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ME 486C

To: David Willy, Connor R. Gaudette

From: *Nathan Krikawa, Nolan Hann*

Date: *1/21/25*

Re: *Engineering Calculations Summary*

1. Top Level Design Summary

1.1 Problem and Solution

Our project is the commissioning, testing, initial operation, and training development of a Concept Laser Mlab cusing R metal 3D printer. This printer was donated by Honeywell to NAU's ME department and is currently stationed in NAU's IDEA Lab in the engineering building. The goal is to have the printer fully functioning by the end of the 2024-2025 school year and ready to be integrated into the ME286L manufacturing lab curriculum as well as have it open for work orders from the IDEA Lab.

The calculations within this project relate to our final print deliverable. After the printer is up and running, we will print a final part to be implemented in an assembly for demonstration. The goal of this demonstration is to show off the capabilities of additive metal manufacturing by using topology optimization to print a part which would be impossible to realize with subtractive manufacturing. Topology optimization uses software to take the geometry of a part and maximize its efficiency under a specific load case by redistributing and subtracting material. This results in a much lighter part without compromising its structural integrity under that load case. We designed two parts to optimize and scale down for this print: a skateboard truck, and a bicycle crank arm.

After initial testing and optimizations, we decided to move forward with the skateboard truck over the bicycle crank arm, as it will be more visually appealing and easier to integrate into a larger assembly such as a hand board. Calculations and CAD models for the crank arm will be in the appendix.

