ANALYSIS OF 3D PRINTER STRUCTURE

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Abstract

With recent innovations in technology, 3D printing has become a rapidly expanding manufacturing method that is being used for a wide range of applications. Their ability to build parts layer by layer instead of cutting away initial material allows this method to have almost no wasted material, creating the potential for a much more efficient, cost effective process. In order to continue the growth of this manufacturing strategy, the performance of 3D printers need to be enhanced to ensure equal or higher quality of produced parts in comparison to other manufacturing methods that are more commonly used. One important part of the performance that is key to making high quality parts is the stability of the 3D printer's frame. No matter how accurate the printer head is, if the structure moves while the printing process is taking place, the accuracy of the produced will be limited.

A detailed analysis was done to study the base corner bracket of the 3D printer structure that is used in the IME labs so that the part can be redesigned to reduce the frames motion. The original design for this part was 3D printed and was made out of ABS plastic. Even though the part seemed extremely strong, by using simulation software, it was found that while the printer is operating, this part can deform as much as 1.34*10^-4 mm at specific locations. By making this part out of 1/8" steel sheet metal, the same loads would cause this part to deform 1.54*10^-5 mm. This mean that the new design would allow for the deflection of this part to be reduced by almost 90%. This may not seem significant, however, 3D printers are able to print layers that are as thin as .001". To give some perspective, a human hair is approximately .003" thick, so as one could imagine, when dealing with dimensions this small, any amount of improvement is advantageous.

In addition to analyzing the stability, a manufacturing process was established, and a scaling and economic analysis was conducted. The manufacturing process is simple and allows for minimal expertise needed in order to create a function part. Also it was found that with sheet metal only available up to ¼" thick, this design could most likely be used in 3D printers that are twice the size as the one in the IME

labs. Lastly, the sheet metal design proved to be economically justifiable in many ways if produced in large quantities, however, the automation involved with 3D printing would most likely provide benefits that would require a much more detailed manufacturing process to be established to come to any realistic conclusions.

Introduction

3D printing is a new and innovative method used to manufacture solid objects. It allows the user to make complicated 3D shapes using a method of manufacturing where a part is made my adding layer after layer (additive manufacturing) of a heated material that cools and solidifies almost instantly. These 3D shapes are initially created on a computer using solid modeling software, which can be downloaded into the printer. In order to function properly, the printing head, which is essentially a hot glue gun, moves very quickly in order to create the object to the level of detail desired. This rapid motion causes sudden forces on the entire structure of the printer. In order to have a high functioning 3D printer, these forces need to be accounted for in the design, so that they do not affect the quality of the produced part. This report will explain and analyze the corner support brackets of a 3D printer currently being used in the IME automation lab.

This project that was introduced by Dr. Macedo, requires skills in Mechanical Engineering in order to help analyze and recreate the existing plastic corner brackets so that the printer can perform at a higher level of accuracy. In order to accomplish this goal, a full stress analysis will have to be done in order to choose and size the correct material for this application. In addition, the design process needs to be taken a step further and include a scaling analysis so that this part can be used for 3D printers of various sizes. Apart from the Mechanical engineering side of the project, skills in Industrial and Manufacturing engineering will be used. In order to justify the design of this part, an economic analysis will need to take place. Lastly, the project scope requires developing an easy and efficient manufacturing method that can be taught to students so that they can recreate the part in class.

Background/Literature Review

Intro

In the last decade, 3D printing has seemed to become the latest and greatest method of manufacturing for all different types of applications. Whether it be for hobbyists, artists, or large industries, there is a huge potential for 3D printers to revolutionize manufacturing and invoke creativity.

Even though 3D printers seem like a new, modern technology, the basic ideas were created decades ago. According to Kirk Hausman, author of 3D Printing for Dummies, "the first 3D printer was patented in the 1980's, but the rate of change was fairly minimal for 30 years. Labs and research departments used early 3D printers in rapid prototyping systems that produced mock-ups quickly. But things really took off after British researcher Adrian Bowyer created the first self-replicating rapid prototyping (RepRap) system using salvaged stepper motors and common materials from a local hardware store." This was the first 3D printer that could actually be used to produce parts to build another printer, hence the name RepRap. This was the start of using 3D printers for wide ranges of applications.

Manufacturing advantages

The main draw towards the use of 3D printers is the fact that it uses additive manufacturing methods. This means that a part is made by accurately adding layer by layer until the entire piece is complete. In comparison, subtractive manufacturing methods involve starting with a large piece that is cut away and shaped to the desired specifications. As one can imagine, subtractive manufacturing creates a lot of waste and debris whereas additive is much more efficient and produces minimal waste. In addition, 3D printers can use a wide variety of different materials from plastics to metals. Plastics that are typically shaped using molds can now be built with 3D printers. Just creating a mold alone can be a timely task that requires precision and can be fairly expensive. 3D printers allow the user to get the same repeatability and detail as a mold without spending extra time or money.

Use in homes (hobbyists/artists/education)

The demand for 3D printers in homes is made clear in a section of the book 3D printing for Dummies which states, "Although 3D printers have been available for years, only recently have they become available at a price most home users can afford. Because they are becoming more widespread, and because innovations in this technology now permit the creation of products in a much wider array of materials-and even combinations of materials-3D printing is poised to make an impact on average consumers in a big way." Due to this drop in price and increase in functionality, 3D printers are used by hobbyists, artists, and are even being used in education. The ease of being able to create a solid model and 3D print without any technical background can allow the average person to test their creativity and their ideas in ways that didn't seem imaginable. Some examples of creations include: model cars, working guns, guitars, phone cases, cups, clothing, toys and other various items.

Applications in Industry

As fun and entertaining as using a 3D printer seems, there are also huge potential uses for them in industry. One of the most anticipated applications for 3D printing is in the medical industry. One case at the University of Michigan proved the usefulness of 3D printing to save lives, and/or improve people's quality of life. According to the magazine article "Print Thyself" by Jerome Groopman, "In February of 2012, a medical team at the University of Michigan's C.S. Mott Children's Hospital in Ann Arbor, carried out an unusual operation on a three-month-old boy. The boy had been born with a rare condition called tracheobronchomalacia: the tissue of one portion of his airway was so weak that it persistently collapsed." In order to fix this problem, the researchers took a scan of the baby's chest and designed a small tube made of biocompatible material that they 3D printed. The tube would fit over the weakened section of airway and would eventually dissolve once the airway was able to remain open. "In May of 2013, in The New England Journal of Medicine the researchers reported that the boy was thriving and that no unforeseen problems related to the splint have arisen." The ease of using scans to create 3D prints of replacement biocompatible body parts is continuing to become more and more common in medicine and may one day become standard.

Another industrial application of 3D printing is in space. Even though it hasn't been proven, there is talk that 3D printing might even contribute to the potential for sustainable living in space. According to the authors of 3D Printing in Space, "the Committee on Space-Based Additive Manufacturing determined that additive manufacturing in and of itself is not a solution, but presents potential opportunities, both as a tool in the broad toolkit of options for space-based activities and as a potential paradigm-changing approach to designing hardware for in-space activities." In other words, having access to such manufacturing techniques allow astronauts to more efficiently design and build hardware that could be critical in space exploration.

Nowadays 3D printing has become a standard manufacturing method in industries such as: automotive, aerospace, architecture, entertainment, defense, and many others. With its cost and material efficiency and wide applications, 3D printing will continue to be adopted by industries as a go-to form of manufacturing.

Understanding the Stresses on Printer Frame

The first step in analyzing how to improve the functionality of the 3D printer structure is to understand the forces that are acting on corner brackets so that the resulting stress can be found. There are several options when it comes to finding the amount of force being induced on the corner brackets by the 3D printer motion. Some of these methods include doing traditional hand calculations or using force sensors.

The key to understanding the stresses is to find the forces that are acting on the part. One way that is much cheaper but not very accurate is to estimate these forces using the printer head acceleration and translate those forces to the corner brackets of the printer frame. In doing this, several assumptions would have to be made in order to make the analysis feasible but would also take away from the accuracy. However, another option is to use force transducers (sensors). These devices record the measured force and output their data to an acquisition system. This data would make it easy to understand how the forces are acting with the printer motion and would provide an accurate measurement that will lead into more accurate stresses.

For this type of problem, the book, "Shigley's Mechanical Engineering Design" suggests finding the stresses using a fatigue failure analysis. This is due to the fact that fatigue will be the most likely cause to failure of lack of functionality in the part. Since the printing head is moving in repetitive motions, the force acting on an individual bracket fluctuates constantly. This results in a slowly weakening structure, unless designed for infinite life. In order to do this type of analysis several aspects of the project need to be defined or assumed. To sufficiently do this analysis one would need to know: material of the part, surface finish, desired reliability, temperature conditions, and several other criteria. If any of these cannot be found or estimated then logical assumptions will need to be made.

Another method of understanding the stresses in the part would be to use FEA software such as Abaqus. The article “Machine Design (June 1992)” describes FEA as a computer based technique for solving field flow problems, where the most common application is finding the stresses and deflections in a structure. This method takes a finite number of elements within a given part and analyzes the stresses and deflections of each element individually. The more elements one chooses to evaluate, the more accurate the results. This approach requires software because it is based on arrays and large matrix equations that can only realistically be solved by a computer. The article runs through the process of doing this type of analysis. These steps include: modeling the design, select the element nodal variable function, set up element derivatives and constitute relationships, assemble the element equations and add boundary conditions, and solve for element node variables. As tedious as this method seems, when designing critical high performance components the accuracy of this method can be extremely beneficial.

Material

One of the most important parts of this project is to select a new material that will allow the part to function at its optimal level. This decision will be primarily based on the outcome of the stress analysis. This will ensure that a material is chosen that can handle the induced loads of the working system. In addition to being able to handle the loads, the material should have properties that keep if from failing due to working conditions like corrosion, overheating, or sensitivity to chemicals being printed. A few of the key materials that should be considered are stainless steel, carbon steel and aluminum. Each have their own advantages and disadvantages but the tradeoffs of each should reveal the material that is the best choice for this application.

The first material to be considered will be stainless steel. According to "Stainless Steels: An Introduction and Their Recent Developments (January 2012)", the difference between stainless and regular steel is the chromium content. For steel to be stainless, it needs to have at least 11 wt% of chromium alloyed in the base material. This difference in composition results in resistance to staining, rusting, and corroding where normal steels are susceptible to these problems. In addition to being weather resistant, "The British Stainless Steel Association" claims that stainless steel also has a larger ultimate tensile strength then carbon steel and is more ductile. This results in less immediate failure due to loading. Since the material is ductile, it will deflect and show signs of failure before completely malfunctioning. In terms of weld ability of the material, "Mill Handbook 5" states that "stainless steels can be welded by almost any usual technique except carbon arc, provided adequate steps are taken to prevent oxidation or carburization of the weld. The stabilized grades are preferred for welded parts that are used in the as-welded condition under corrosive conditions. The free-machining grades are not recommended for welding. Filler rods should be the same composition, or slightly higher in alloy content, as the material to be welded. Special fluxes designed for use with stainless steels should be employed, except in atomic hydrogen or inert-gas-shielded arc welding. Spot and roll seam welding also are used to a considerable extent."

In comparison to stainless steel, carbon steel is cheaper, has a higher design strength and a higher Young's Modulus. The larger Modulus is advantageous because it directly relates to deflection; the larger the Young's Modulus the less the material will deflect. Since the goal of the project is to minimize the deflection of the supports, this characteristic is crucial for the material choice of this application. Also, "Mill Handbook 5" states that, "the low-carbon grades are readily welded or brazed by all techniques. The medium carbon grades are also readily weld able but may require preheating and post welding heat treatment. The high-carbon grades are difficult to weld. Preheating and post welding heat treatment are usually mandatory."

