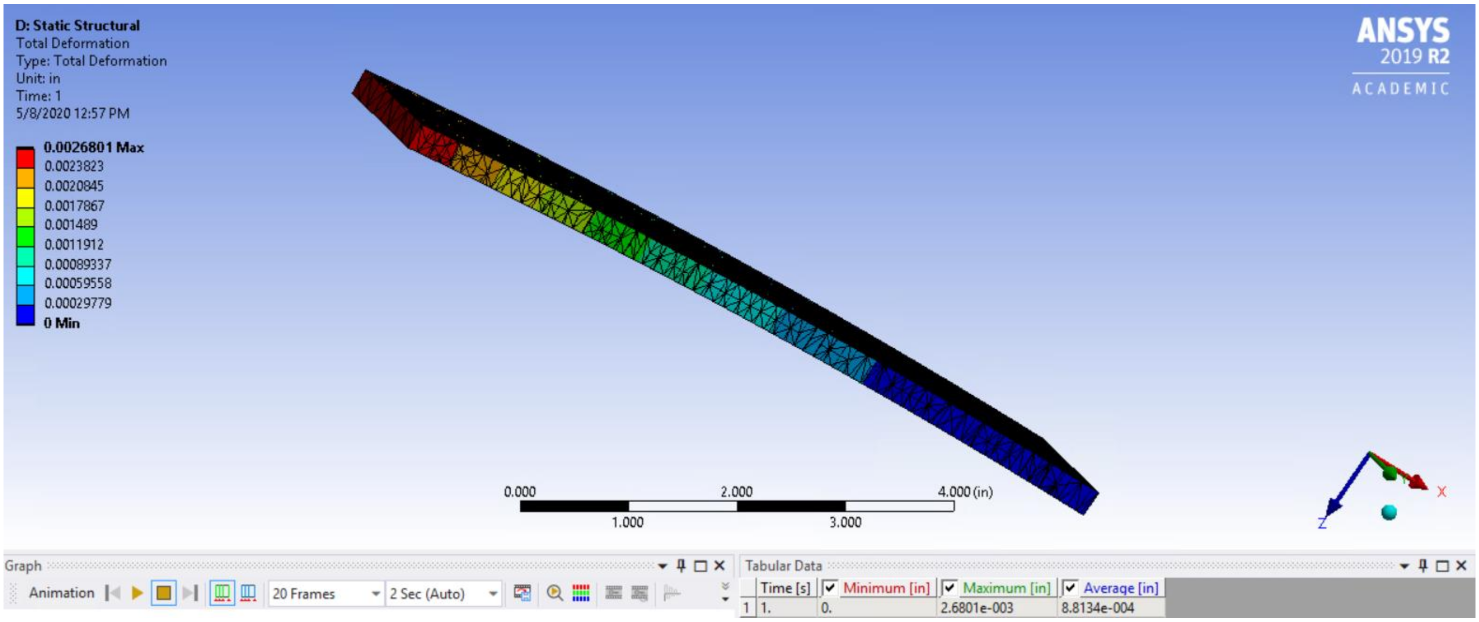
C: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
5/8/2020 12:53 PM

1413 Max
1256
1099
942.01
785.01
628.01
471.01
314.02
157.02
0.016971 Min

	Time [s]	☑ Minimum [psi]	☑ Maximum [psi]	☑ Average [psi]
1	1.	1.6971e-002	1413.	28.87