1.2 Top-Level CAD

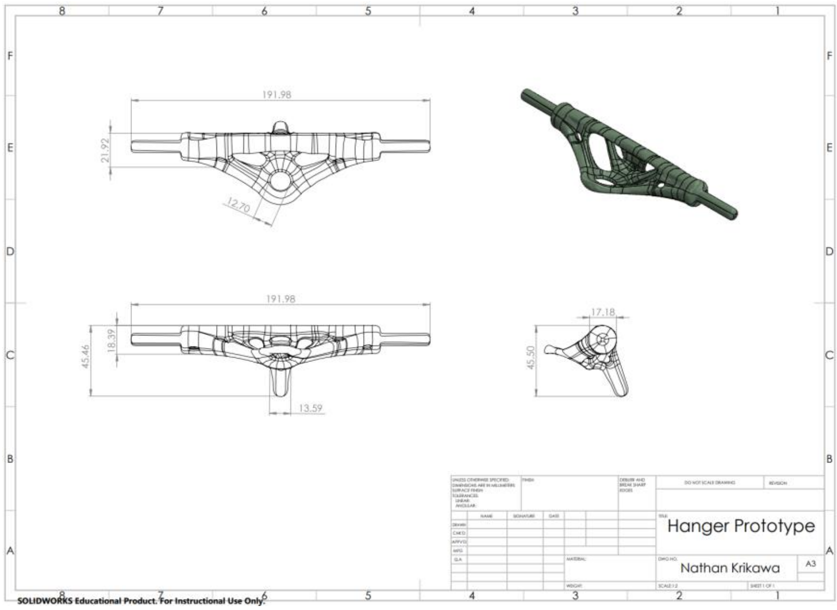


Figure 1: Optimized Truck Hanger

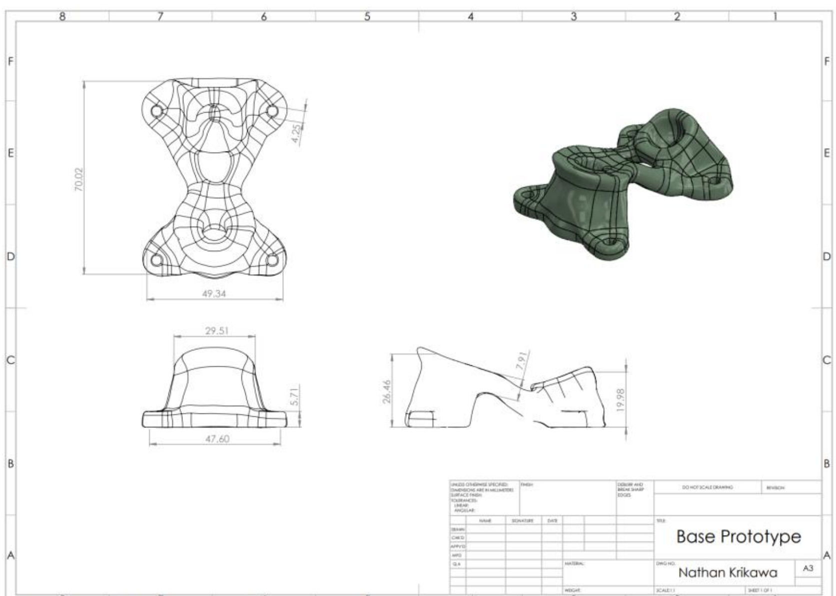


Figure 2: Optimized Truck Baseplate

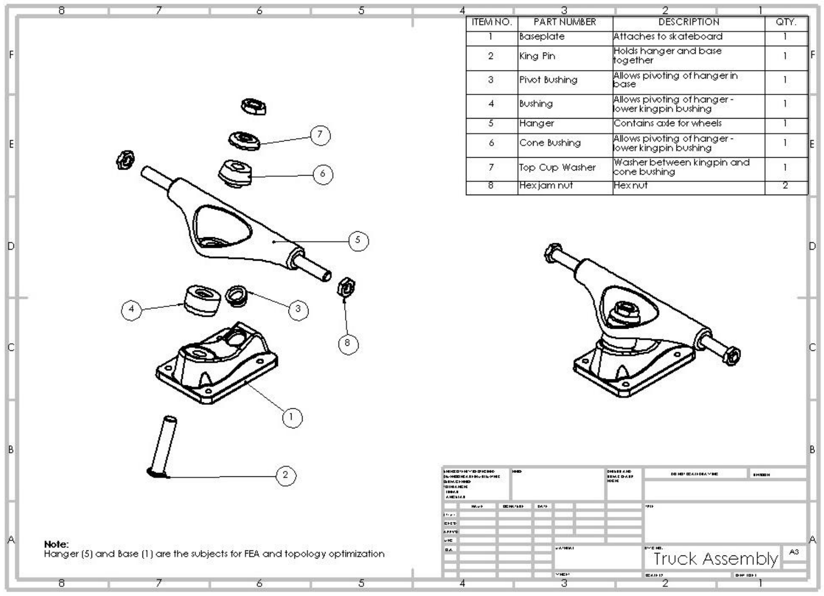


Figure 3: Truck Assembly

1.3 QFD

The requirements of this project are determined through a needs-based assessment of our customers and their desired outcome. Our customer is the ME department chair Dr. Ciocanel, as we are commissioning a machine for use by the ME department. This section will cover our customer's requirements for our project, the engineering requirements for the commissioning of the machine, as well as a house of quality visual analysis of these requirements and their relations to one another.

1.3.1 Customer Requirements

Our customer requirements represent the most important aspects of the project as defined by the customer. These are listed below with a description how they are evaluated:

- **Ease of Use:** Successful and efficient integration of our machine's operating procedure with the existing workflow of the IDEA Lab. Quality of our training program.
- **Safety:** The safety of ourselves and all people in the IDEA Lab during and after operation of the machine. Includes strict adherence to safety protocols along with signs and notices of dangerous procedures and areas and required personal protective equipment.
- **Time:** Installation and repairs completed as soon as possible, with timely completion of deliverables such as the training program. Should be fully operational and ready for use by others by the summer of 2025.
- **Successful Installation:** Fully operational printer.
- **Tensile Test Results:** Comprehensive and accurate results which demonstrate printed material strength.
- **Final Part and Assembly:** Demonstrates capabilities of additive metal manufacturing. Part could not be manufactured with subtractive manufacturing. Part is designed with topology optimization for maximum efficiency.
- **Instruction Manual:** Completed training program along with a simplified operating and safety manual for future ease of use.

1.3.2 Engineering Requirements

The engineering requirements of this project relate to our printing constraints and the physical requirements of the printer. These are listed below along with a description of each:

- **Materials Tested:** There is a wide range of materials that can be used in this machine including aluminum, stainless steel, titanium, and bronze. We will be using 316L stainless steel initially as it is safer than more reactive metals such as aluminum and titanium, and was donated to us by the U of A.
- **Final Print Material:** The main contenders for a final print material are 316L stainless steel, aluminum, and titanium. This will depend on our capabilities at the time as well as the desired strength and weight as determined by the assembly. This will affect customer requirements such as safety, time, ease of use, and final part and assembly.
- **Final Print Volume:** This is the main constraint of the machine, as we are limited to a print volume of 90 x 90 x 80mm.
- **Power:** The machine requires a 230V, 16A outlet to operate.
- **Inert Gas:** Nitrogen or Argon gas can be used to create an inert environment for the safe melting of powder. We will be using Argon gas as it is the most widely useable across different metals.
- **Young's Modulus Tested:** The result of the tensile tests, to be measured in GPa. Normally 316L stainless steel tests at around 193 GPa.
- **Dog Bone Size:** Determined by print volume, testing apparatus, and availability of machined dog bones.