The last material to be considered is aluminum. According to "aluminumdesign.net", one of the best known properties of aluminum is its weigh to density ratio. Aluminum is claimed to have a density that is about one third the density of steel. In addition, aluminum has fairly high tensile strengths that range between 70 and 700 Mpa, depending on the alloy type. Unlike most types of steel that get brittle at low temperatures, aluminums strength actually increases at lower temperatures, however the opposite effect occurs at elevated temperatures and weakening effects need to be accounted for. Also, aluminum is a very weather resistant material. Aluminum is corrosion resistant because the thin layer of oxide that forms is dense and the material can protect itself if damaged. However, even though the material can handle neutral and slightly acidic environments, corrosion is rapid when exposed to environments characterized by high acidity or basicity. Finally, for welding aluminum, "Mill Handbook 5" informs that, "the ease with which aluminum alloys may be welded is dependent principally upon composition, but the ease is also influenced by the temper of the alloy, the welding process, and the filler metal used. Also, the weld ability of wrought and cast alloys is generally considered separately. Several weld ability rating systems are established and may be found in publications by the Aluminum Association, American Welding Society, and the American Society for Metals."

Scaling

One of the goals of this project is to create a design that can be used in future 3D printers. In order to do this, a scaling analysis will have to be done of the initial design to be able to understand the required dimensions of parts for larger scale printers. This analysis will be done by finding the options for material sizing available for purchase and by examining the material size limitations of the equipment used to conduct the manufacturing process. Due to this, the scaling analysis will be one of the last parts of my design analysis.

Manufacturing

In the world of manufacturing, there are several methods that could be used to reproduce the part needed to improve the support of the 3D printer frame. For this project, the idea is to manufacture the part using the IME department's robotic welder and plasma cutter. These both require understanding the material properties in order to ensure that the manufacturing process will work with the specified material. Since the material for this project has not been chosen yet, each material will have to be researched in order to determine their weld ability and other manufacturing characteristics.

First off, in order to be able to use a robotic welder for this project, several factors will need to be accounted for. For starters, with all welders, knowing the type of welding method required for the job or material specified is very important and is specific to the welding machine being used. In addition, by using a robotic welder, the use of fixturing becomes necessary in order to hold the part in the most simple and efficient way as possible. According to the Lincoln Electric website, “One of the first steps in designing a robotic welding fixture is to choose the fixture base-metal. Factors include initial cost, long-term maintenance costs, and special characteristics particularly suited to the robotic welding application, such as the critical aspect of maintaining accuracy and part repeatability in an environment exposed to elevated heat and weld spatter.” Lincoln electric provides a table on their website that lists ratings for different types of materials:

Table 1. Material Choice for Fixturing

	Mild Steel	Tool Steel	Aluminum - 6061	Stainless Steel	Copper/Copper Alloys
Material Cost	Low	Medium	Medium	High	High
Wear Resistance	Medium	High	Low	Medium	Low / Medium
Electrical Conductivity	Low	Low	Medium	Low	High
Thermal Conductivity	Low	Low	High	Low	High
Thermal Expansion	Low	Low	High	Medium	Medium

This table will be very useful for designing the fixturing once the manufacturing process has been more specifically defined. In addition to choosing the fixturing material, using the most effective clamping mechanism is also very important. On the Lincoln Electric website, they explain the thought process behind choosing the correct clamping system, “There are many clamping / locating options to choose from when you approach a fixture at the design stage. The least complex involves simple manual clamping such as swing, push, or plunger clamps applied to a fixed or stationary table and are typically applied for short-run or prototype parts. In an R&D or short-run setting, these are very simple, low-cost methods to locate a part. The labor intensive nature of manual clamping is overcome by flexibility and versatility in these settings. Modular fixturing is a secondary option that provides benefits of flexibility while maintaining dimensional control." The decision behind the clamping method will be based on the desire to reproduce the part and the cost of the mechanisms.

Lastly, in order to be able to adequately manufacture that part, a plasma cutter will need to be used to shape the initial work piece. According to the article, "Plasma Cutters (2005)", "Plasma cutters work by applying an electric arc to gas that passes through a constricted opening. The electric arc heats the gas until it enters a fourth state of matter called plasma." The high energy of the plasma state allows the cutter to make fast, precise cuts while still having limited heating affects on the workpiece. There many variations of plasma cutting including: conventional plasma cutting, dual gas plasma cutting, water shield plasma cutting, water injection plasma cutting, and precision plasma cutting. In addition, having a high quality plasma cutter provides durability, easily controlled torch components, and consistent power. Even though these qualities are benficial, the extra cost for a better, more sophisticated cutter might not justify its advantages for the application of this project.

Design/Theory

In order to guarantee that I would generate an accurate result for my design of the 3D printer corner bracket, I developed a design process that I followed throughout my project. This process consisted of: estimating forces seen by the base corner bracket, finding the stresses and deflection that occur, choosing a material, and constructing a manufacturing process.

Forces

In order to be able to effectively redesign this part, the forces that the 3D printer bracket experiences first need to be found. The magnitude of the forces will allow me to continue my analysis by helping me find the stresses and the deflections, which will have a major effect on my decisions as I proceed with the design process. Two different methods were established to find these forces:

1. Using force transducers to record forces in real time while the printer is running
2. Find the acceleration and mass of the print head and estimate the forces using hand calculations

When evaluating which method I would use, the main focus was accuracy, so I anticipated using the first method. However, I have not had experience with using force transducers and do not know what it takes to perform tests with them. After discussing this option with my advisor, Dr. Macedo, he informed me that this method would be too time consuming and could even be an entire project on its own, so I was left with my second option.

The fundamental equation that would be used to find the reaction forces experienced by the structure is Newton's Second Law of Motion:

$$Force=(mass)x(acceleration)$$

The first step I took to estimate the forces was to find the print head acceleration. In order to develop a conservative design, I wanted to find the maximum acceleration that the print head will experience in a run, which will give me the largest forces that the structure will experience. I started by trying to do research to find typical accelerations with 3D printers of similar size, and was only able to find fairly wide ranges of values. In order to narrow down my options, I talked with a fellow Mechanical Engineering student, Justin James, who is building a 3D printer for his senior project and has past experience with 3D printers. He informed me that you can select the accelerations that you want the print head to run at, but that typically when he was running, the acceleration would be 1 m/s^2.

The second step is to find a value for the mass in Newton's Second Law, which would be the mass of the print head. Again research was done online to find typical values, but I was not able to find any consistent values since the print head and its supports differ significantly depending on the type of 3D printer and the application that it is used for. I discussed this problem with Dr. Macedo and we came to an agreement that 0.25 lbm (.1134 kg) would be a reasonable estimate.

The third step is to conduct the calculation by drawing a free-body diagram (FBD) and to use the fundamental equation to find the resulting forces. For the design of the bottom corner bracket, the forces that will cause the support to deflect are those that act on the plane parallel to the ground. In order to find the largest of these forces, the calculations will find the force that is parallel to the ground and normal to the support. Since this part of the process is where most of the accuracy is lost because the motion of the print head is fairly complicated, assumptions are required in order to obtain values with only hand calculations. Some of these assumptions include:

-Reaction forces of two other supports are equal

-Print head is accelerating directly at one of the supports

Even though these assumptions will take away from the accuracy of the answer, they were made with the intention to overestimate rather than underestimate so that the design will be conservative. With these conditions I found the force acting on the vertical support to be .0831 Newtons. This force analysis can be seen in Appendix A.

After completing the force calculations, I came to the realization that when doing a deflection comparison between two parts, the magnitude of the force does not need to be accurate as long as: both part's deflections are analyzed with the same force, and that the force does not cause the stresses in the part to exceed the yield strength of the part. For this reason, I chose to use a uniform force of 1 Newton to perform the rest of the analysis in order to account for incorrect mass or acceleration. The EES plot shown below shows that potential for the reaction force to increase with a change in print head mass, or acceleration where the lines labeled 'a' and 'm' represent the acceleration and mass respectively:

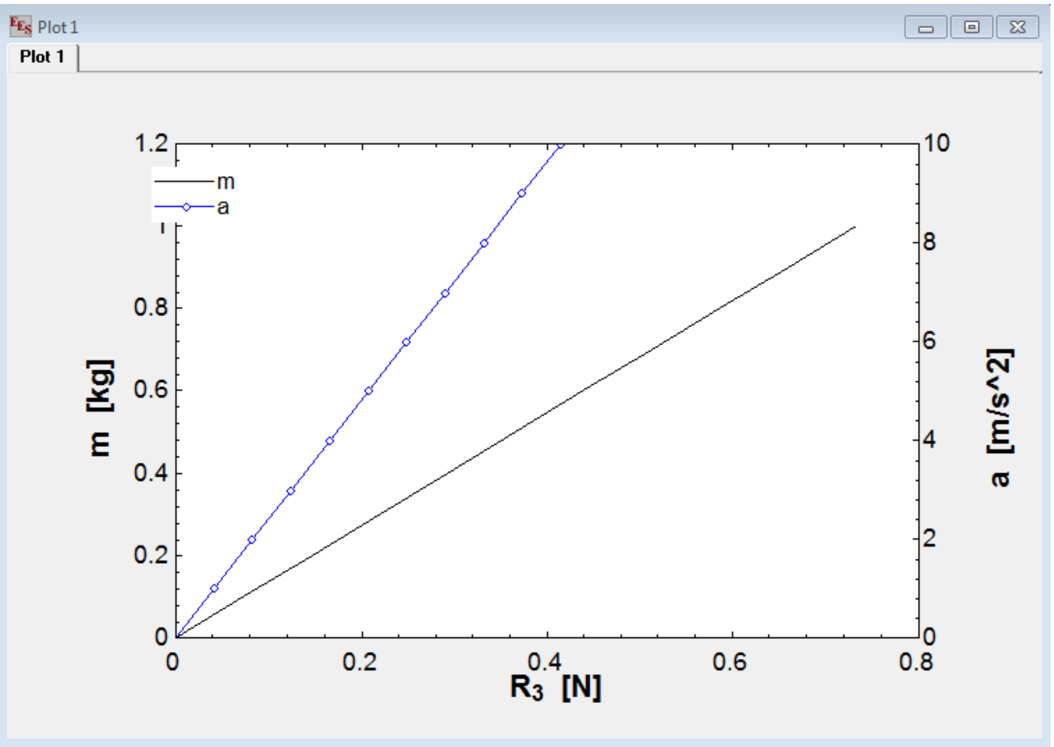

Figure 1. Reaction Force with Varying Acceleration or Mass

By plotting these effects of changing acceleration and mass separately, one can see that if both were underestimated, the value of the reaction force at the point of interest would dramatically increase.

Stresses and Deflection

One of the most critical parts of my design process is determining the stresses and deflection of my part when reacting to the loads that are caused by the motion of the 3D print head. By finding the deflections of each of the parts (steel and 3D printed) I will be able to see if my new design is more functional than the part that currently exists. In theory, the part that is made with the material that has the largest Modulus of Elasticity (E) should have the least amount of deflection, however the thickness of the part has a role in the amount it will deflect also. Since the goal of my project is to create a part out of metal that will limit deflection in comparison to the existing plastic brackets, I will perform a stress and deflection analysis to see what thickness of carbon steel sheet metal will be needed in order to actually cause the deflection to be lessened.

There are two different methods that can be used to perform a stress/deflection analysis:

1. Perform hand calculations using equations from Shigley's design book
2. Perform an FEA analysis using SolidWorks or Abaqus

For my project, I chose to use the second option. This method is advantageous to the first option because it provides a much more accurate and thorough stress/deflection analysis. In addition, since the parts have fairly complex geometry, finding these values using hand calculations would be a gross estimation, and would not provide accurate enough results to come to a valid conclusion for my design evaluation. Finally, I have chosen to perform my FEA analysis using SolidWorks because I am more comfortable working within the software and already have solid models made in the same program that can be used for the analysis.

