Group 19 - Final Design Report

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1. Team Roles

- Scheduling Lead - Seoyoon Kwon
- FEA and Topology Lead - Corey Dubin
- CAD & Manufacturing Lead - Ryan Chung
- Documentation Lead - Price Collier

These were the roles we initially assigned ourselves at the beginning of the quarter, and we stuck with these roles throughout the quarter.

2. Needs and Metrics Tables

Our brake caliper needs and metrics were determined from the project definition–to create a brake caliper for a rear bike wheel while minimizing mass–and they are displayed in Tables 1 and 2 respectively below. The priority of the needs was based on safety and the project definition. We used ISO standards to address the stopping distance of the bike, and OSHA standards to address temperature. The rest of our metrics were determined based on focus groups, surveys, engineering analysis, and benchmarking as outlined in Table 3.

Table 1: Needs Table

#	Need		Priority, 1-5
1	The brake caliper	is lightweight.	1
2	The brake caliper	is safe to touch.	3
3	The brake caliper	is durable.	1
4	The brake caliper	is aesthetic.	5
5	The brake caliper	stops the bicycle within an acceptable distance.	1
6	The brake caliper	smoothly stops the bicycle.	2
7	The brake caliper	brakes reliably.	1

Table 2: Metrics Table

#	Needs Addressed	Metric	Units	Ideal Value	Marginal Value	Source
1	1	Total Weight	kg	0.15	0.35	C
2	2	Maximum Temperature of Brake	C	< 45°C	60 °C	B
3	4	Visual Appeal Likert Scale	1-5	5	1	E / None
4	5	Compliant with ISO Standard 4210-2	Binary	Yes	Yes	A
5	6	Smooth Stop Likert Scale	1-5	5	1	E / None
6	3, 7	Successfully Brakes Over Multiple Tests	Numeric	100	15	A

Table 3: Source of Values

Source	Description
A	ISO 4210-2 section 4, page 6, Table 1, on braking requirements
B	OSHA, 1910.261(k)(11) and 1910.262(c)(9)
C	Benchmarking analysis, found on page 4
D	Price analysis, found on page 4
E	Focus group study, found on page 4
F	Analysis of a typical crash scenario, found on page 4

C: From research on Amazon, brake calipers are typically made of metal and a package of two sets of calipers weighs 0.25-0.35 kg.

Our brake calipers will be made of Nylon-12, which is less dense than metal, meaning they will likely be lighter. Thus, our ideal value for one set of calipers is 0.075 kg, as it is very achievable for our brakes to be lighter than those on the market. Our marginal value is 0.175 kg because clearly, brake calipers are still functional at this weight.

D: From the same links seen in Source C, the average price of a caliper bike brake is around $15. Considering that this price is certainly more expensive than the initial manufacturing cost as well as our classroom setting, we can assume our production cost to be half of the selling price.

E: We will survey either 25 cyclists or Professor Jeremy Keys, our ideal user, and determine their preferences on repairability, aesthetics, and the ability of the bike to smoothly stop via Likert scale.

F: Using the average mass of an adult male of 90.6 kg, the speed used in the brake testing methods found in ISO 4210-5:2023 of 16 km/h, and an estimated crash duration of one second, we can calculate the net force generated by a potential crash.

$$F_{net} = m_{person}g \; + \; m\frac{dv}{dt}$$

$$F_{net} = (90.6\,kg)(9.8\,\frac{N}{kg}) \; + \; (90.6\,kg)(4.44\,\frac{m}{s^2})$$

$$F_{net} = 1290.55\,N$$

The marginal value is determined from a speed of 1 km/h, using the same mass and crash duration.

$$F_{net} = m_{person}g \; + \; m\frac{dv}{dt}$$

$$F_{net} = (90.6\,kg)(9.8\,\frac{N}{kg}) \; + \; (90.6\,kg)(0.28\,\frac{m}{s^2})$$

$$F_{net} = 913.05\,N$$

3. Design Concept Development

Estimation of the Design Space

The three criteria for the design space were as follows: (1) the brake pad mounting holes of the two components are co-linear, (2) the brake cable mounting holes are co-linear, and (3) the pivot bolt holes are co-linear. Given these constraints, we set an arbitrary value of 47 mm between the brake pivot hole and the brake cable mounting hole. We set arbitrary values for width and height, estimating the maximum possible spaces that could realistically fit into the bike. Implementing our design spaces into CAD, we get the following results, seen in Figure 1 and Figure 2, below:

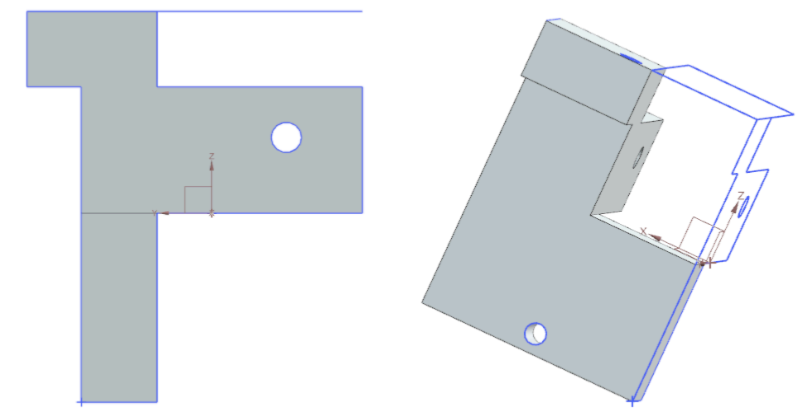

Figure 1: Views of the initial design space for the left caliper.

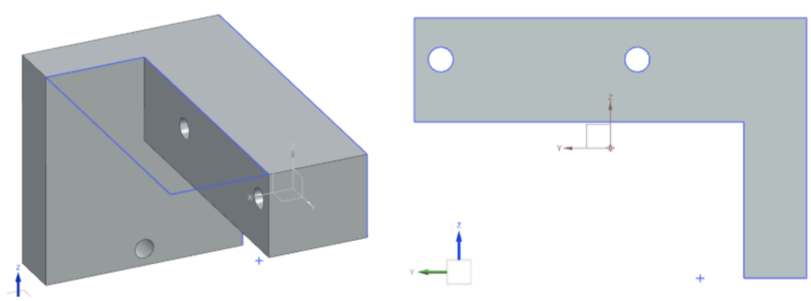

Figure 2: Views of the initial design space for the right caliper.

Hand Calculations

<u>Force calculations</u>

We calculated the necessary distance from applied force to the pivot point to account for bending stresses. Calculating the forces present on the connecting points, we took those values to FEA and topology optimization. We considered the set up of a bicycle braking system, as outlined in Figure 3 below, to inform our calculations.

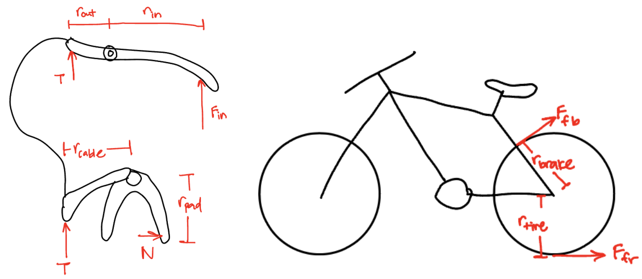

Figure 3: Diagram of braking system with force and radius labels

With the moment about the hand brake we can obtain the following equation for torque:

$$F_{in} r_{in} = T r_{out} \tag{1}$$

$$T = \frac{F_{in} r_{in}}{r_{out}} \tag{2}$$

Equating the force around the caliper we can obtain the following equation for the normal force:

$$N r_{pad} = T r_{cable} \tag{3}$$

$$N = \frac{T r_{cable}}{r_{pad}} \tag{4}$$

Considering the moment around the wheel we can obtain the following equation for the force of friction:

$$\Sigma M = 0 \tag{5}$$

$$F_{fb} r_{brake} = F_{fr} r_{tire} \tag{6}$$

$$F_{fr} = \frac{F_{fb} r_{brake}}{r_{tire}} \tag{7}$$

We can use a kinetic energy and work analysis assuming negligible air resistance to compute the braking force:

$$\Delta KE = Work \tag{8}$$

$$\frac{1}{2} m v^2 = F_{fr} d \tag{9}$$

$$F_{fb} = \mu N \tag{10}$$

Using the above equations (9) and (7) we can solve for d, the max braking distance

$$\frac{1}{2} m v^2 = \frac{\mu N r_{brake} d}{r_{tire}} \tag{11}$$

$$d = \frac{m v^2 r_{tire}}{2 \mu N r_{brake}} \tag{12}$$

Rearranging equations (12), (4), and (2), we can solve for the required input force, $F_{in,}$ and the force of friction, F_{fr}.