Case 4

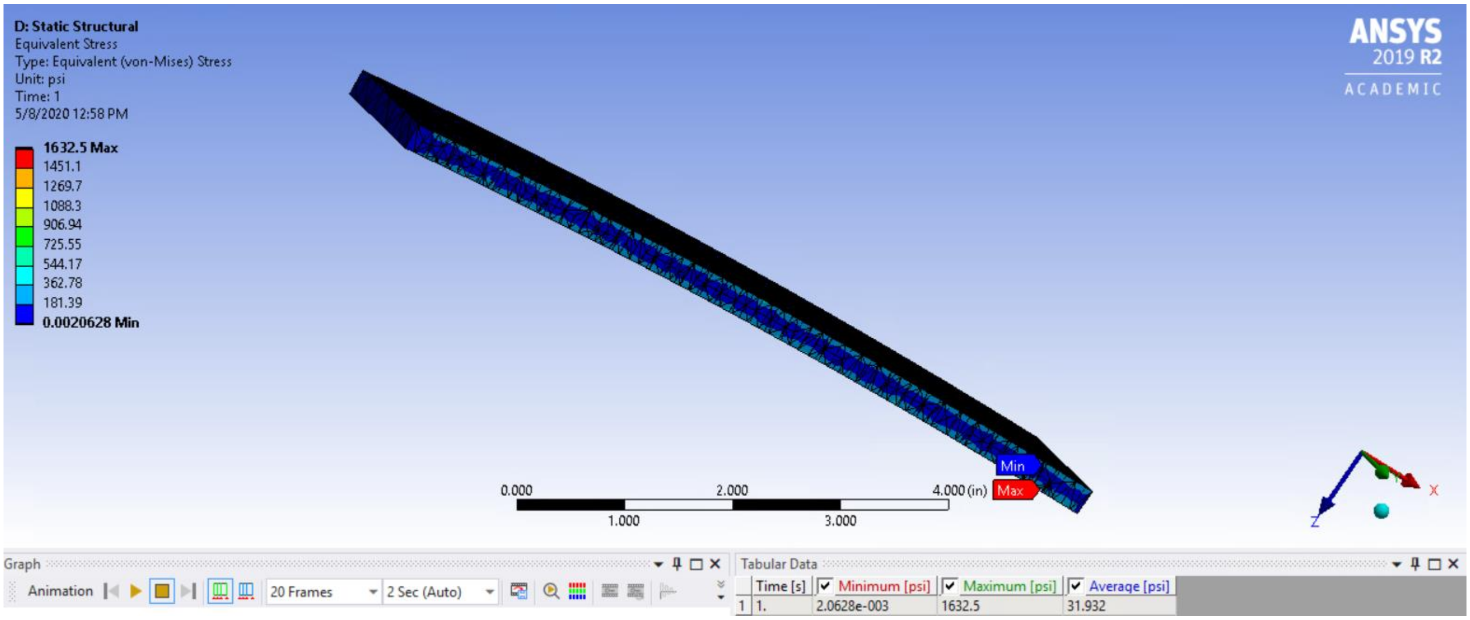
The fourth case of these simulations is when $\Delta x = 2.0mm$. This figure shows the total deformation the material experiences in Case 4. The locations where the material experiences the maximum and minimum deformation is indicated in the figure.



D: Static Structural
Total Deformation
Type: Total Deformation
Unit: in
Time: 1
5/8/2020 12:57 PM

Time [s]	☑ Minimum [in]	☑ Maximum [in]	☑ Average [in]
1.	0.	2.6801e-003	8.8134e-004

This figure shows the total stress the material experiences in Case 4. The locations where the material experiences the maximum and minimum stress is indicated in the figure.



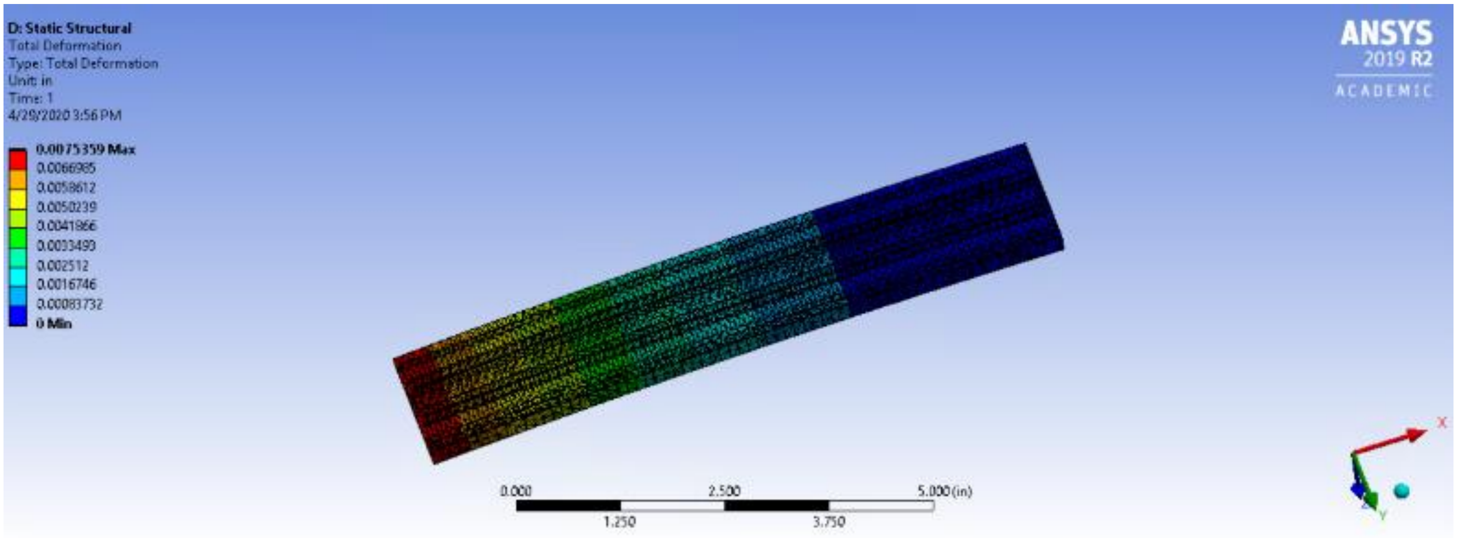
D: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
5/8/2020 12:58 PM