Material Choice

One of the key steps in the design process for the 3D printer corner bracket was choosing a material that would best suit the application. Some of most important criteria for choosing a material was:

-Affordability

-Ease of Manufacturing

-Availability

-Weather Resistant

-Material Properties (Elastic Modulus)

With these criteria in mind the materials considered were: Stainless steel, Carbon Steel, and Aluminum. Each of these materials have their advantages and disadvantages for this particular application. Stainless Steels provide weather resistance, fairly large stiffness and are easy to work with when trying to manufacture parts. In comparison, carbon steel is not very weather resistant, has a higher stiffness and is one of the easiest materials to work with. In addition, carbon steel is easy to find in the form of sheet metal and is on the low side of the price range. Lastly, aluminum is a material that would also possibly work well for this application. The material is weather resistant, has high strength to weight ratio, and is commonly found. However, aluminum can be more expensive than steels and for this application, and a material that weighs less provides no added benefit to the design. The table below provides an organized summary of the critical properties for each of the materials being analyzed:

Table 2. Material Comparison

	Material Properties		
	Density (g/cm^3)	Modulus of Elasticity (Gpa)	Machinability
Carbon Steel	7.85	205	70%
Stainless Steel	8	196	45%
Aluminum	2.7	68.9	50%

With these ideas in mind the material that I chose to use to remake the 3D printer corner bracket is Carbon Steel. The one criterion that carbon steel does not satisfy is weather resistance, but since the printer will most likely be in doors in a lab, I don't think that this will be a critical requirement. By choosing carbon steel I will be able to limit the price and manufacturing time of the part which will allow me to create an economic comparison between the new and old design.

Manufacturing Method

The goal for the manufacturing of this part was to create a simple, yet functional method that still allowed for the detailed geometry that the part requires. With the decision to use carbon steel in the form of sheet metal, the manufacturing method was simplified but still allowed for a functional outcome. The idea when making this part with sheet metal, is to make decisions between which joints to weld and which to bend/shape. I was instructed by Dr. Macedo to draw and summarize every option for manufacturing and list the pros and cons of each. This allowed me to easily narrow down my options and eventually led me to the optimal solution. However, even after this process, I was able to adjust the design to make the part even easier to build while increasing the ability to have detailed geometry. The idea is to perforate the joints that are going to be bent so that they can easily be tweaked, use tabs and corresponding slots to locate the cross beam, and then to weld the joints to permanently hold them in place. An illustration of this can be seen in Figure 2. In addition to the general method, the main tool that is going to be used is a CNC plasma cutter. Since this tool is a CNC based machine, I will be able to create a detailed solid model of the part that the machine can interpret and use to cut the sheet metal to the precise dimensions that are required for this part to be as functional as the existing plastic piece. 2D drawings with these dimensions can be seen in Appendix B.

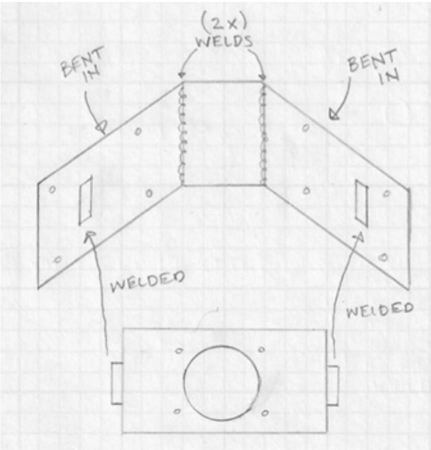

Figure 2. Sketch: Manufacturing Method

Methods/Experimentation

In order to see if my design for the 3D printer corner bracket would perform better than the existing 3D printed one, I needed to be able to run tests to gauge each designs performance. The main criteria I chose to focus on with my experimentation was deflection, since the overall goal of my project was to design a part that would deflect less when subject to the loads that occur during the operation of the printer.

To analyze this type of response from the printer's motion, I decided to use the simulation feature of SolidWorks to perform an FEA analysis. This approach divides up the 3D model into a finite number of sections (elements) and conducts a stress and deflection analysis on each. This allows for a fairly accurate and realistic analysis of the reactions that the part experiences from the induced load. However, to do this analysis I needed to establish parameters required to run the analysis. The main two that I used were that the bottom surface of the part is fixed to the ground and that the external force is a 1 Newton uniform force acting normal to the surface where the vertical support of the frame is connected. Figure 3 shows a screenshot of the results of this analysis for the 1/8" steel sheet metal design.

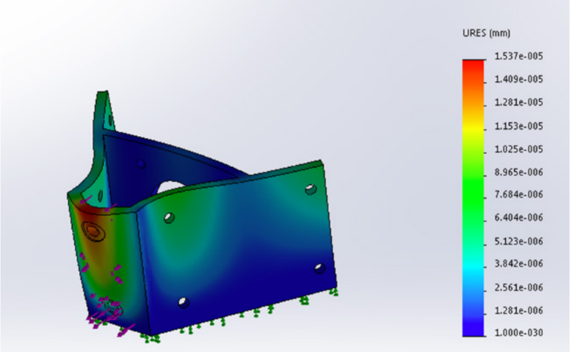

Figure 3. Image of Deflection Analysis in SolidWorks

I performed my experimentation by first running the simulation with the existing 3D printer bracket to get an idea of the stress and deflection that exist with the current design. I found the largest stresses and deflections to occur at the top portion of the face where the bracket is attached and found them to be 9,479 N/m^2 and 1.308*10^-4 mm respectively. From there, I ran the analysis on the new steel sheet metal design for four different thicknesses: 1/32”, 1/16”, 1/8”, and 3/16”. After running each thickness I clarified that the parts stress did not exceed the yield strength to ensure accurate results. From doing this analysis I found that the minimum thickness needed to limit deflection to be the 1/16” steel sheet metal with a deflection of 1.012*10^-4 mm which is only 2.96*10^-5mm less than the existing piece. For this reason, if I were to choose a thickness to use, I would most likely go one step thicker and use the 1/8” sheet metal because of its significant decrease in deflection compared to the original. This thickness resulted with deflection of 1.537*10^-5 mm which limits deflection from the initial design by 8.8*10^-4 mm. These methods allowed me to prove that in theory, my new design should be successful in limiting the deflection of this part. To view the results of each of the trials in more detail, see the illustrations shown in Appendix C.

Results and Discussion

Deflection

After having completed the force analysis and material selection, I was able to perform an FEA analysis in order to reach a conclusion in regards to deflection. I ran an analysis on the 3D printed part and found the deflection to be 1.308*10^-4 mm. Next, I ran the same simulation using my new design that was to be made out of carbon steel sheet metal. I chose to use four different thicknesses that range from 1/32”-3/16” and plotted the deflections for each and compared to the original part as shown on the plot below:

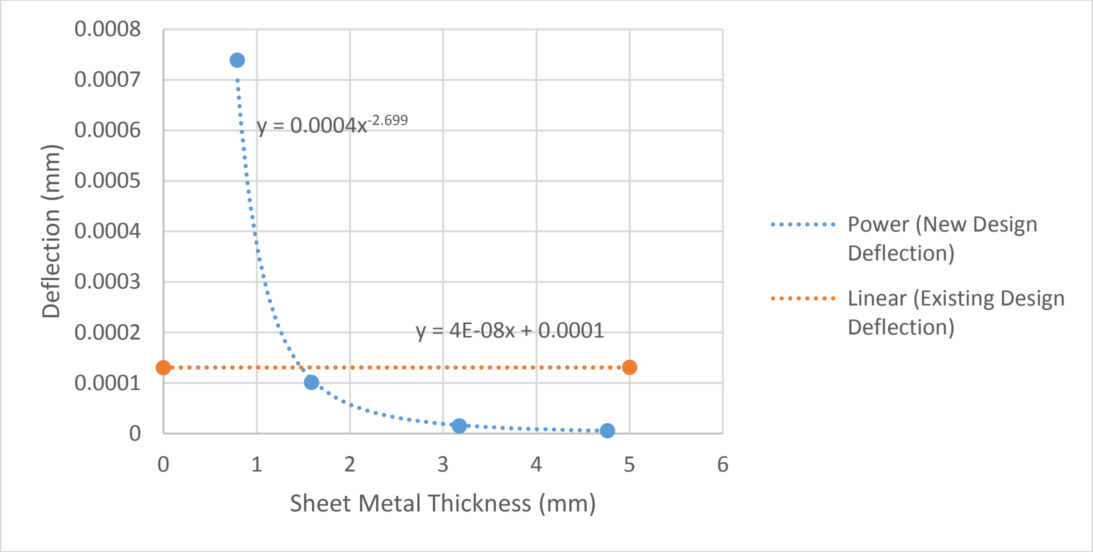

Figure 4. Deflection of Existing Design Compared to Deflection of New Design

On this plot, the orange line represents the deflection that occurred in the existing 3D printed part. This line is horizontal because the part was analyzed at one thickness and creating a line made it easier to visually tell the point where the new design deflection (blue line) is less. So from analyzing the plot, one can see that the first point that has less deflection is the second point or 1.5875 mm (1/16”) thick part. Therefore, from my FEA analysis I was able to prove that the new design will in fact deflect less while using a reasonable thickness of sheet metal. However, from looking at the plot, if I was to choose a design that I would actually attach and use with the 3D printer, I would make the part with sheet metal that is 3.175 mm (1/8”) thick in order to have a more significant increase in performance with the new design. With this design the deflection would be 1.537*10^-5 mm which is only 11.7% of the deflection that the original design was experiencing.

Manufacturing

For my project, the plan was to design and eventually remake the part that I analyzed for my project. Dr. Macedo and I met several times to discuss the best way to manufacture the part. Through this I was able to create a fairly simple manufacturing process that would allow the part to function properly with the 3D printer. This process consisted of using a CNC Plasma Cutter and a welding equipment (most likely TIG) to create the final part. The plasma cutter would cut the sheet metal to the desired dimensions, create holes and cut perforations to make bending easier, and then welding would be used to attach the two pieces and lock the bent angles of the part. Even though I had developed the manufacturing process, I was unable to actually conduct the process due to the fact that the equipment I was planning to use had not been received by the IME department in time. However, with the design and manufacturing process established I hope that someone in the future is able to build and test the part to analyze its performance in a realistic scenario.

Scaling

One of the key benefits to designing the part the way that I did is that it makes it capable of being scaled for larger size printers. The main limiting factor for producing this part in a larger size is the thickness of sheet metal that is available. For the scale of my design, I found the optimal sheet metal thickness to be 1/8", which was for a 2.5 ft tall printer. From researching online I was able to find that manufacturers sell sheet metal as thick as ¼". So, based off of my initial design I would assume that this thickness of sheet metal would allow for the part to perform similarly in a 3D printer that is about twice as large as the existing printer. If a larger scale printer is desired, than sheet metal would not be a feasible material choice meaning that the tools used for manufacturing would most likely have to also be changed. I estimated the sheet metal thickness that would need to be used to get similar performance as the printer in the IME lab. This is shown in Table 3 below:

Table 3. Estimation of Sheet Metal Thickness Required for Various Sized Printers

Printer Height (ft)	Sheet metal Thickness (in)
1	0.05
1.5	0.075
2	0.1
2.5	0.125
3	0.15
3.5	0.175
4	0.2
4.5	0.225
5	0.25

Several assumptions were made in order to obtain these values. First off, one would have to be using the same style of printer, since 3D printers have various structural designs. In addition, I assumed that the loads on the bracket would increase proportionally to the increase in height of the printer. By analyzing Table 3 one can see that the 5 ft printer would require the maximum thickness of sheet metal sold, therefore making this the largest printer that could utilize my design.