System HOQ — Project: **Metal 3D Printer** — Date: 10/20/2024

Engineering Requirements	Materials Tested	Final Print Material	Final Print Volume	Power	Inert Gas	Young's Modulus Tested
Materials Tested						
Final Print Material	+9					
Final Print Volume	-1	-1				
Power						
Inert Gas	+9	+9				
Young's Modulus Tested	+9	+3		+1	+1	
Dog Bone Size	+1		+9			+3

Customer Needs	QFD	Materials Tested	Final Print Material	Final Print Volume	Power	Inert Gas	Young's Modulus Tested	Dog Bone Size
Ease of Use	3	3	3					
Safety	5	9	3		3	3		
Time	4	1	1	1	3	3		1
Successful Installation	5	9	1	1	9	9		
Tensile Test Results	2	3	9				9	3
Final Part and Assembly	4		9	9	9	9	3	
Instruction Manual	5	3					3	
Engneering Requirement Units		Al, SS 316L, Ti, Bronze	Al, SS 316L, Ti, Bronze	mm^2	V, A	N, Ar, bar, purity	Gpa	mm
Engineering Requirement Targets		All	SS 316L	<90x90x80	230V, 16A	2 bar N, Ar, purity >=2.5	193	N/A
Absolute Technical Importance		124	87	45	108	108	45	10
Relative Technical Importance		12.41241	8.708709	4.504505	10.81081	10.81081	4.504505	1.001001

Figure 4: QFD

2. Summary of Standards, Codes, and Regulations

Operating Manual, Type: Mlab cusing R
This manual from the Hofmann Innovation Group provides detailed operational guidelines for the Concept Laser Mlab cusing R, a metal 3D printer that uses powder bed fusion (PBF) technology. The document covers essential aspects of machine operation, including setup, calibration, safety protocols, and maintenance procedures. It also provides instructions for optimizing printing parameters to achieve high-quality prints in various metal alloys. This manual is critical for technicians and operators working with the Mlab cusing R, as it offers comprehensive instructions to ensure proper machine function and maximize part quality, making it an important resource in the practical deployment of metal additive manufacturing systems.

"Additive manufacturing of metals — Finished part properties — Post-processing, inspection and testing of parts produced by powder bed fusion"
This document specifies requirements for the qualification, quality assurance and post processing for metal parts made by powder bed fusion. It also specifies methods and procedures for testing and qualification of various characteristics of metallic parts made by additive manufacturing powder bed fusion processes, in accordance with ISO/ASTM 52927, categories H and M. This standard is helpful for adjusting and post processing any parts that were made by the school's machine so that they are up to industry standards for additive manufactured parts.

"Standard Practice for Reporting Data for Test Specimens Prepared by Additive Manufacturing"
This standard specifies a standard procedure for reporting results by testing or evaluation of specimens produced by additive manufacturing. establishes minimum data element requirements for reporting of material and process data for the purpose of: Standardizing test specimen descriptions and test reports, assisting designers by standardizing AM materials databases, aiding material traceability through testing and evaluation, and capturing property-parameter-performance relationships of AM specimens to enable predictive modeling and other computational approaches. This standard is important for

"F3592 Standard Guide for Additive Manufacturing of Metals – Powder Bed Fusion – Guidelines for Feedstock Re-use and Sampling Strategies"
This standard is intended to support AM users with the selection of the optimum re-use strategy for their AM process and provide guidance on how to implement re-use strategies in their organization. This guide suggests possible control measures that AM users can use to maintain powder quality, and factors to consider when validating selected re-use strategies, including guidance on sampling techniques.

"F3184 Standard Specification for Additive Manufacturing Stainless Steel Alloy (UNS S31603) with Powder Bed Fusion"
This standard for the usage of 316L steel in powder bed fusion from 2023 is a great up-to-date resource that we will be referencing often throughout this project. It covers everything we need to know about the material, how it prints, and how best to utilize it for good results.

3. Summary of Equations and Solutions

3.1 Load-Case Conditions

This section contains the assumptions used to calculate the loads which the skateboard truck was subjected to in the topology optimization simulation.

The assumptions of this optimization regard the load conditions with which we performed the simulations. There are three separate loads we included: a vertical impact load on the ends of the truck (wheels), a horizontal impact load on the ends of the truck, and a vertical impact load along the truck. In both vertical load cases, horizontal momentum is not accounted for to consider the worst-case scenario. It should be noted that while each of these load cases are for different scenarios, the topology optimization must be performed with all potential worst-case loads applied to the model at the same time to account for all situations in the result of the simulation.

Vertical impact load on ends of truck (1):
This load was calculated with the conditions of a 250lb person and 5.5lb skateboard falling 5 feet onto a single truck with an impact time of 0.1 seconds. The load calculated is split between both ends of the truck, as the truck would tilt and intersect with the board if the load was only applied to one.

Horizontal impact load on ends of truck (2):
This load was calculated with the conditions of a 250lb person and 5.5lb skateboard hitting an obstacle while traveling at 10mph with an impact time of 0.1 seconds. The load calculated is applied to both ends of the truck to simulate hitting a rock or similar object and is applied to both ends of the truck separately. This is to simulate a worst-case scenario where the skateboard and person are stopped completely by a rock hitting one wheel. It is applied to both sides of the truck for symmetry in the topology optimization simulation.

Vertical impact load along the truck (3):
This load was calculated with the conditions of a 250lb person and 5.5lb skateboard falling 3ft onto a hard surface with an impact time of 0.1 seconds. This is to simulate a person attempting to grind along a ledge, rail, or other surface in which all the force is directed along the truck and bypasses the wheels.