$$F_{in} = \frac{m v^2 r_{pad} r_{out} r_{tire}}{2 \mu d r_{in} r_{cable} r_{brake}} \tag{13}$$

$$F_{fr} = \mu F_{in} \frac{(r_{in} r_{cable})}{(r_{out} r_{pad})} \tag{14}$$

Inputting the values values m = 100 kg, v = 6.94 m/s, r_{in} = 80 mm, r_{out} = 20 mm, r_{pad} = 47.5 mm, r_{cable} = 47 mm, r_{brake} = 12 in, r_{tire} = 13 in, μ = 0.75, and d = 15 m, and μ = 0.9 between the brake pad and tire into equations (2), (13) and (14) we obtain the following values which we used in our following analyses.

$F_{in} = 58.6\ N$ $\qquad T = 234\ N$ $\qquad F_{fr} = 209\ N$

<u>Stress calculations</u>

In order to determine the maximum allowable stress, we assumed that Jeremy Keys uses his bike every day and operates the brakes 20 times per day. Over three years, the brakes will undergo 21,900 cycles. Referencing the bending fatigue tests in Figure 4, we found the most conservative maximum stress value of 27 MPa. Given that our calipers would primarily experience bending, we used a load Marin factor of 1. Moreover, considering that the geometry of the calipers will inevitably result in stress concentrations around the mounting holes, we decided to be more conservative with this value and reduced it to a final maximum stress value of 25 MPa.

This is reinforced by our calculations regarding the given Max Stress Tension (ST) of Nylon-12 of 50 MPa and our determined factor of safety of 2, which we found considering that our brake calipers fall under the condition of "For use with ordinary materials where loading and environmental conditions are not severe."

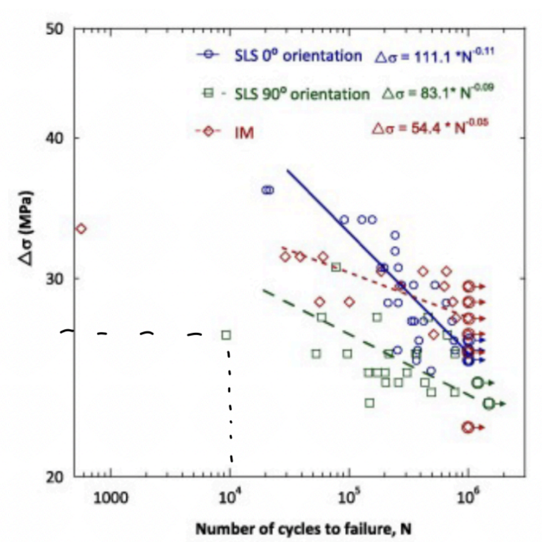

Figure 4: Graph showing results of reversed bending fatigue tests on cylindrical SLS-Nylon-12 beams printed in differing orientations (Salazar, 2022; Engineering *Fracture Mechanics*)

Topology Optimization

Implementing our hand calculations into our design space, we ran a topology optimization to determine the optimal load paths considering the applied forces. Our topology results are seen below in Figures 5 and 6:

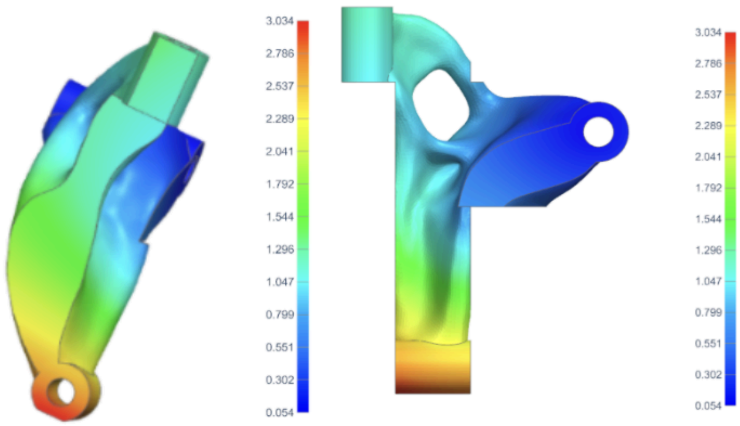

Figure 5: Topology results on the design space for the left caliper

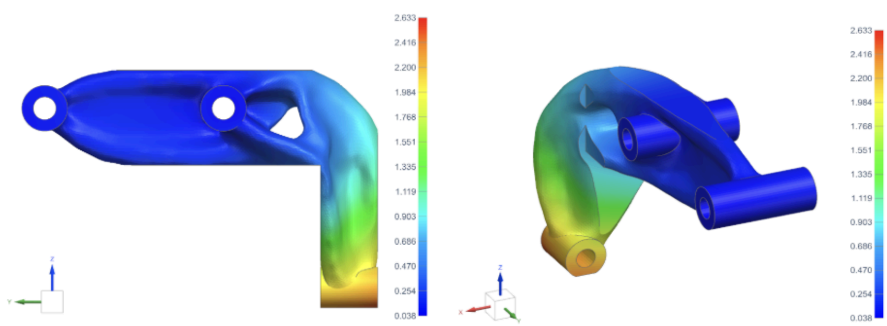

Figure 6: Topology results on the design space for the right caliper

Iterative Use of Finite Element Analysis

Throughout the design process, we ran multiple Finite Element Analyses (FEAs) on both the left and right calipers to ensure the forces and displacements didn't exceed the maximum values and that the brake calipers would be functional and safe to use. To ensure that this was the case, we aimed to have the maximum stress of each caliper not exceed our calculated maximum stress of 25 MPa, and the maximum deflection of each caliper not exceed 5.5 mm near the cable mounting holes. Given that the brake handles and cable have a maximum travel distance of 11 mm, a combined deflection larger than this value would result in calipers with inhibited motion: they would not be able to impart the maximum amount of force. Every new iteration of the brake calipers underwent FEA again to double-check safety. The results of our FEA for the first printed calipers are seen below in Figures 7, 8, 9, and 10:

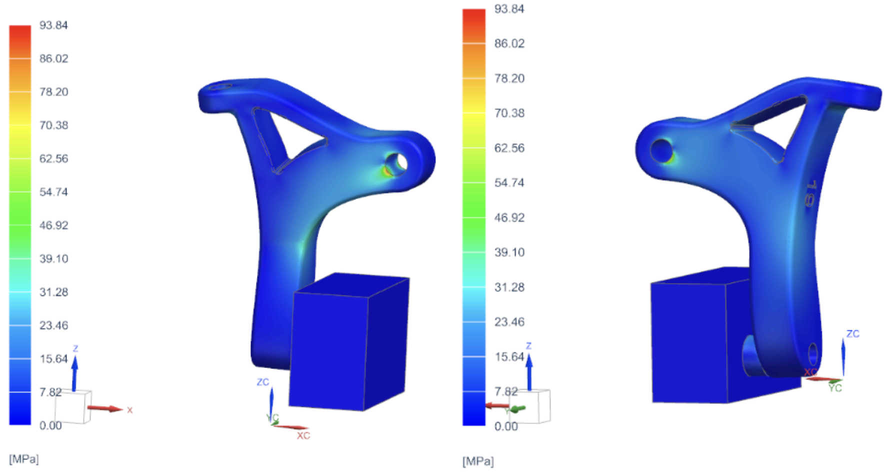

Figure 7: Initial FEA results for element-nodal stress for the left caliper

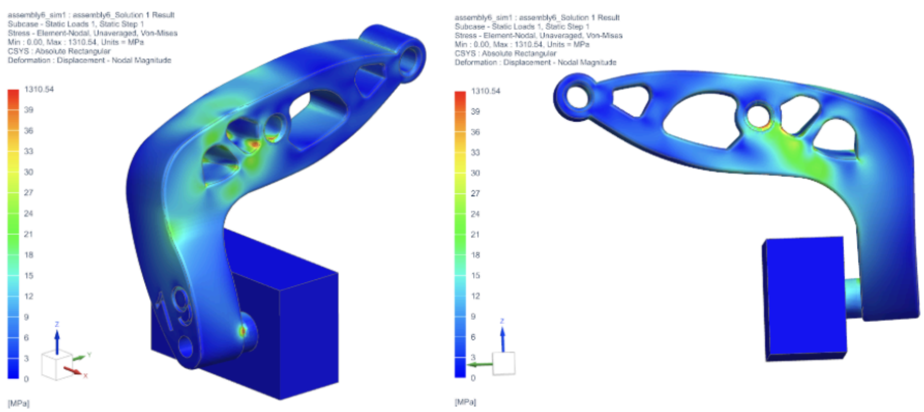

Figure 8: Initial FEA results for element-nodal stress for the right caliper

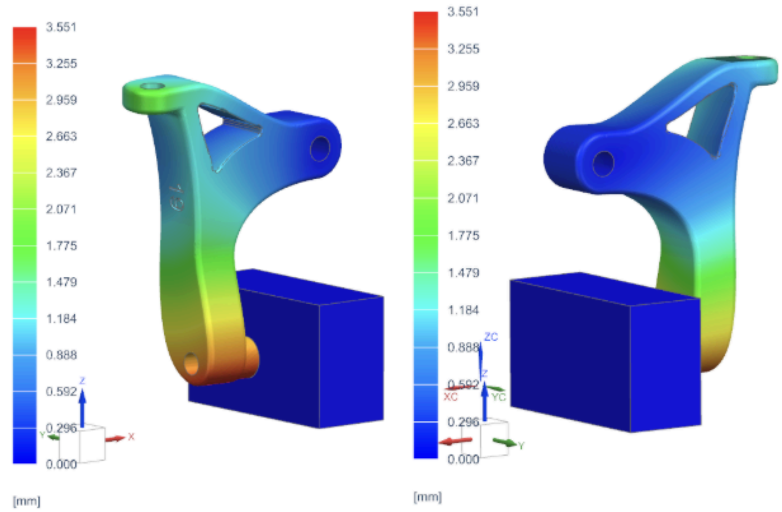

Figure 9: Initial FEA results for deflection of the left caliper

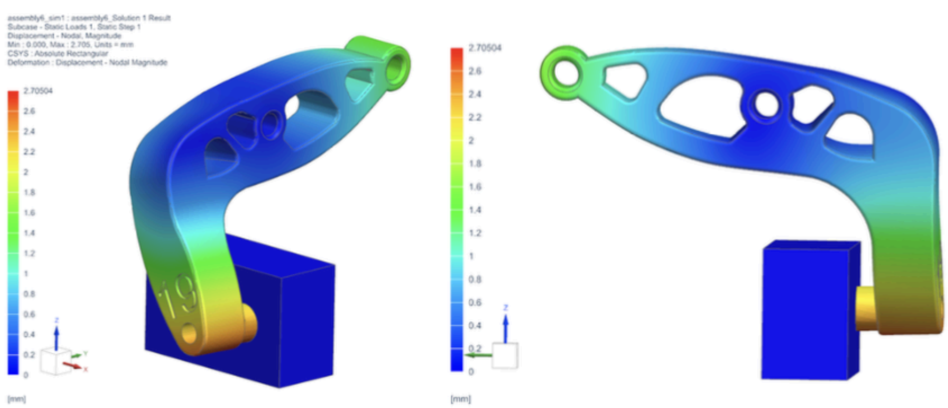

Figure 10: Initial FEA results for deflection of the right caliper

4. Initial Testing Results

On our first day of testing, our design proved successful and met the requirements. The results from the initial testing are listed below in Table 4:

Table 4: Initial Testing Results

Metric	Marginal Value	Ideal Value	Measured	Units	Tool
Weight	350	150	50	Grams	Scale
Braking distance	15	5	10.8	Meters	Measuring Tape
Maximum Temperature of Brake	60	< 45	N/A	Degrees Celsius	Thermometer
Visual Appeal Likert Scale	1	5	4	Numeric	Likert Scale
Smooth Stop Likert Scale	1	5	5	Numeric	Likert Scale
Successfully Brakes Over Multiple Tests	15	100	N/A	Numeric	Count

Our most important insight from the initial testing was that our brake met the ISO standard and stopped well within the acceptable braking distance. However, we exceeded the maximum stress value of 25 MPa. From this, we determined that we could improve other aspects of our design while still meeting the physical standard. We therefore decided to reduce the weight of the part and reduce the measured stress for our final design.