Economics

As part of my analysis to justify using my new design over the existing 3D printed design I performed an economic comparison between the two. I found that the main advantage of using sheet metal to produce the part was the material cost. The sheet metal would cost around $1.30 per part and includes the cost of the material that is subtracted and thrown away; and the ABS for the printer costs about $3.00 per part. However, even though the material costs are much cheaper for the sheet metal design, the initial cost of the tooling is much more expensive. Because of this, in order for the new design to be more cost effective, a large quantity of parts will need to be produced. In order to find the quantity that would need to be produced in order for the new method to be more cost effective, I did an analysis by plotting the total cost in comparison to quantity of parts for each method and fit them to a line. Assumptions were made about the initial cost of the tooling required based off of research on the internet in order to do this analysis. These values can be seen in the Table 4 below along with the results of the analysis in Figure 5:

Table 4. Estimation of Initial Cost of Tooling

	Initial Cost of Tooling
CNC Plasma Cutter	$6,000
Welding Equipment	$1,000
3D Printer	$3,000

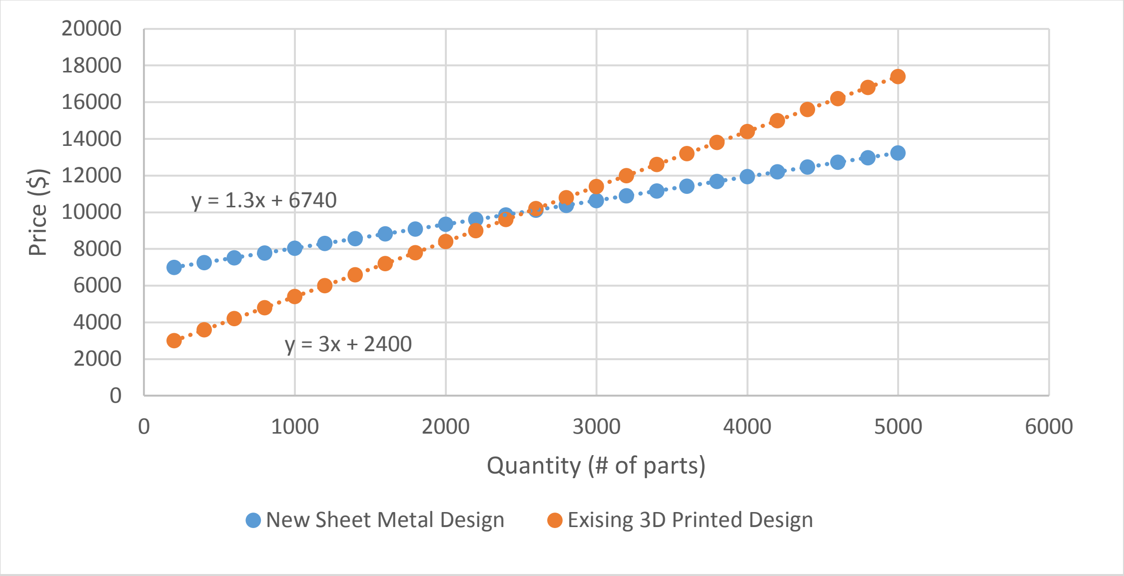

Figure 5. Cost Analysis of Both Methods w/High Volume Production

From this analysis I was able to solve for the break-even point, the point where the cost of both options are equal. By equating the two equations shown on the plot I was able to find that this point occurs at 2,553 parts. This means that if one were to want to produce a larger quantity of parts, the sheet metal design would have lower manufacturing costs when it comes to tooling and material. This seems extremely advantageous, however, there are other criteria to consider in order to fully evaluate the economics between the two methods such as the turnover time for each part and the expertise needed to operate these machines.

In addition to being more cost effective in high quantities, the sheet metal design would most likely have a shorter turnover time when produced in high volume. This is mainly due to the fact that having a multiple stage manufacturing process allows for the ability to work in teams and be simultaneously working on different parts of the process. If done correctly, there is potential for an extremely efficient manufacturing process to be conducted.

The largest drawback to manufacturing the part out of sheet metal is the expertise needed in comparison to 3D printing. The CNC plasma cutter is automated similarly to the 3D printer, however, welding is an extremely difficult skill to master making the labor fairly costly. This fact alone could most likely cause the 3D printer to be more economically feasible. In order to further evaluate this, a detailed high volume manufacturing strategy would need to be created in order to estimate the labor costs per part associated with each of the methods.

Conclusion

Overall, in the end I was successful in accomplishing my main goal of designing a new bracket that would limit the deflection of the 3D printer frame. By making the base corner bracket out of carbon steel sheet metal I found that I could limit the deflection of this part by almost 90%. Even though this does not necessarily mean the entire frames deflection will be reduced by the same amount, the criticalness of this part on the structures stability infers that the deflection of the structure should also be greatly reduced. Even though my analysis was successful, I was not able to conduct the manufacturing process because the IME department had not received the CNC Plasma Cutter I planned to use. However, I created a process that is simple and requires minimal expertise for the tooling used. I would hope that with that process available, someone that has the desire to improve the stability of a 3D printer will try to eventually make the part in the future and test its functionality. Lastly, I found that there were several economic advantages to making the part out of sheet metal such as material cost and tooling/material cost effectiveness with large scale manufacturing. However, without delving deeper into the details of a large scale manufacturing process, it is hard to justify whether or not the labor costs associated with not having a fully automated process would prevent the sheet metal design from being an economically feasible option.

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Appendix A:
Force Calculations

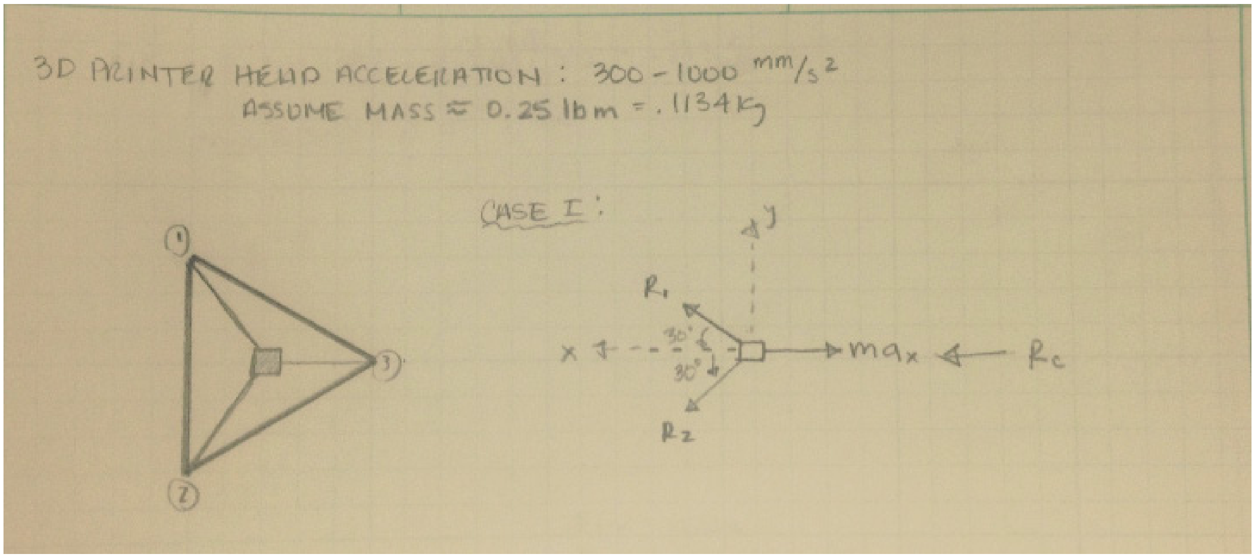
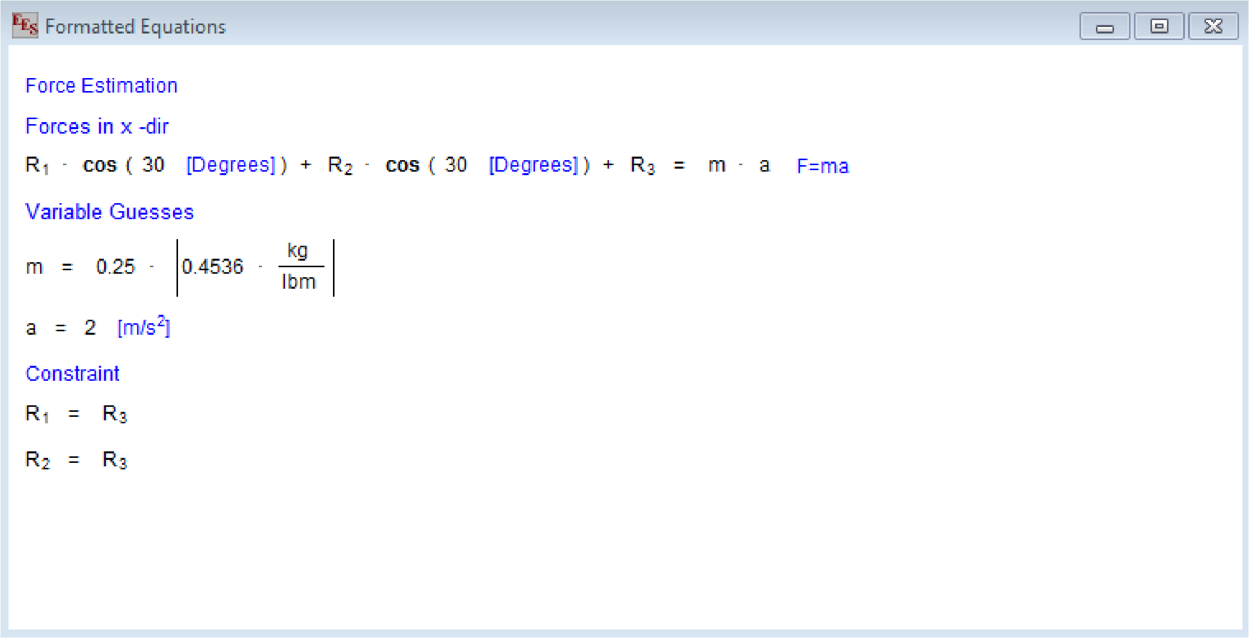


Figure A-1. Free Body Diagram for Force Analysis



Force Estimation

Forces in x -dir

$R_1 \cdot \cos(30\ [\text{Degrees}]) + R_2 \cdot \cos(30\ [\text{Degrees}]) + R_3 = m \cdot a$ F=ma

Variable Guesses

$m = 0.25 \cdot \left| 0.4536 \cdot \frac{\text{kg}}{\text{lbm}} \right|$

$a = 2\ [\text{m/s}^2]$

Constraint

$R_1 = R_3$

$R_2 = R_3$

Figure A-2. EES Formatted Equations that show fundamental equations and assumptions

Unit Settings: SI C kPa kJ mass deg

a = 2 [m/s^2]   m = 0.1134 [kg] R_1 = 0.08301 [N] R_2 = 0.08301 [N] R_3 = 0.08301 [N]

No unit problems were detected.

Calculation time = .0 sec.

Figure A-3. Solution with initial mass and acceleration guesses

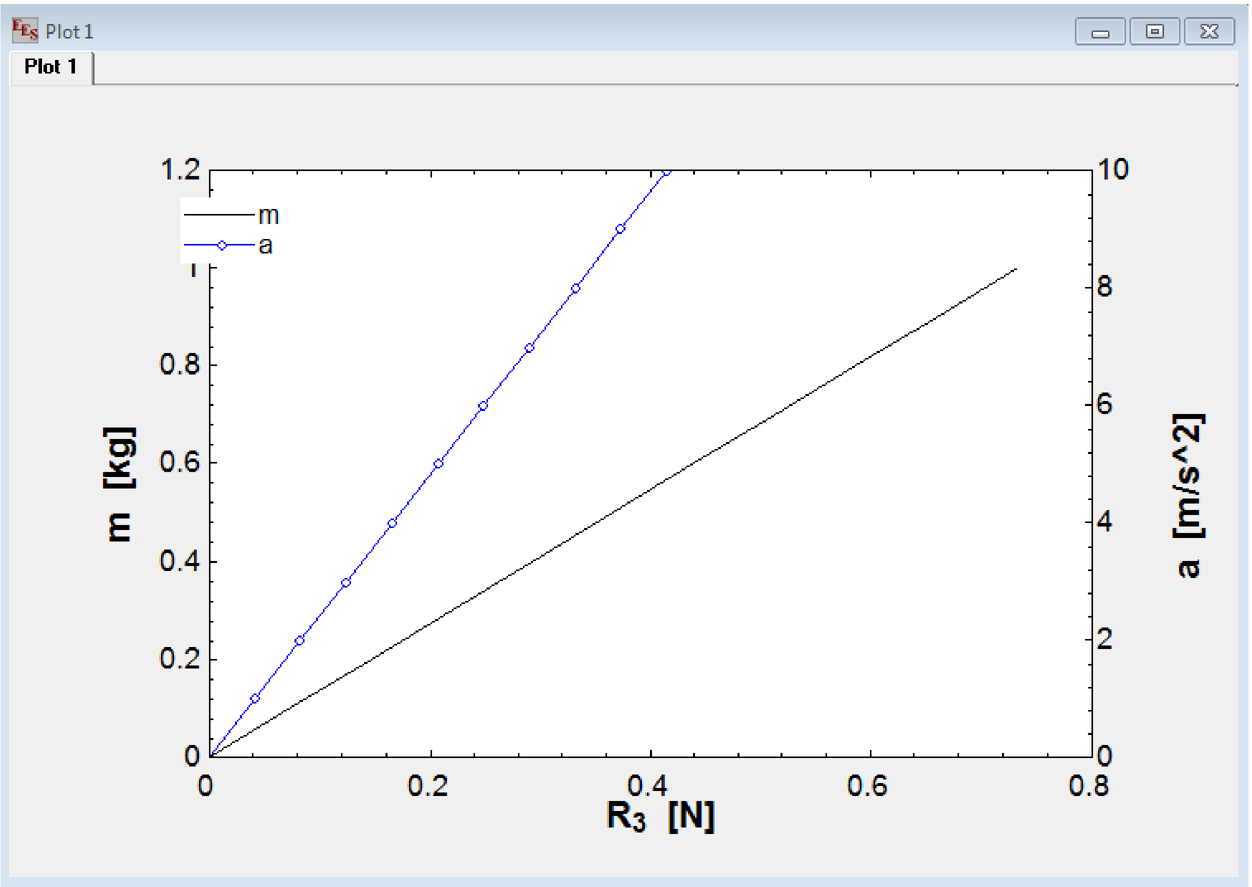


Figure A-4. EES Overlay Plot showing reaction force as mass and acceleration vary separately