3.2 Equations and Solutions

Vertical impact load on ends of truck (1):
Impact velocity: $v = \sqrt{2gh}$ $\quad g = 9.81\left(\frac{m}{s^2}\right)$ $\quad h = 5ft = 1.524m$ $\quad v = 5.47\left(\frac{m}{s}\right)$
Total mass: $m_{total} = 250lb + 5lb = 255lb = 115.89kg$
Change in momentum: $\Delta p = m_{total} \times v = 634.5kg \times \left(\frac{m}{s}\right)$
Impact load: $F = \frac{\Delta p}{\Delta t} = \frac{634.5}{0.1} = \mathbf{6345N}$

Horizontal impact load on ends of truck (2):
Impact velocity (m/s): $v = 10mph = 4.4704\left(\frac{m}{s}\right)$
Total mass: $m_{total} = 250lb + 5lb = 255lb = 115.89kg$
Change in momentum: $\Delta p = m_{total} \times v = 518.6kh \times \left(\frac{m}{s}\right)$
Impact load: $F = \frac{\Delta p}{\Delta t} = \frac{518.6}{0.1} = \mathbf{5186N}$

Vertical impact load along the truck (3):

Impact velocity (m/s): $v = \sqrt{2gh}$ $g = 9.81\left(\frac{m}{s^2}\right)$ $h = 3ft = 0.9144m$ $v = 4.24\left(\frac{m}{s}\right)$

Total mass: $m_{total} = 250lb + 5lb = 255lb = 115.89kg$

Change in momentum: $\Delta p = m_{total} \times v = 492.7kg \times \left(\frac{m}{s}\right)$

Impact load: $F = \frac{\Delta p}{\Delta t} = \frac{492.7}{0.1} = \mathbf{4927N}$

3.3 Factors of Safety

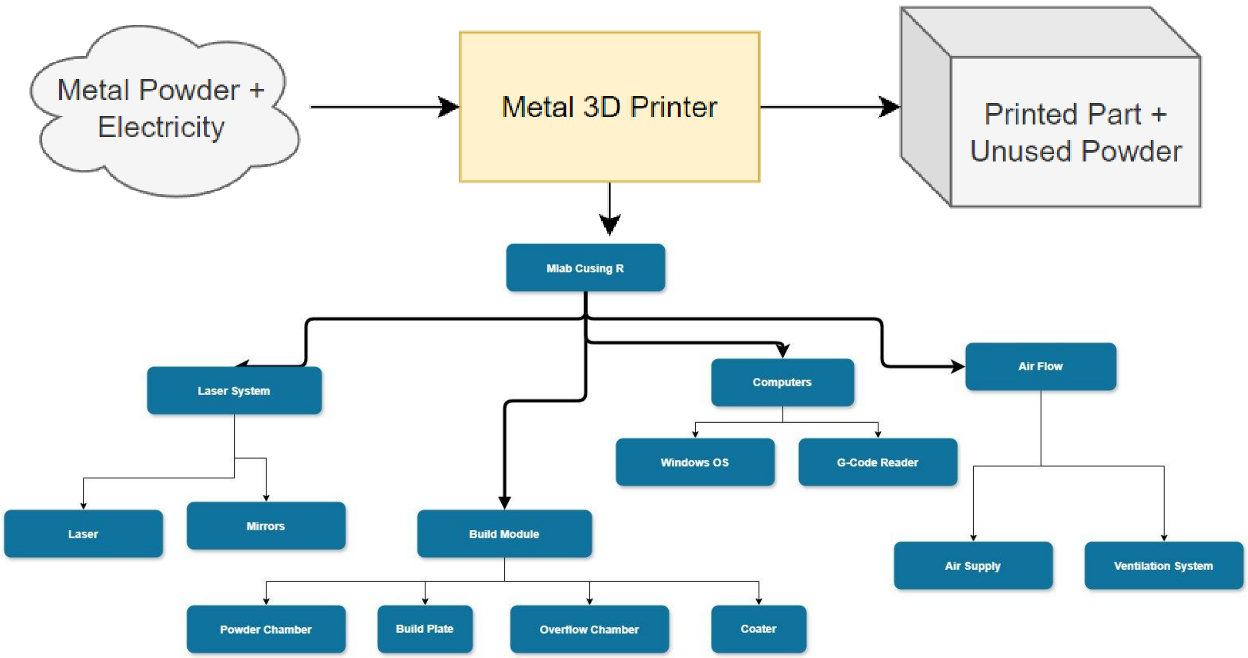
This section covers the factors of safety for both the hanger and the baseplate of our optimized skateboard truck. Action sports equipment typically have safety values between 2 and 4, which is our target for these optimized parts.