Time [s]	☑ Minimum [psi]	☑ Maximum [psi]	☑ Average [psi]
1.	2.0628e-003	1632.5	31.932

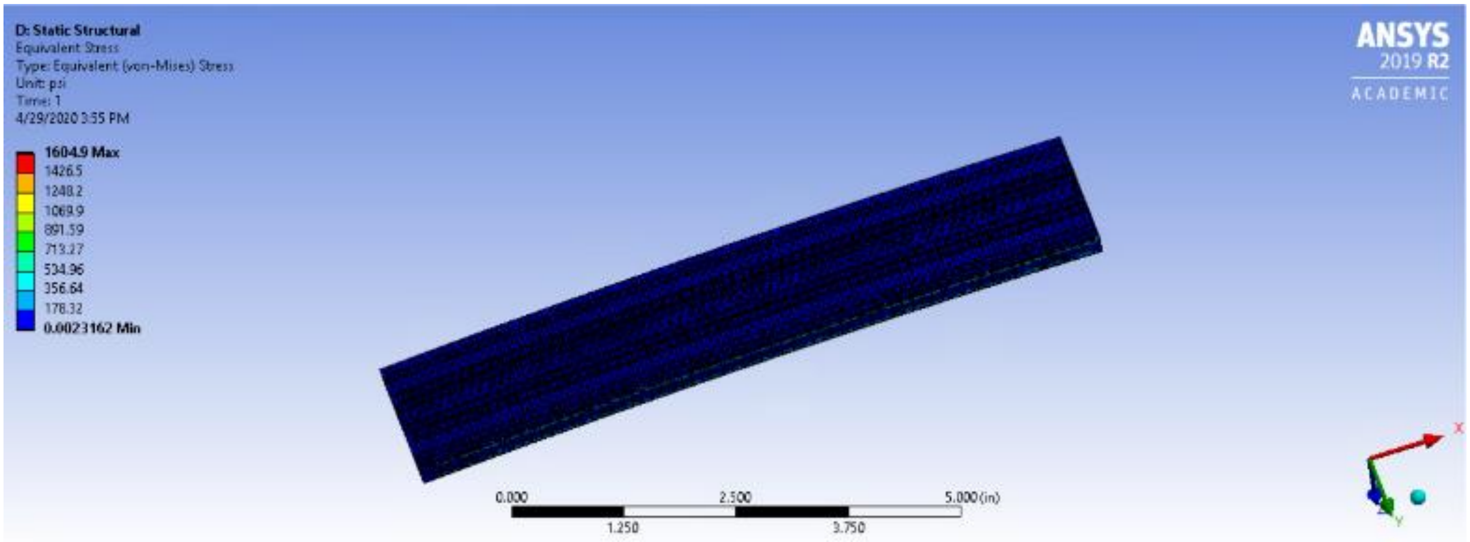
Testing Different Materials

Case 1

The first case of these simulations is when the selected material is Aluminum Alloy. This figure shows the total deformation the material experiences.