5. Design Improvements Between Tests

Our calipers met all standards in the first test, but exceeded the maximum stress value. As discussed in Section 4, our main goal after testing was to reduce the weight of our initial design. To do this, we added indentations and thinned the curved section between the mounting hole and the brake pad holes to reduce the material of the design. We also reinforced some parts of the calipers to resolve the excess stress measured in the previous iteration. After we made these changes, we used FEA to ensure that we had not increased the stresses past our allowable stress value of 25 MPa. We delve into the specific changes for each caliper below.

Left Caliper:

On the left caliper, we first added material along the inner length of the caliper and increased the radius of the fillets to reduce the maximum stress to an acceptable value per our factor of safety. Once that was accomplished, we moved on to attempting to reduce the weight of the caliper beyond what it was before the additional material. To accomplish this, we made several changes, including adding an indent in a low-stress area, increasing the size of the cutout between the cable mounting hole and the caliper body, and reducing the material near the brake pad mounting hole. Some other changes that were made for reasons other than decreasing mass were decreasing the cable hole primary diameter from 4 mm to 2 mm to increase the amount of material for the cable sheath to push on, and enlarging and deepening the group number for improved legibility. These changes are reflected in Figures 11, 12, and 13 below:

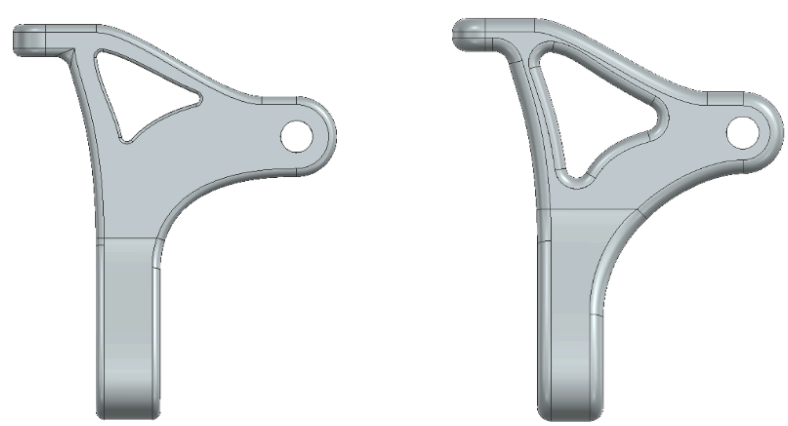

Figure 11: Comparisons of the front faces of the left caliper before (left) and after (right) design improvements

Figure 12: Comparisons of isometric views of the left caliper before (left) and after (right) design improvements

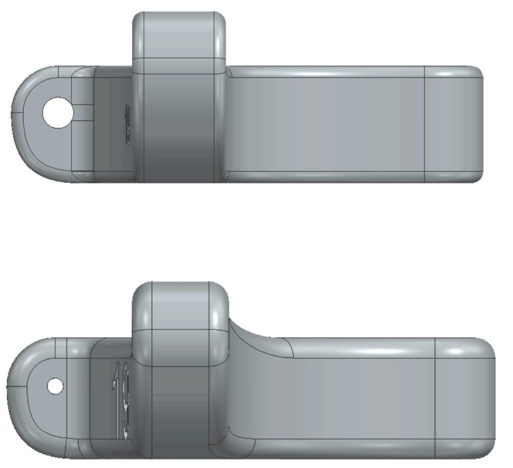

Figure 13: Comparisons of the bottom faces of the left caliper before (top) and after (bottom) design improvements

Right Caliper:

On the right caliper, we slightly reduced material via fitted indents near the brake pad mounting hole and the underside to reduce mass. We also added edge blends in the corner area in the topologically-inspired weight reduction hole closest to the brake pad hole arm in order to reduce the stress concentration in that area. This contributed to the mass and stress reductions shown in our final FEA and testing results below in Figures 14, 15, and 16:

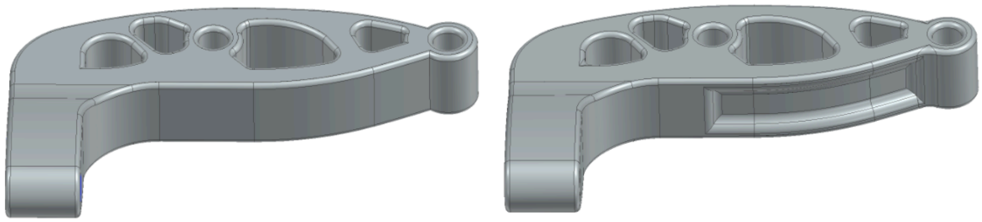

Figure 14: Comparisons of the bottom Y-Z faces of the right caliper before (left) and after (right) design improvements

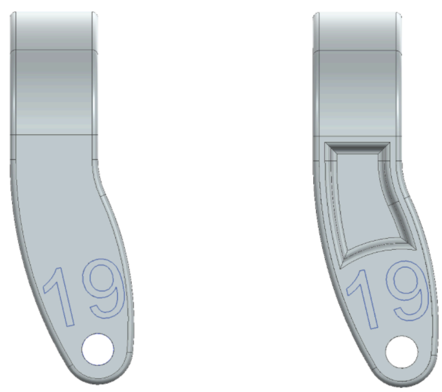

Figure 15: Comparisons of the X-Z face of the right caliper before (left) and after (right) design improvements

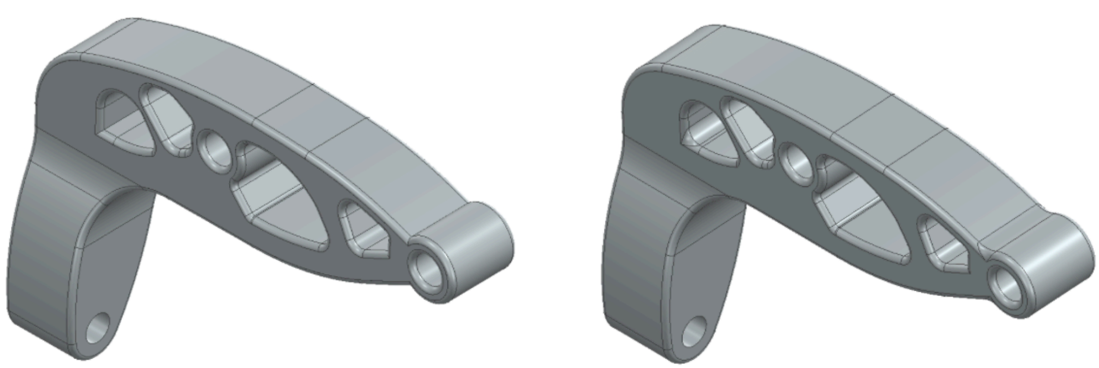

Figure 16: Comparisons of the isometric faces of the right caliper before (left) and after (right) design improvements

6. Final Testing Results

Our final tests were also successful in meeting the project requirements, and the new measured values are listed below in Table 5:

Table 5: Final Testing Results

Metric	Marginal Value	Ideal Value	Measured	Units	Tool
Weight	350	150	47.5	grams	Scale
Braking distance	15	5	14	meters	Measuring Tape
Maximum Temperature of Brake	60	< 45	N/A	Degrees Celsius	Thermometer
Visual Appeal Likert Scale	1	5	5	Numeric	Likert Scale
Smooth Stop Likert Scale	1	5	5	Numeric	Likert Scale
Successfully Brakes Over Multiple Tests	15	100	N/A	Numeric	Count

The key insights from our final testing are as follows: (1) our design changes successfully reduced the weight of our brake calipers, (2) this weight reduction did increase the stopping distance, but it remained acceptable by the ISO standard, and (3) that other factors that we were already satisfied with were unchanged or improved. For example, the visual appeal of our calipers increased by 1 point on the Likert scale. Overall, our calipers were improved by the design changes we made.