Sub-System	Part	Load Case Scenario	Material	Method of Calculating Fos	Minimum FoS
Skateboard Truck					**0.150**
	Hanger	(1), (2), (3)	316L SS	SolidWorks FEA	**0.150** (Appendix C)
	Baseplate	(1), (3)	316L SS	SolidWorks FEA	**0.489** (Appendix C)

These numbers are much lower than our target factors of safety due to our chosen load case conditions exceeding the factors of safety of the original part. The goal of the optimization is to make our optimized parts as safe as the original non-modified skateboard truck while significantly decreasing its weight. We used an industry standard model as our pre-optimization starting point and are confident that it meets safety standards. The issue arose when we used arbitrary "worst case scenario" load cases in which the forces were too high to begin with, rather than choosing our load case based on what the original skateboard truck could withstand. These solutions showed us that we need to re-do our optimization simulations using new load cases derived from the original part and our desired factor of safety. This will be described further in section 5.

4. Flow Charts and Other Diagrams

4.1 Functional Decomposition



The Laser System is the most important system within the printer, as it is what primarily contributes to the theory behind powder bed fusion. The laser is what sinters the printed part to completion. Consequently, it also is the most complex part of the system, requiring a variety of mirrors and lenses to properly move and size the beam. Should any part of the laser system fail it would require the operator to contact the manufacturer of said laser for repairs.

The Build Module is the second most important system, as it is where the powder is stored, sintered, and overflows. The powder chamber itself is an elevator that progressively rises over the duration of the build, allowing the coater to swipe across the surface of the module and apply a new thin coat of powder over the main build plate. The main build plate, like the powder chamber, is an elevator that lowers itself as the build continues. The plate itself is removable and comes in a variety of materials and styles, however, it is finite in the sense that parts are more or less welded to the plate and require special machining to remove. To remove any excess material, the plates need to be slowly milled down so that the surface is smooth. Finally, there is the overflow chamber, where extra unused powder is sent into a spare container at the bottom of a funnel.

The printer has two separate computers, one as a front end for the operator, and another as a means to send specific commands to the various moving parts within the printer. The front end runs on Windows and allows the user to easily access files, or any sort of documents relating to parts or printing and comes preinstalled with an application to read sliced 3d objects and control the system. Any information from this program is sent to the back-end computer to command the machine.

Airflow is another part of the system, as the build process requires an inert environment to properly and safely print out the parts. This means that an inert gas, such as nitrogen or argon, must be supplied to the machine from an external source and constantly flowing inside the build chamber. The gas is eventually filtered and recycled back through the system. This filtration process can be considered the most dangerous aspect of the machine, as the condensate that often is left inside the filters is more combustible than its powdered form. As such, extreme care must be taken to safely maintain the machine.

5. Moving Forward

Since we failed in meeting the factor of safety requirements for our optimized parts, we will be performing the simulations again with new load cases derived from the structural capabilities of the original skateboard truck model, as our initial load cases were too large to begin with.

We will subject the original skateboard truck model to loads that result in a factor of safety of 3, then apply those same loads to the optimized model while subtracting as much mass as possible to allow for a resulting factor of safety >2. This should provide a more convincing comparison between the safety capabilities of the optimized and non-optimized skateboard truck parts. These simulations and the resulting accurate factors of safety will be completed by 1/31/2025 as a part of Nathan's individual learning assignment.

After those simulations are completed, there will be no more design calculations left for this project. The rest of the project will be getting the printer up and running, comparing tensile test specimen, printing the final part, then writing an instruction manual in preparation for handing the machine off to the department.

Appendix A

Crank Arm CAD and Calculations

Top Level CAD

One of the team's early concepts was to use topology optimization on a bicycle crank, reducing weight similar to the skateboard truck. Below are the drawings.