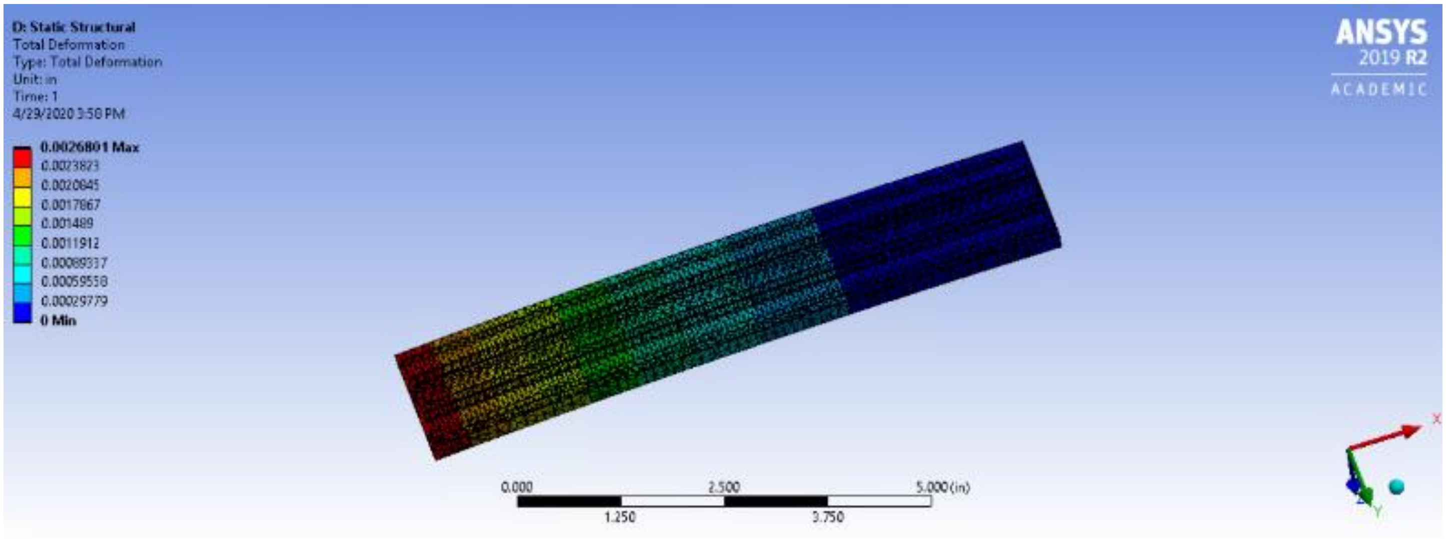


This figure shows the total stress the material experiences in Case 1.

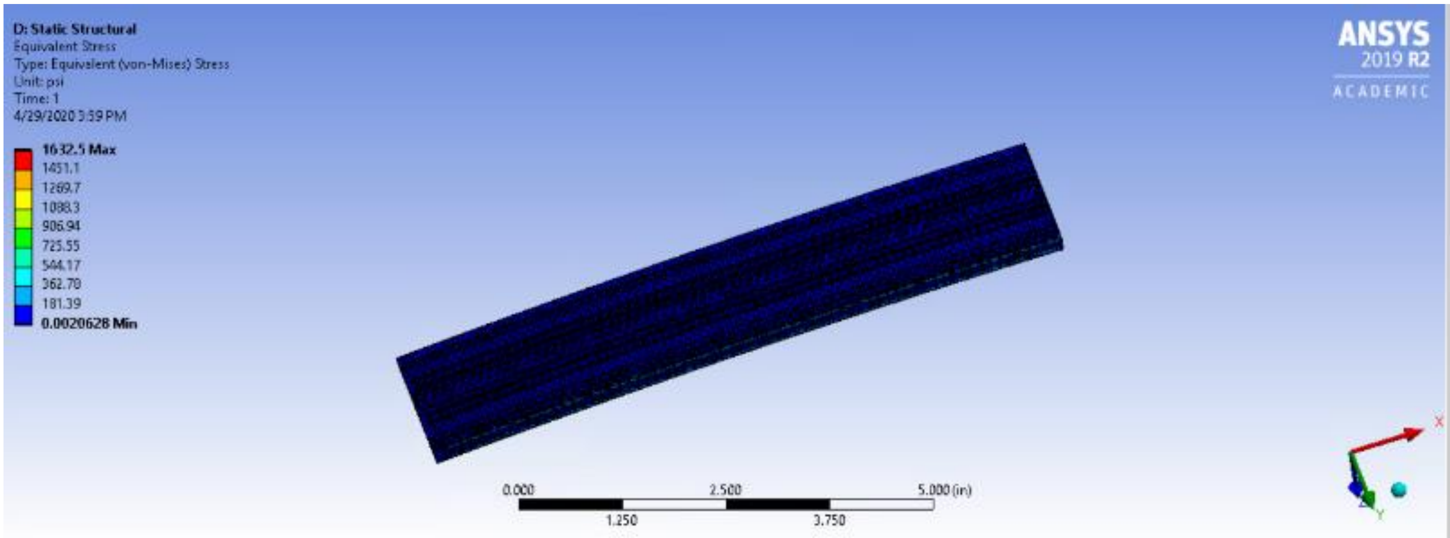


Case 2

The second case of these simulations is when the selected material is Stainless Steel. This figure shows the total deformation the material experiences.