Appendix B:

SolidWorks Dimensioned Drawings

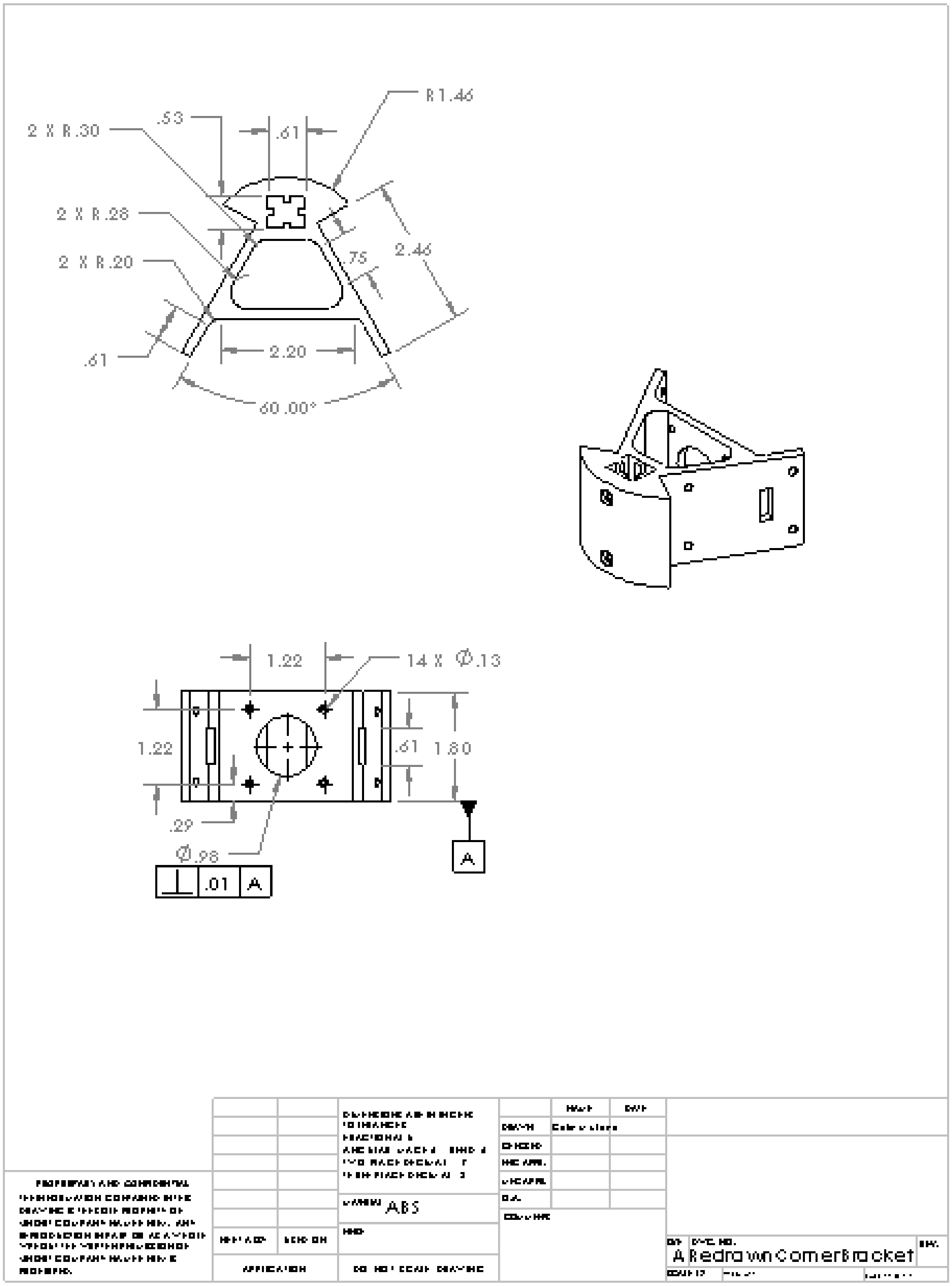


Figure B-1. Dimensioned Drawing of Existing 3D printed corner bracket

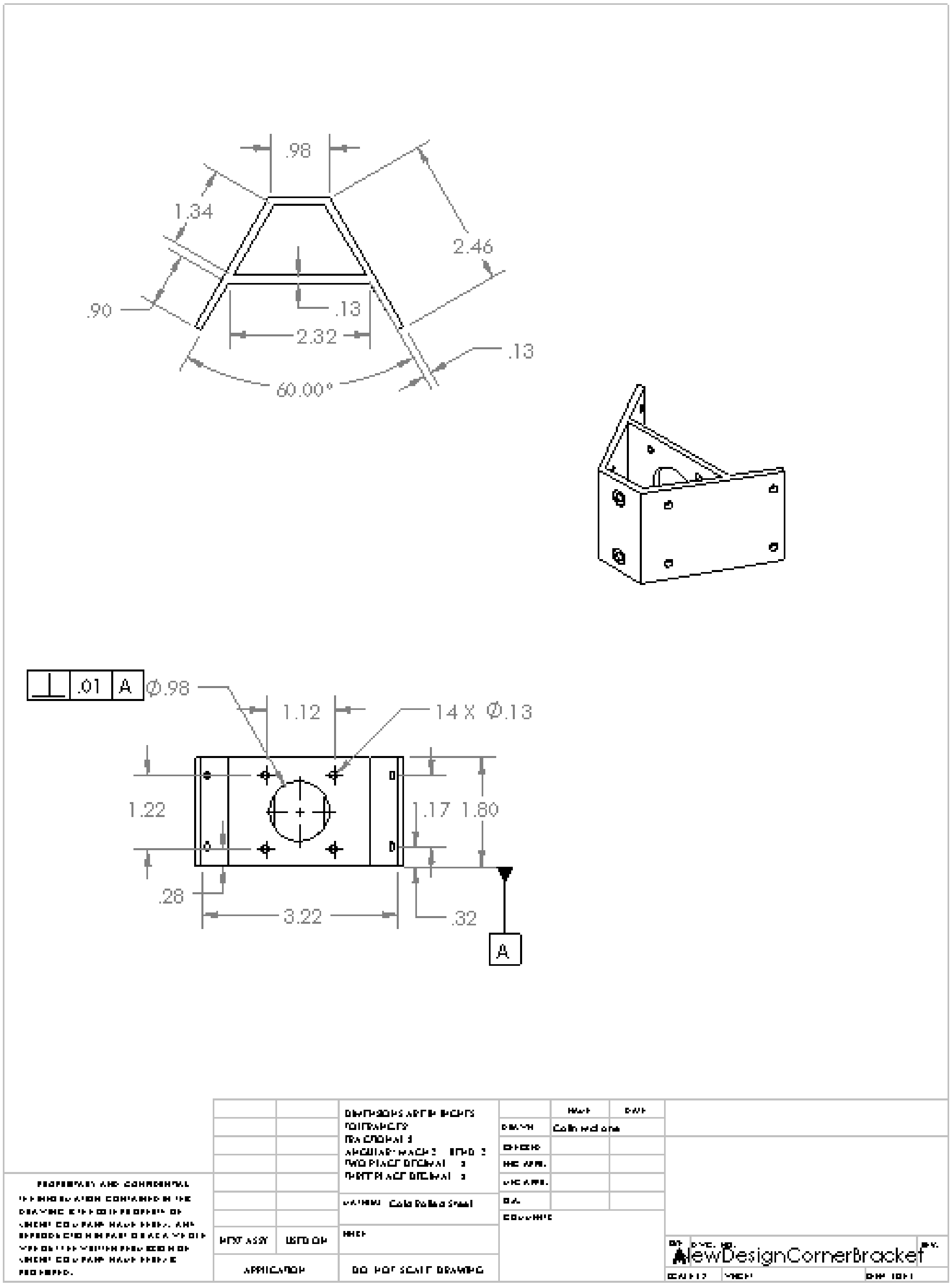


Figure B-2. Dimensioned Drawing of Completed New Design

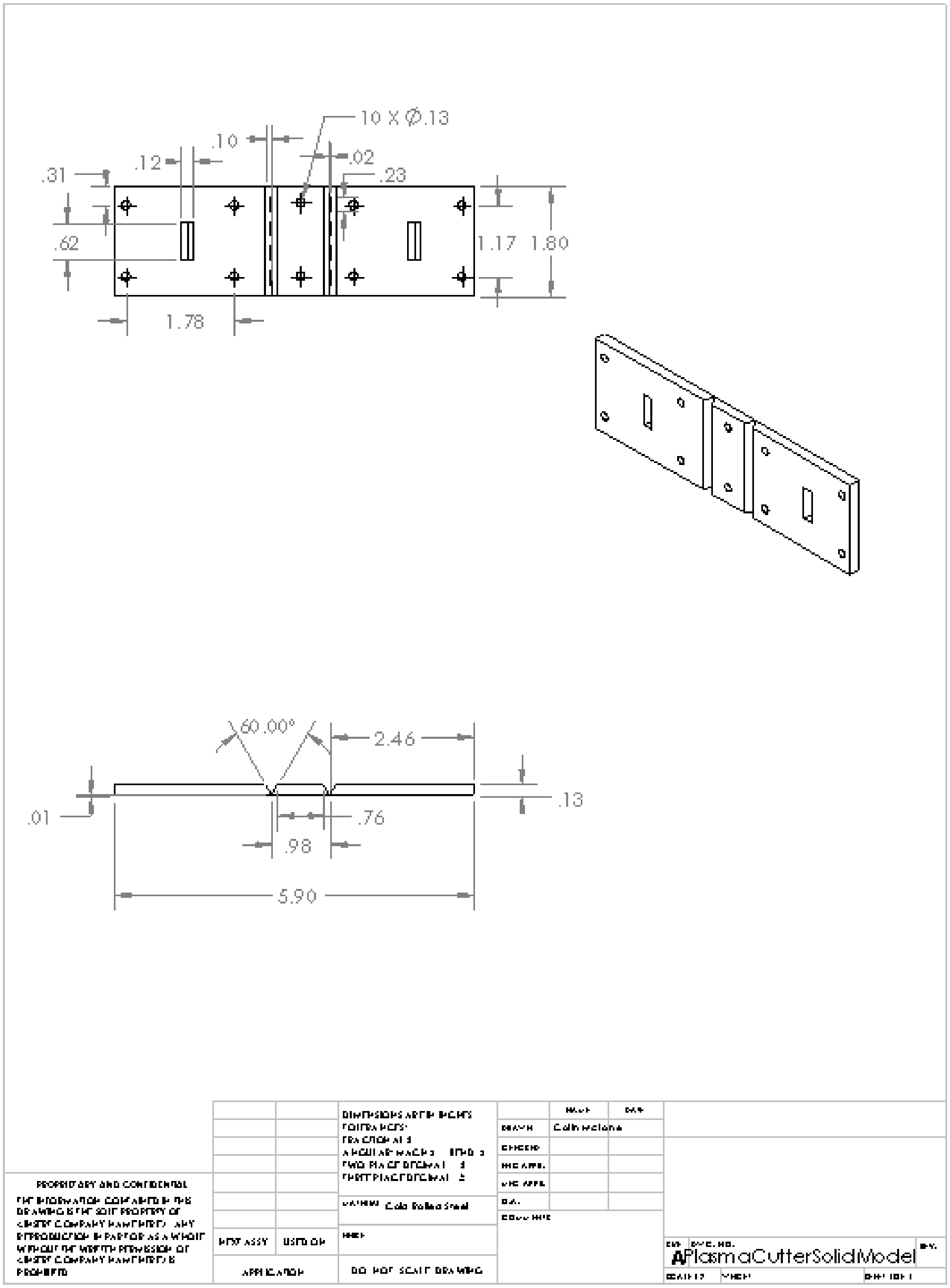


Figure B-3. Dimensioned Drawing of Angled Section of New Design

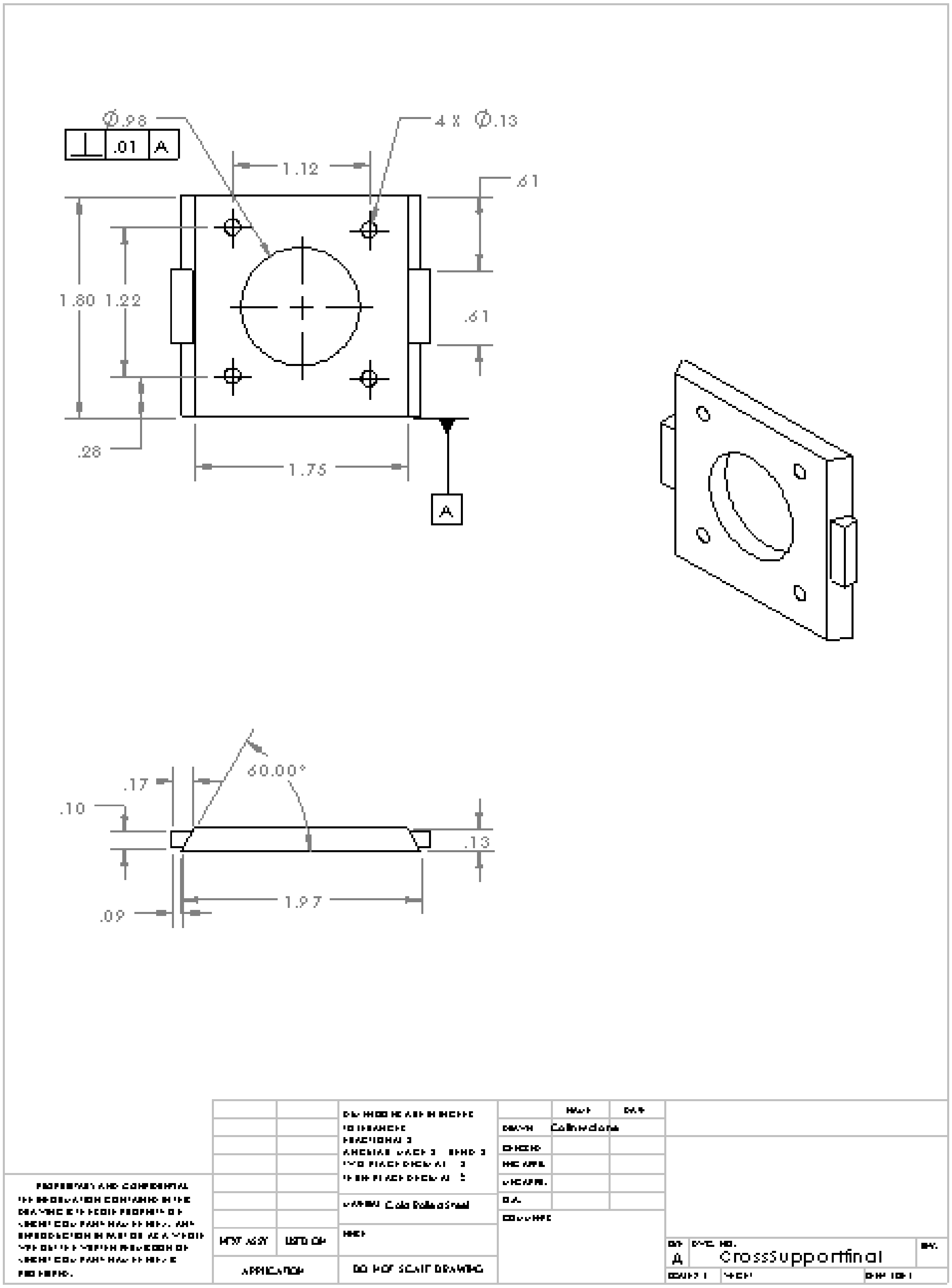


Figure B-4. Dimensioned Drawing of Cross Support of New Design

Appendix C:

Stress and Deflection Results

Analysis Assumptions:

-Uniform Force of 1 Newton @ Vertical Support Mount

-Base is fixed to the ground

Existing 3D Printed ABS design

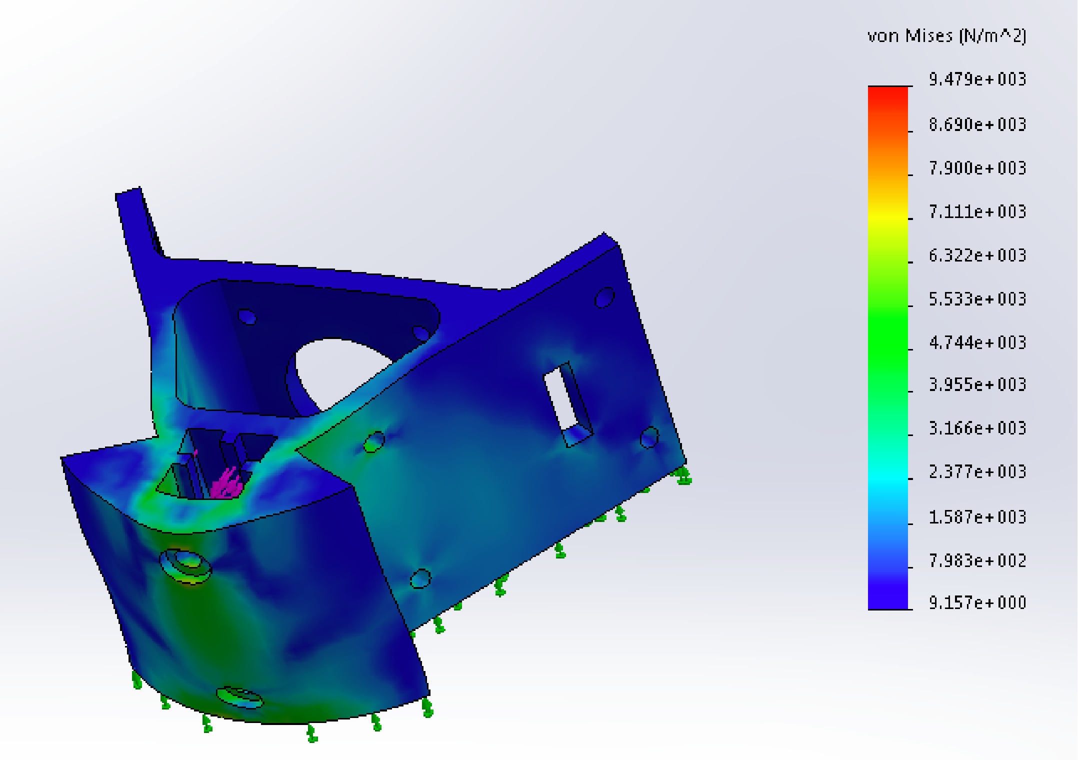


Figure C-1. Stress Analysis on Old Design

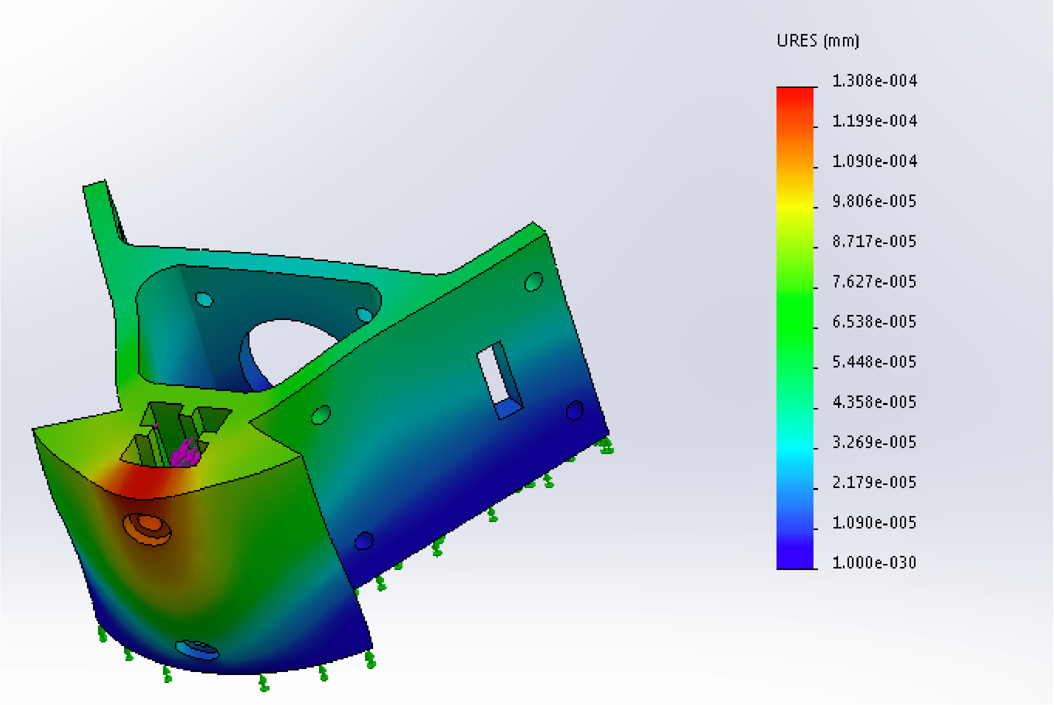


Figure C-2. Deflection Analysis on Old Design

1/32" Carbon Steel Sheet Metal

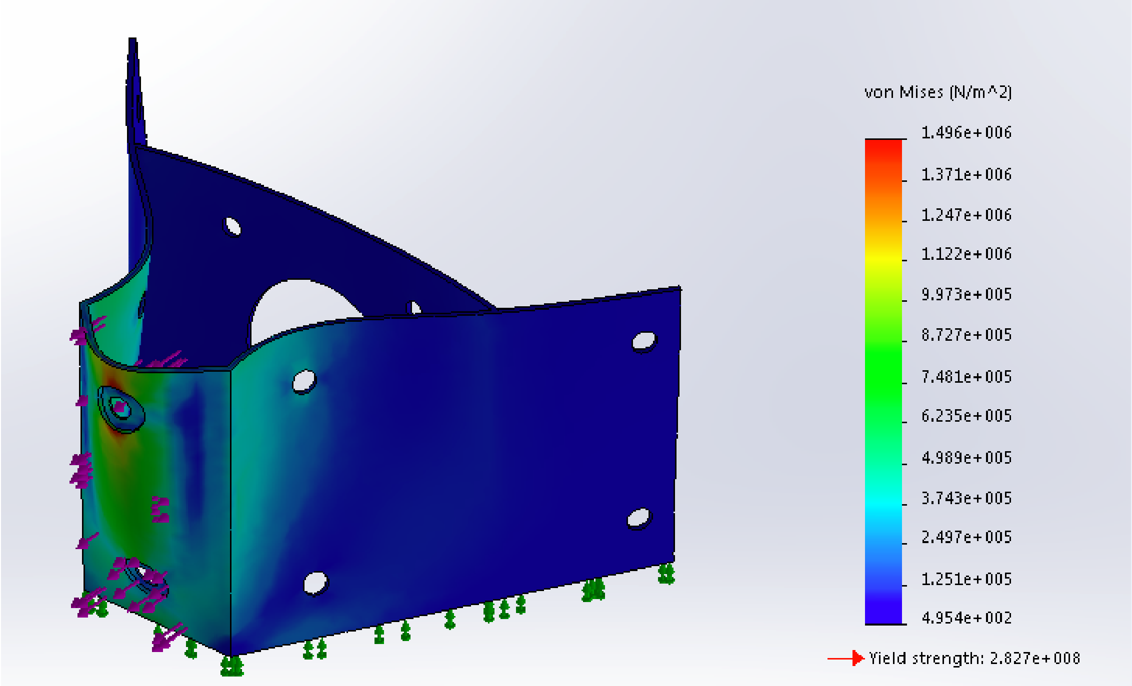


Figure C-3. Stress Analysis on New Design

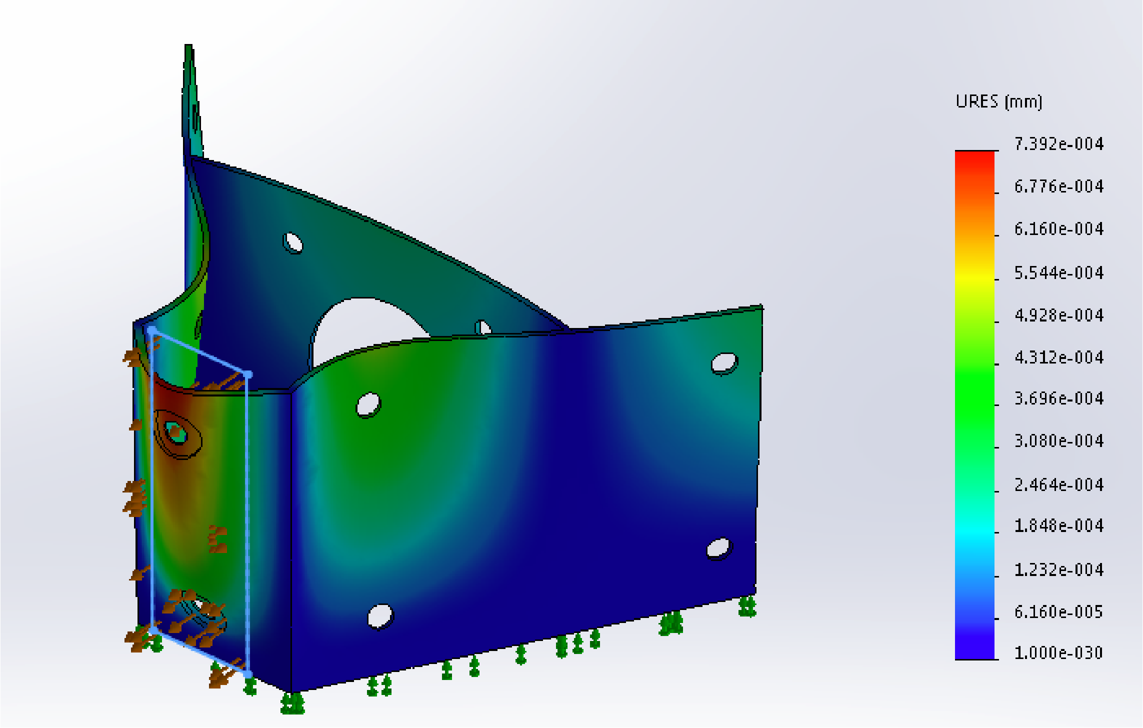