Figure A1: Crank Arm

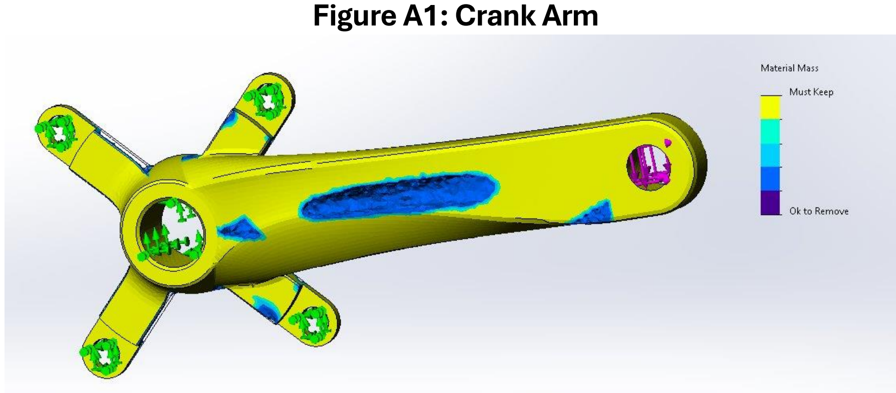


Figure A2: Crank Arm with 40% Weight Reduction

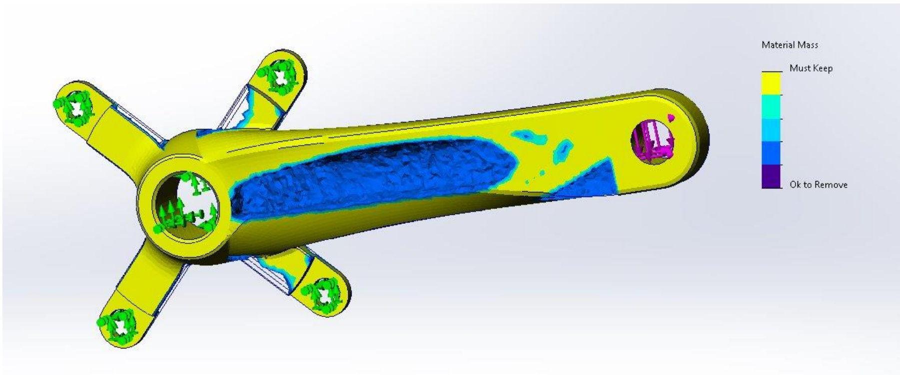


Figure A3: Crank Arm with 60% Weight Reduction

Load-Case Conditions

This specific load case relates to a study conducted to find the average amount of force used to pedal a bicycle. The forces specifically applied to the slot where the pedal would sit at a 45-degree angle, and fixtures applied to the screws and central shaft. Shown below are SolidWorks FEA Simulations

Equations and Solutions

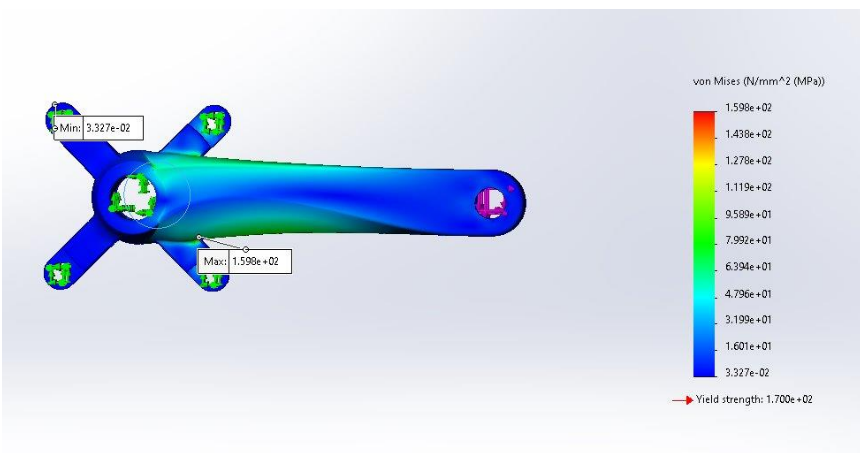


Figure A5: FEA of Crank Arm

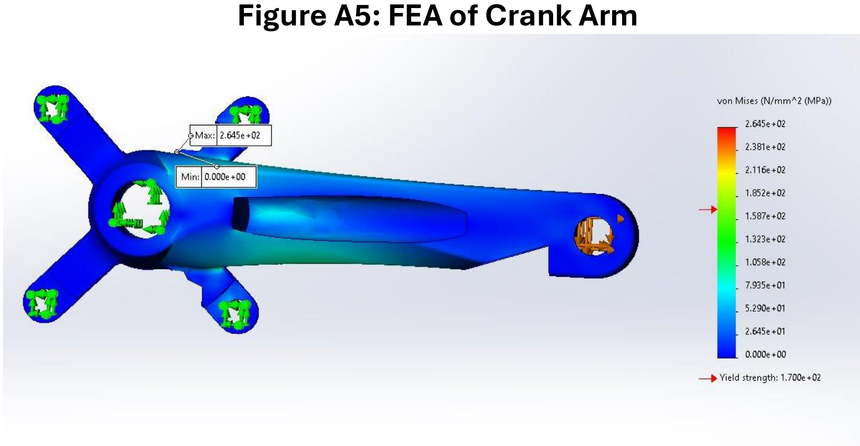


Figure A6: FEA of Modified Crank Arm

Unfortunately, the optimized crank arm failed at certain vertices near the left side. Whether or not this is a failure or just an issue with the program, other elements of this design are not very well suited for the small size of our printer.

Appendix B

Supplemental FEA Calculations

Finite Element Analysis - Hand Calculations:

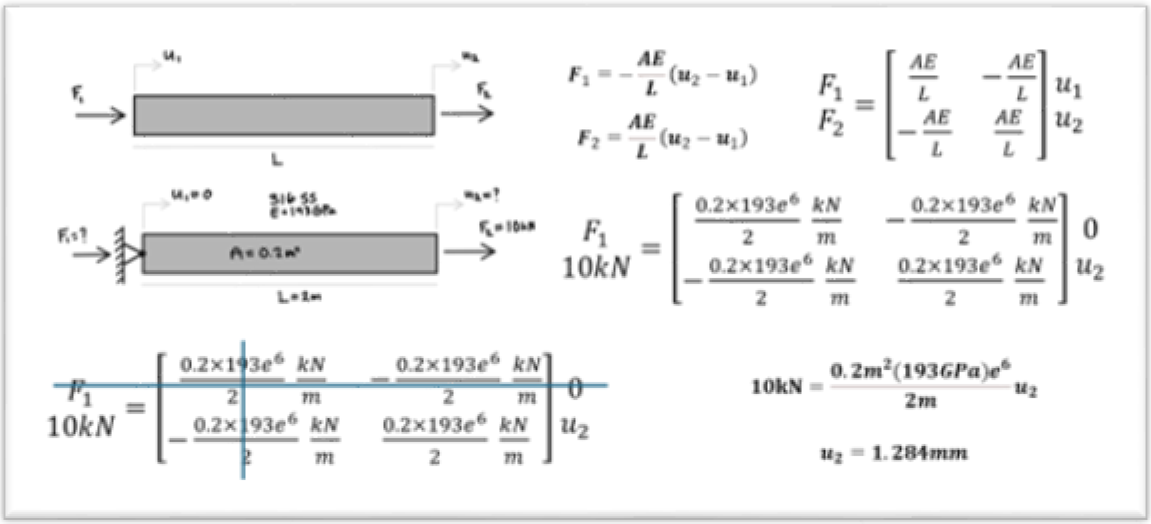


Figure B1: FEA Hand Calculations

We performed basic finite element analysis hand calculations on a single element to further understand it from an internal point of view as shown in figure 4 above. This proved very useful when later using SolidWorks simulations to complete this for a full object, as we understood exactly what was happening and why.

Finite Element Analysis Simulation - Simple Bracket Analysis

This is a full simulation of the effect of a static 300lb load on a simple 316L steel bracket we made in SolidWorks. The bracket is fully supported on one side with a distributed load on the other. The next step will be to use topology optimization to decrease the weight of the bracket while maintaining the stress zones of this structure.