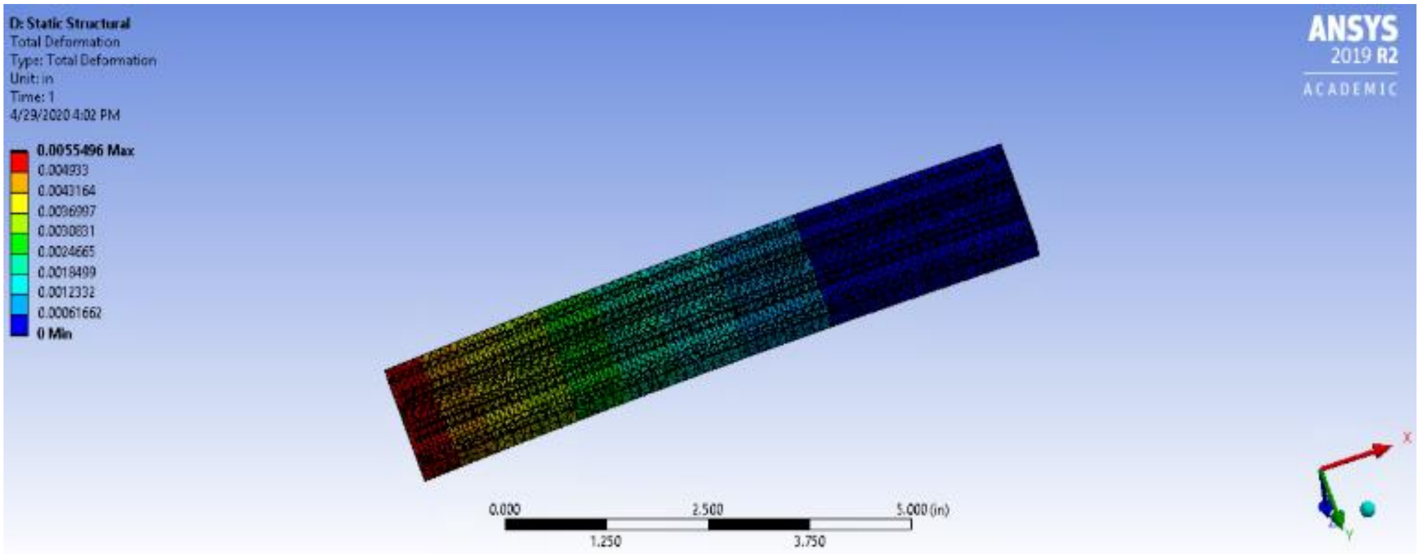


This figure shows the total stress the material experiences in Case 2.

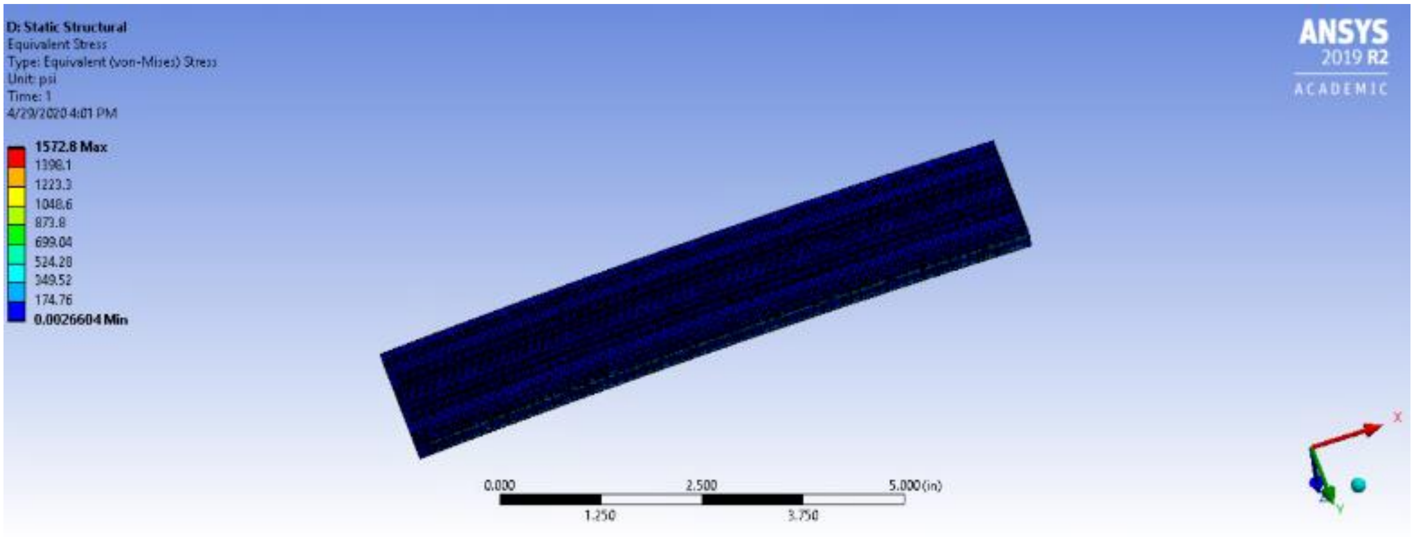


Case 3

The third case of these simulations is when the selected material is Titanium Alloy. This figure shows the total deformation the material experiences.