Figure C-4. Deflection Analysis on New Design

1/16” Carbon Steel Sheet Metal

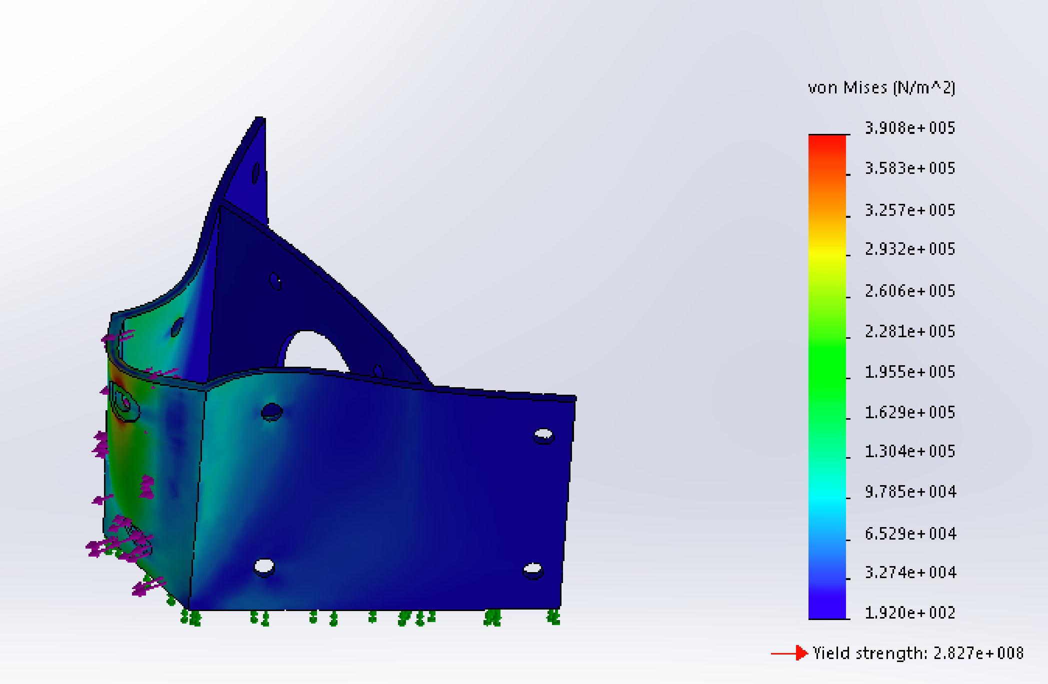


Figure C-5. Stress Analysis on New Design

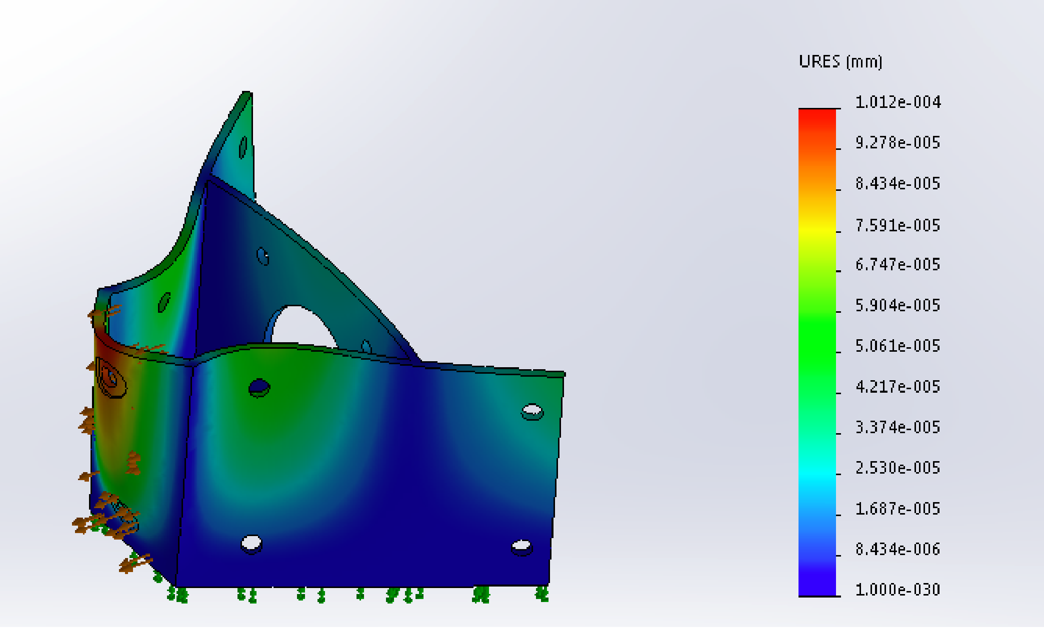


Figure C-6. Deflection Analysis on New Design

1/8” Carbon Steel Sheet Metal

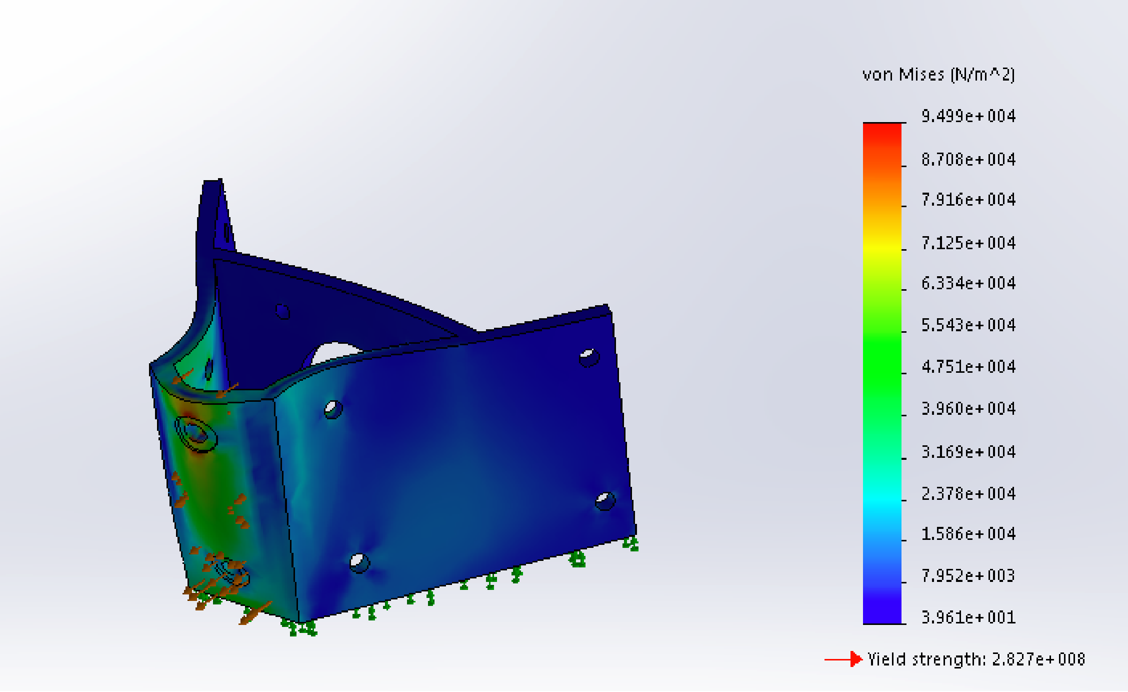


Figure C-7. Stress Analysis on New Design

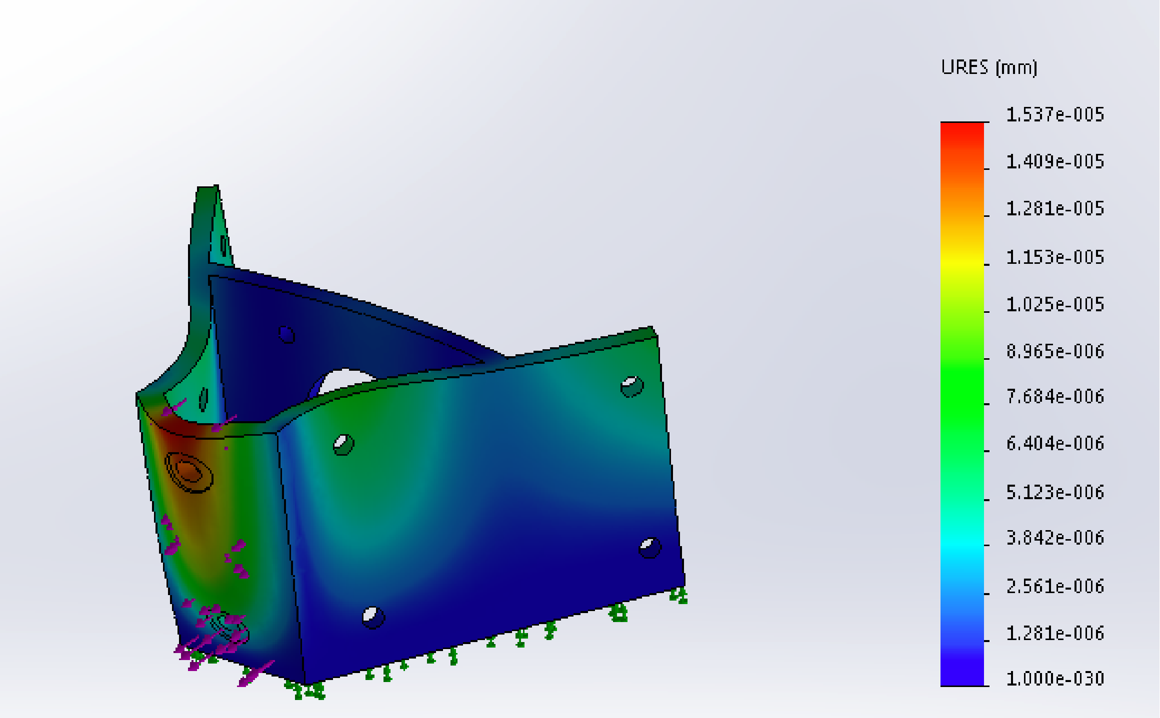