7. Additional Improvements and Adjusting for Manufacturability

All of the measured design metrics satisfied our marginal value, with three of our metrics meeting or exceeding the ideal standard. As such, there are not many improvements necessary to our design. However, one thing we could improve is to add slightly more material to create a design that is somewhere in between our final design and initial design in weight and stopping distance. Our final stopping distance, while it met the ISO standard, was quite close to the maximum stopping distance. As such, after long-term use, the brakes could experience fatigue and no longer meet the ISO standard. Therefore, we could bring the design slightly closer to our initial design.

To adjust for manufacturing out of aluminum alloy instead of SLS-Nylon-12 we would need to consider several factors of our design: (1) our design is required to support moderate structural loading, and to have high precision mounting holes (2) we consider our design to have a moderate complexity (3) our part is visible, and would ideally have a cosmetic finish (4) tolerances of ±0.1 mm are required on the key features.

Scenario A:

- Target price: $400 bike
- Production volume: 50,000 units per year
- Focus: Cost efficiency, acceptable aesthetics
- Manufacturing options: Casting, forging, forming, machining

For scenario A, forging would be the best manufacturing option. Forging is best suited for this scenario because it is ideal for producing a large quantity of parts, typically gives parts an acceptable surface finish, and can create both strong and complex geometries. The tooling cost of forging is offset by the large volume of parts produced per year. Sheet forming can be ruled out because it would be difficult to produce the complex geometries in our part with high precision and would also not provide the necessary structural strength. Material costs are also minimized by forging as it is an additive manufacturing technique, whereas machining would require a high amount of excess material. Machining is not ideal because it has a high labor cost and is not optimal for large volumes of production. Casting is not ideal because it often results in a poor surface finish and requires post-processing for high precision features.

Scenario B:

- Target price: $5,000 bike
- Production volume: 10,000 units per year
- Focus: Strength, weight reduction, premium finish
- Manufacturing options: Forging, CNC machining, additive manufacturing

CNC machining would be optimal for scenario B. CNC machining is ideal because it can create complex geometries, can achieve high precision and strength, and creates a smooth, premium finish. CNC machining also limits labor cost as opposed to traditional machining, so although cost is not a focus for this scenario, this is an added benefit of CNC machining. Forging is not ideal because only 10,000 units are being produced per year; this is only a medium amount of production, and forging is optimal for high production volume. Additive manufacturing is not ideal because it produces parts with anisotropic properties, and the surface finish typically requires post-processing.

Scenario C:
- Target price: $7,000+ custom bike
- Production volume: 200 units per year
- Focus: Flexibility, low tooling cost, fast design iteration
- Manufacturing options: CNC machining, additive manufacturing

For scenario C, additive manufacturing is the best option. Additive manufacturing is ideal for low production volume, low tooling cost, and flexibility of design. CNC machining is not optimal because there is a very high tooling cost, which is not ideal for such a low volume of production. For additive manufacturing, it is much easier to create variations of a model and print each one than it is to machine various different parts. Also, additive manufacturing minimizes excess material cost as CNC machining is a subtractive manufacturing process.

8. Discussion

Overall the design process was very informative and offered invaluable experience with engineering tools and techniques. However, some sections were oddly timed and overly complicated.

Throughout the design process, the most useful tools were topology optimization, FEA, and testing. Additionally, these processes are used in all levels of professional engineering, and learning how to use them in a classroom setting was very helpful. FEA and topology optimization were useful because they gave us more confidence in our hand calculations and allowed us to more easily visualize the stresses and loads on our part. This was especially useful because we lacked the mathematical know-how to accurately analyze the more complicated calipers that were necessary to most efficiently minimize the weight. This led to the latter half of our design process boiling down to guesswork and an overreliance on FEA, which made the secondary testing process stressful. Testing was useful because it allowed us to see our part in action and see how it behaves in a real loading situation. The least useful/most confusing tools were some of the things that we did at the beginning of our design process. For example, when we created our needs and metrics tables, we had a very limited idea of what our testing and design constraints were. As a result, we included things like safe temperature and force resistance in our needs table, but these were not things that we ended up measuring. If we had had a clear point in our design process where we refined our tables, this would have made more sense. Another example of a confusing part of the design process was in Lab 5, when we ran FEA on our design spaces. This was not useful because we already knew that our design spaces had too much material, so the initial FEA did not give us very much new information.

This concludes our report.