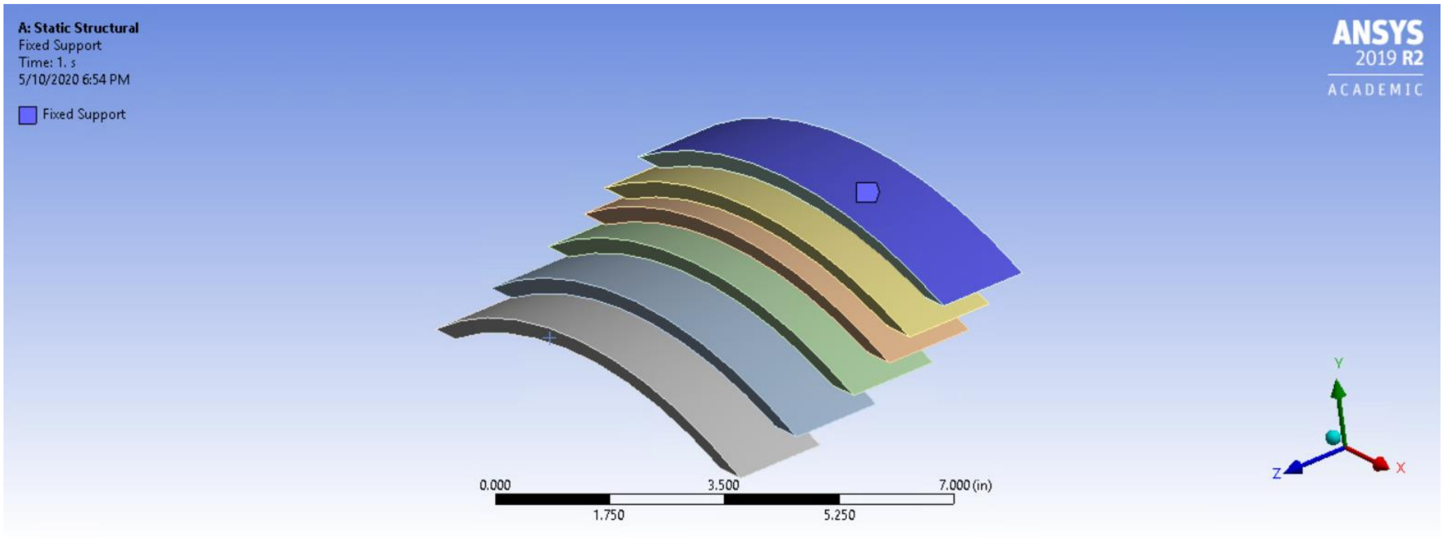


This figure shows the total stress the material experiences in Case 3.