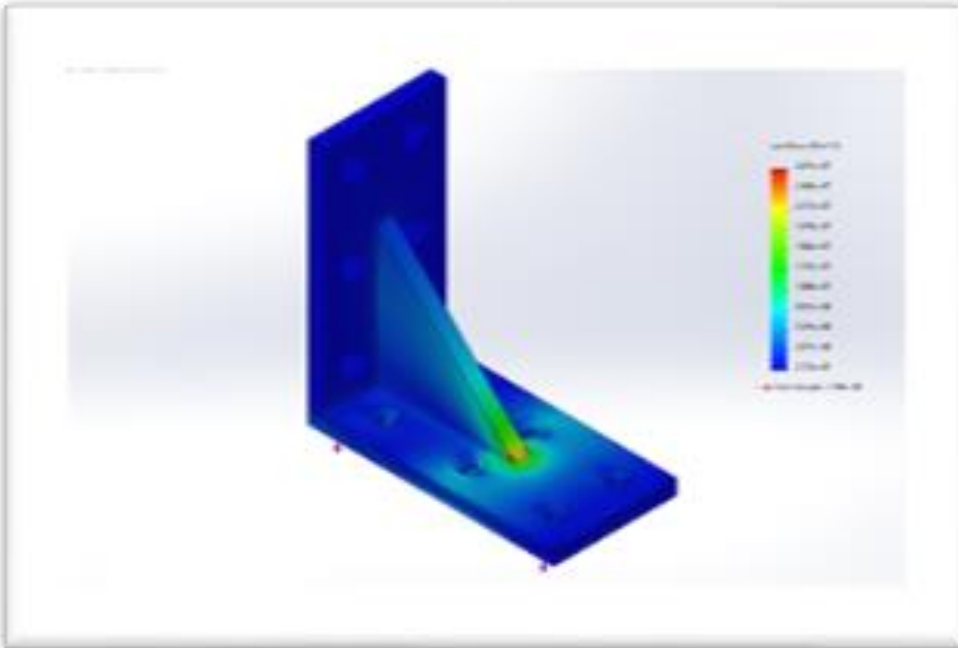


Figure B2: Bracket FEA Simulation - Stress

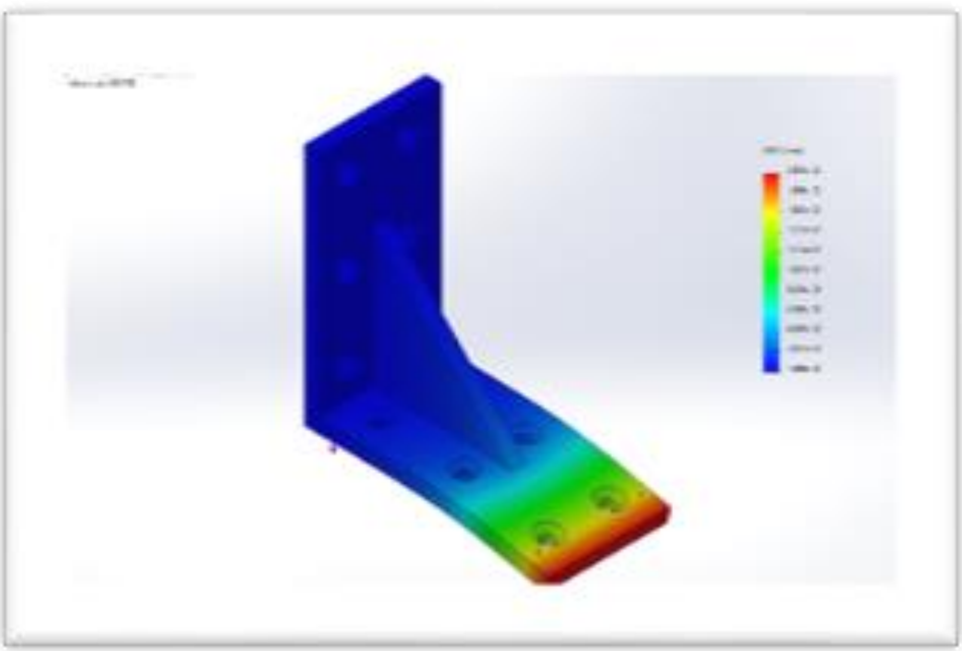


Figure B3: Bracket FEA Simulation - Displacement

Appendix C

Factor of Safety Calculations

Optimized Hanger FoS Calculation:
Max Stress: 1.135e+09 N/m^2
Yield Strength: 1.700e+08 N/m^2

Factor of Safety = Yield Strength / Max Stress = **0.150**

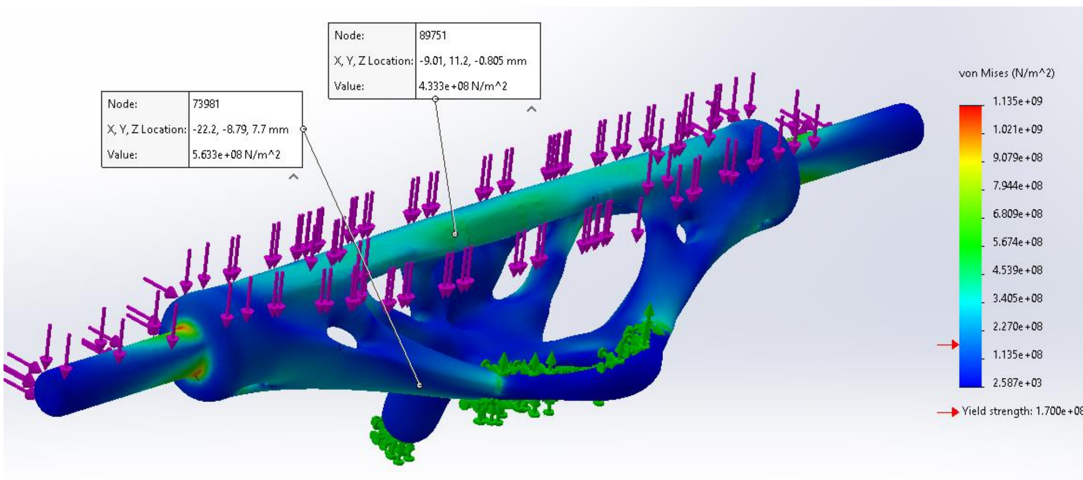


Figure C1: Optimized Hanger FEA

Optimized Baseplate FoS Calculation:
Max Stress: 3.473e+08 N/m^2
Yield Strength: 1.700e+08 N/m^2

Factor of Safety = Yield Strength / Max Stress = **0.489**

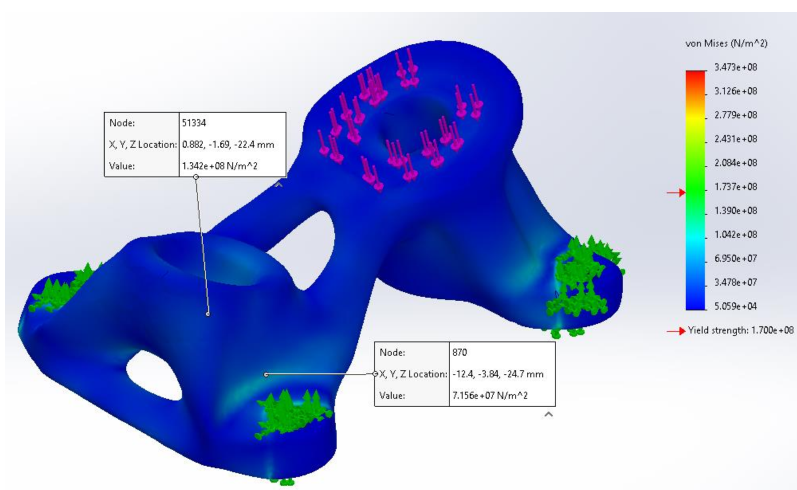


Figure C2: Optimized Baseplate FEA