Figure C-8. Deflection Analysis on New Design

3/16" Carbon Steel Sheet Metal

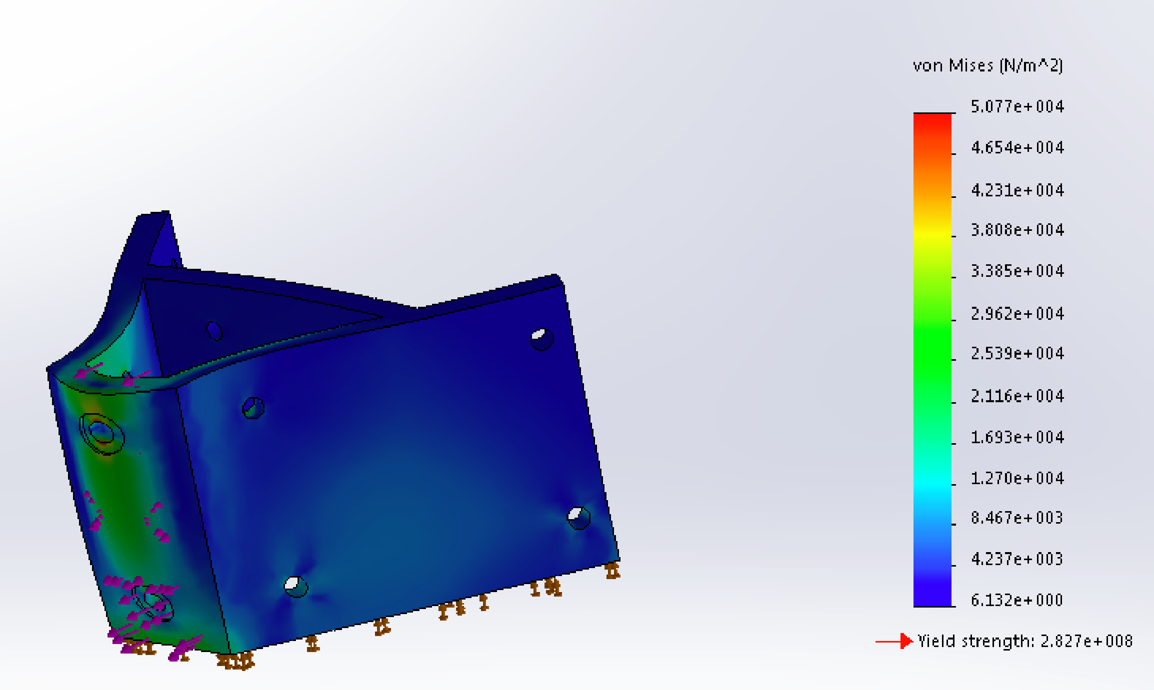


Figure C-9. Stress Analysis on New Design

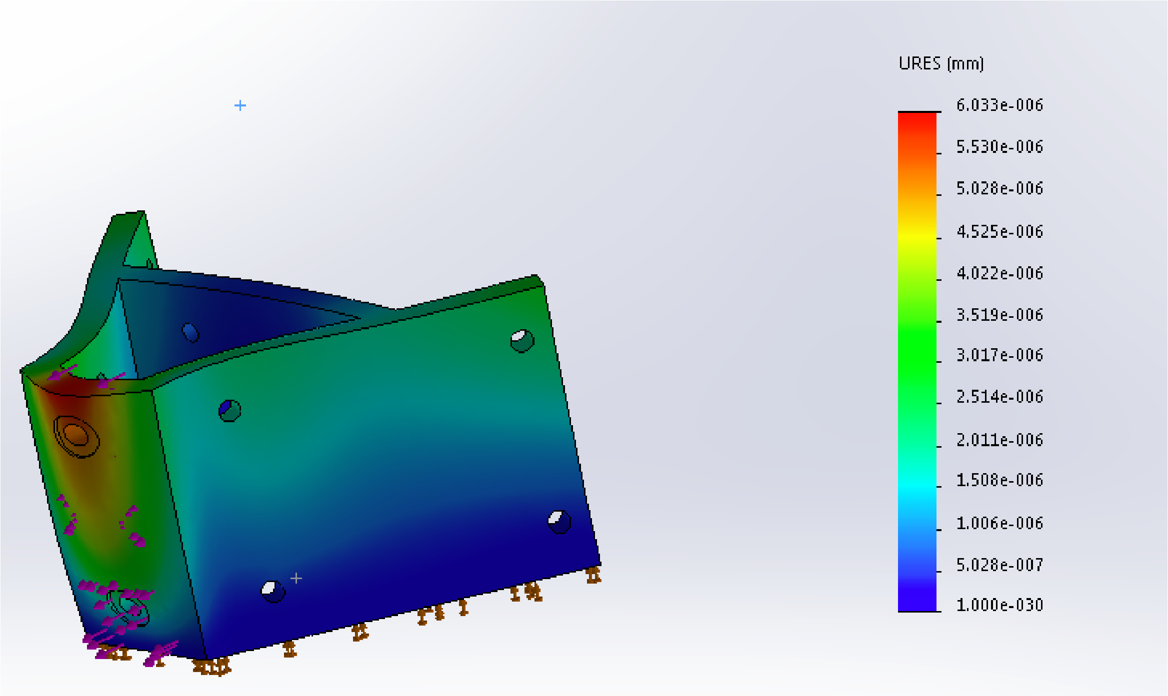


Figure C-10. Deflection Analysis on New Design

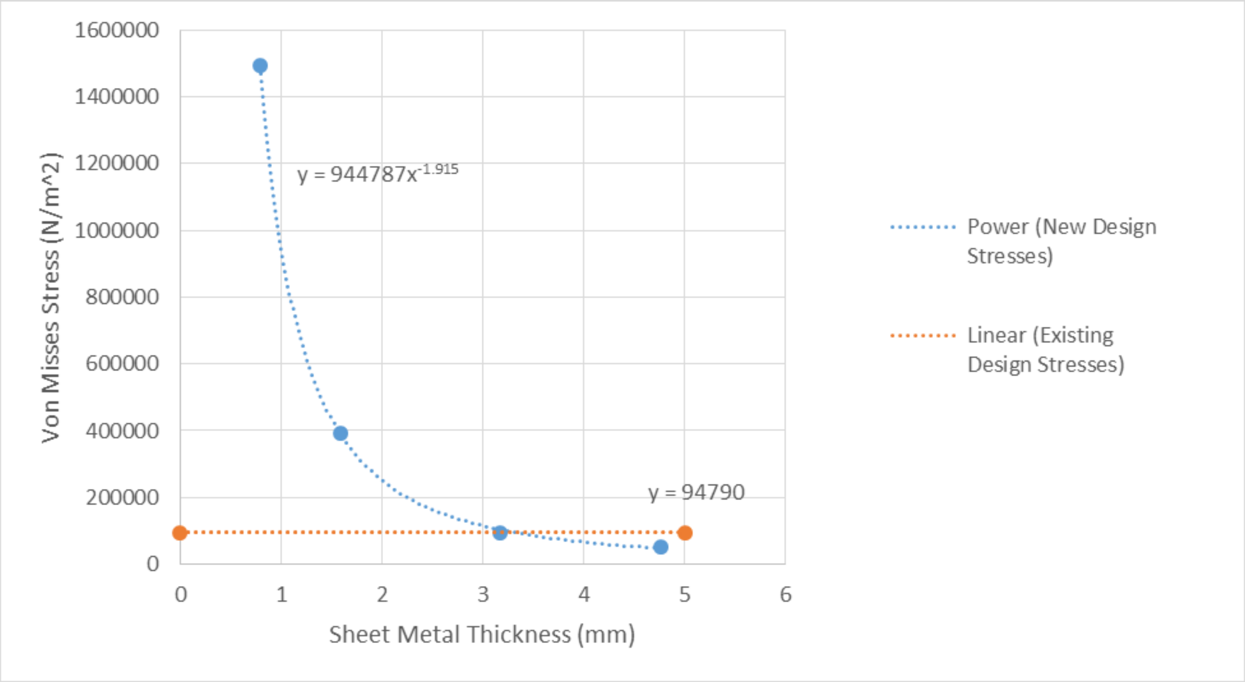


Figure C-11. Plot of Maximum Stresses for Each Design

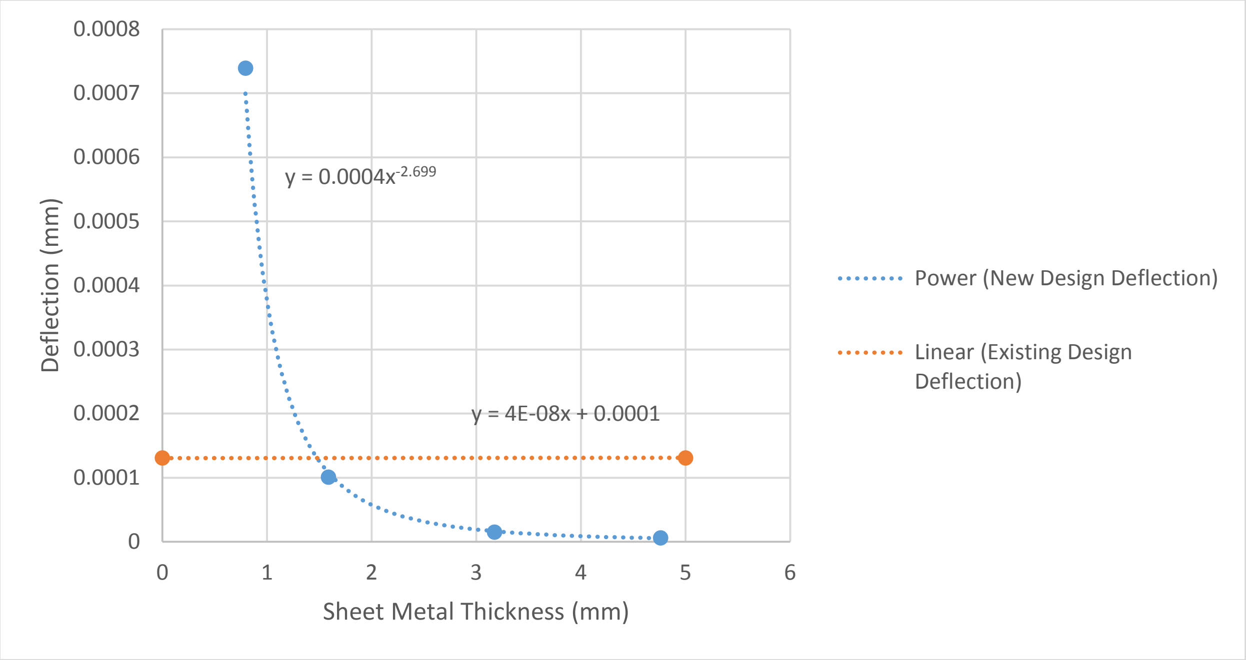


Figure C-12. Plot of Maximum Deflection for Each Design