Shoulder Pad Simulations

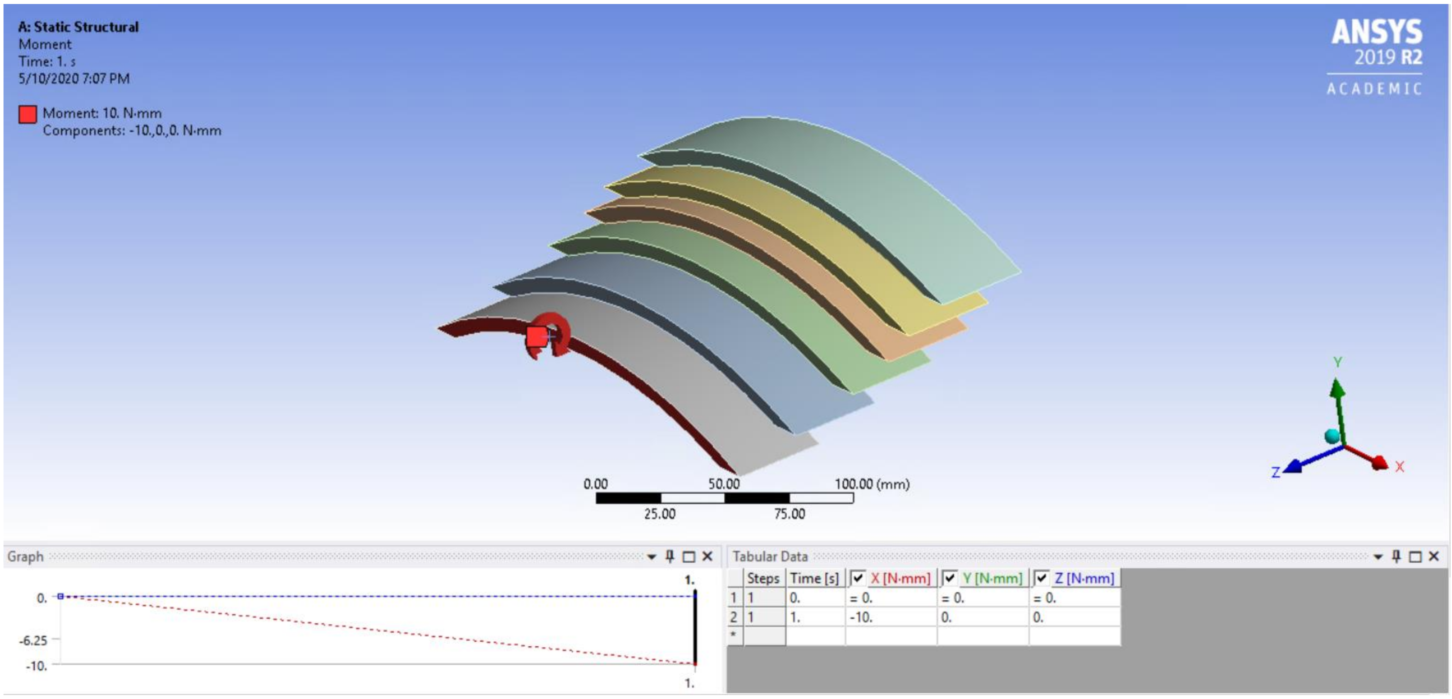
This round of simulations measures the deformation and stress that the assembled should pad design experiences. The figures below show the boundary conditions that our team set for these simulations. This figure highlights the part of the shoulder pad that we fixed in place.



A: Static Structural
Fixed Support
Time: 1. s
5/10/2020 6:54 PM

🟦 Fixed Support

This figure shows where the moment acts on the shoulder pad part, where $M = 10\ N \cdot mm$.

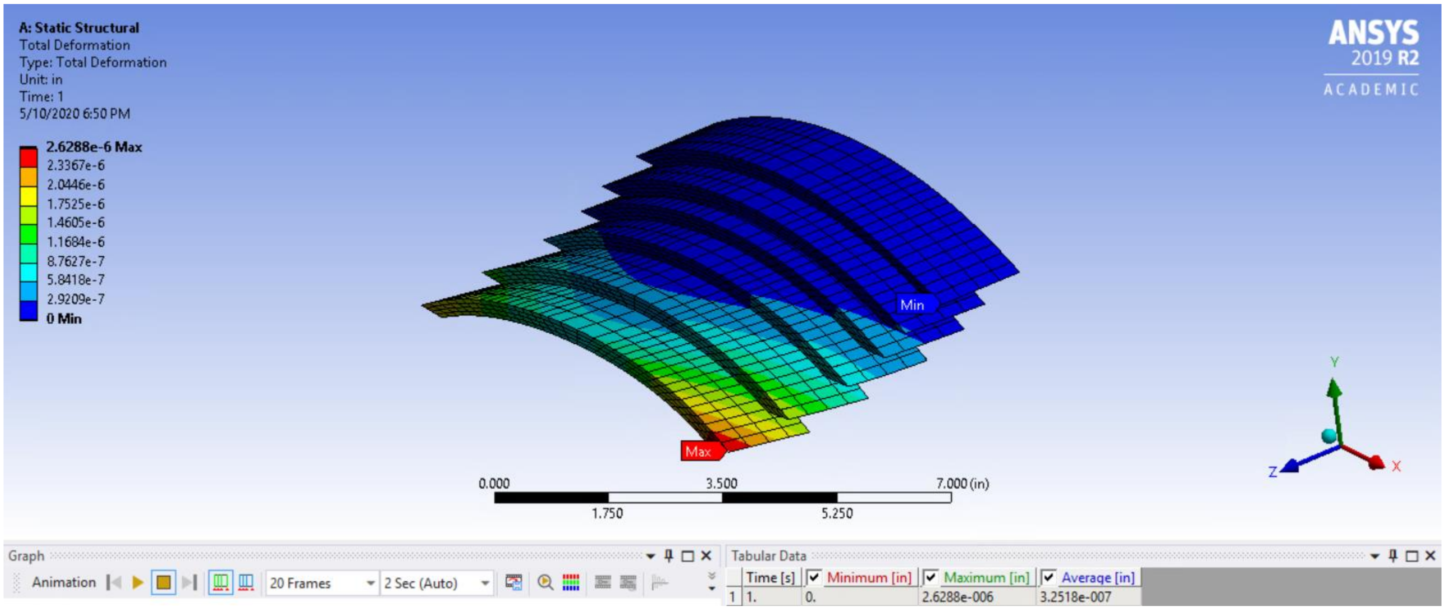


A: Static Structural
Moment
Time: 1. s
5/10/2020 7:07 PM

🟥 Moment: 10. N·mm
Components: -10.,0.,0. N·mm

	Steps	Time [s]	☑ X [N·mm]	☑ Y [N·mm]	☑ Z [N·mm]
1	1	0.	= 0.	= 0.	= 0.
2	1	1.	-10.	0.	0.
*					

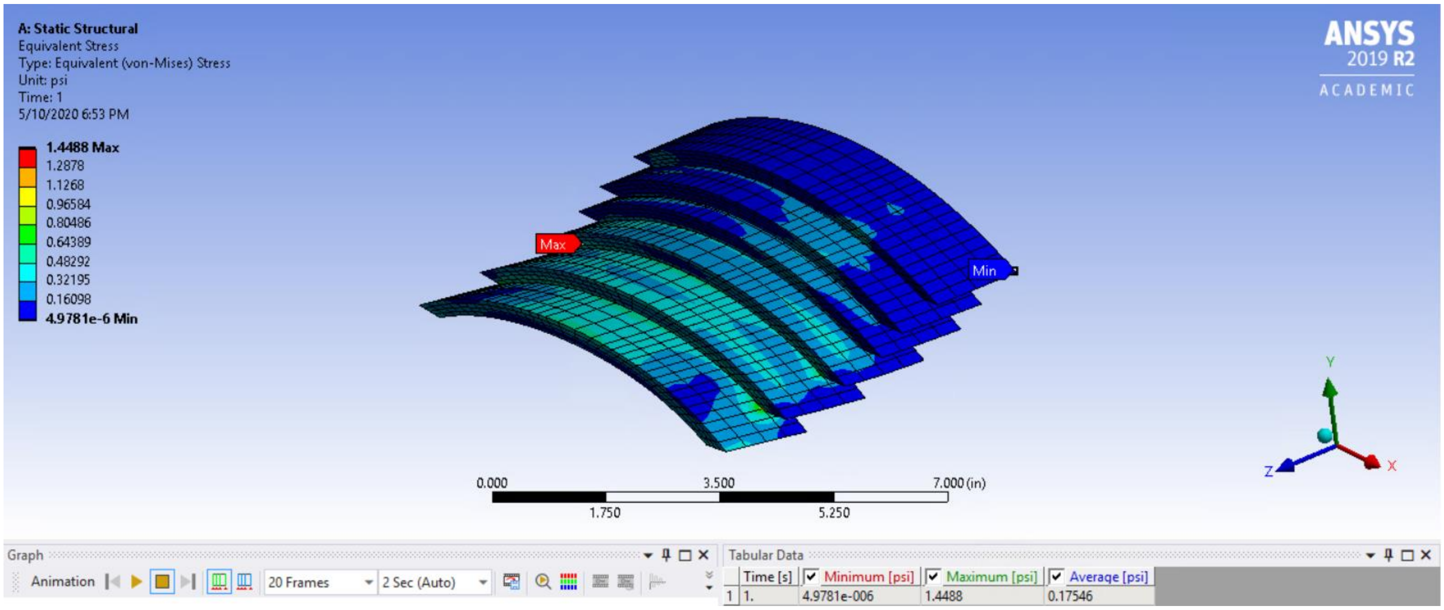
This figure shows the total deformation the assembled shoulder pad design experiences. The locations where the material experiences the maximum and minimum deformation is indicated in the figure.



A: Static Structural
Total Deformation
Type: Total Deformation
Unit: in
Time: 1
5/10/2020 6:50 PM

	Time [s]	☑ Minimum [in]	☑ Maximum [in]	☑ Average [in]
1	1.	0.	2.6288e-006	3.2518e-007

This figure shows the total stress the assembled shoulder pad design experiences. The locations where the material experiences the maximum and minimum stress is indicated in the figure.



A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: psi
Time: 1
5/10/2020 6:53 PM

	Time [s]	☑ Minimum [psi]	☑ Maximum [psi]	☑ Average [psi]
1	1.	4.9781e-006	1.4488	0.17546

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