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Additive Manufactured Formula SAE Brake Caliper

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3D PRINTED FORMULA STUDENT BRAKE CALIPER

By

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Final Report for 4600:471 Senior/Honor Design, Spring 2021

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Final Report May 2021

Project No. 21

Abstract

The purpose of the brake caliper is to direct the pressurized fluid, created by the driver's mechanical input on the brake master cylinder, into an outward force that can then be applied to the vehicles brake rotors. The theory behind the modern brake caliper has not changed throughout multiple generations of automobiles. This sense of complacency has created a void in the evolution of technology as far as the brake caliper is concerned.

With the evolution of manufacturing methods, many new avenues for component design have been opened up and it is our belief that we can utilize these advances in order to create a brake caliper for the Formula SAE competition that will set us apart from the other competing teams.

The goal for this project is to design, analyze, and potentially build a prototype front brake caliper for the Formula Student cars. The desired outcome would be for this brake caliper to out-perform all of the "commercially" available calipers that other FSAE teams are using in order to gain an advantage when it comes to vehicle dynamics and braking related events for the future of the car.

Contents

1. Introduction

This brake caliper's primary focus is to provide a component to the Formula Student teams that is not currently commercially available. The caliper itself will utilize additive manufacturing in addition to the current topology technology offered in various 3D modeling programs in order to create a component that is overall more efficient and optimized compared to a traditional billet aluminum counterpart. The objective of this project is to create a brake caliper that will perform at the same level as the current aluminum part fitted on the Formula SAE car while reducing the weight of the un-sprung mass.

1.1 Calculation Background

In order to properly design and select the parameters for this component, an overall analysis of the vehicle dynamics package is required. This includes an in-depth look at the vehicle's handling characteristics when it is performing a stopping event. This will allow us to examine the brake system as a whole and record what operational range of values are being dealt with when the car is performing a "worst case scenario" stopping event. From this vehicle dynamics model, we can plot the affect that the brake caliper components have on the braking characteristics of the vehicle. We are primarily concerned with the mechanical input that the driver will need to apply to the brake pedal in order to achieve the constant rate of deceleration for each stopping event. This will give us an idea as to how the dimensions of these components will affect the overall effectiveness of the brake system.

2 Theoretical Calculations

This section of the report will cover the theoretical calculations that were performed for the vehicle dynamics portion of the project. These calculations were completed using MATLAB in order to create an easy to modify code that can be used to iterate and loop varying caliper specifications for each run. The full MATLAB code can be found in *Appendix A.*

2.1 Model Definition

Like stated previous, this vehicle will be examined during a straight-line deceleration event where the brake system will be subject to the highest forces required. This will allow us to understand how each component of the brake caliper will affect the vehicle's stopping performance as well as what internal force parameters the brake caliper will have to withstand. The goal for these calculations is to create a mathematical model that will give us to the possibility to rapidly explore the design space that is available to us.

2.2 Vehicle Dynamics Calculations

To begin, this vehicle will be analyzed in purely longitudinal deceleration. The reason for this is that it will result in the vehicle decelerating at the fastest rate possible which roughly equates to the highest forces created in and by the brake calipers. The code that has been written is thoroughly commented in order to clear any confusion as to what each variables definition is. In this section, the calculations will be explained and walked through in a theoretical sense in order to understand the mathematical process that was followed to arrive at the results that were generated. It is important to understand that the deceleration of a vehicle is highly dependent on the forces present on the front and rear axle of a vehicle.

2.1.1 Suspension & Tire

The suspension geometry of a vehicle can drastically affect how it is able to decelerate. A few key variables to understand for this portion of the mathematical model are the wheelbase of the vehicle as well as the location of the center of gravity. Braking events are very sensitive to how the weight of the vehicle is being distributed and both the wheelbase and the center of gravity can drastically affect the results.

The wheelbase is essentially the length of a moment arm that will resist the rotation of the vehicle around its pitch center. A vehicle that was designed purely for being the best at braking would utilize the longest wheelbase achievable. This will allow for the vehicle to better distribute the weight that is being transferred.

The center of gravity of the vehicle, both front to rear and bottom to top, will also have a large effect on the braking characteristics. The location of the center of gravity will determine the size of the moment arm that the vehicle mass will rotate around. A higher CG will result in more weight transfer front to rear which is not ideal for braking. A vehicle that is designed purely for maximum braking would have the lowest possible CG.

Shown below is a graphic that displays both the wheelbase of the vehicle (L) as well as the center of gravity (CG).

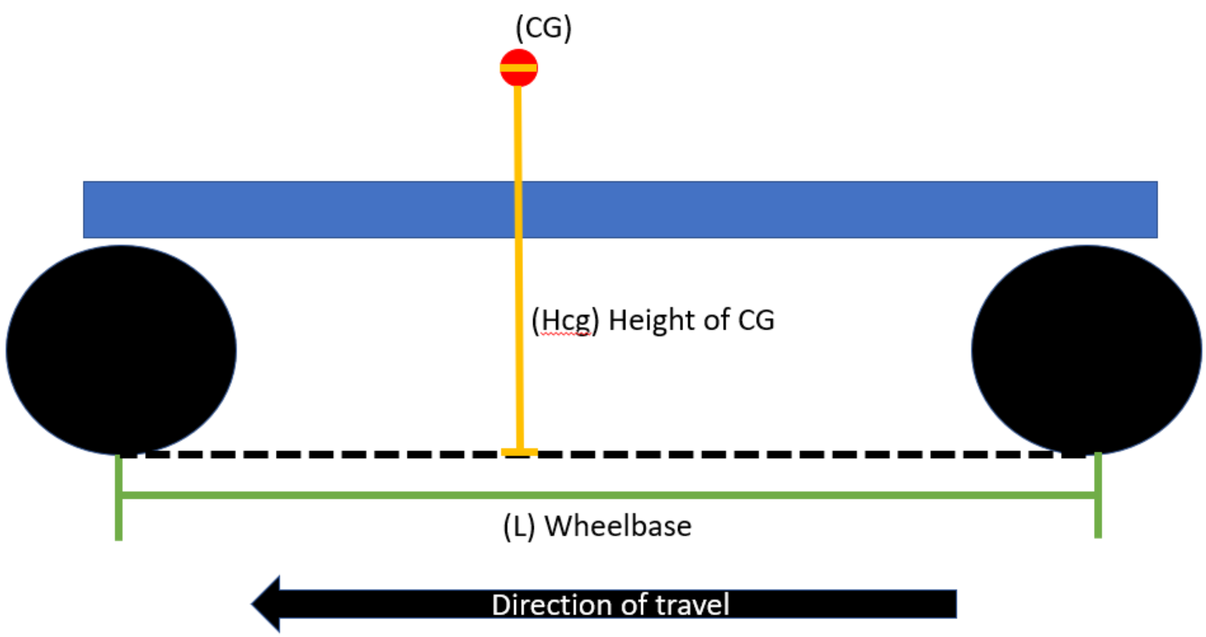


Figure 1 Schematic with the wheelbase and center of gravity location of a vehicle

The first step was to record the geometric parameters for the vehicle. This was achieved by talking to Ray Hilbert, Zips Racing's suspension lead. Ray was able to provide information such as the location of the center of gravity, wheelbase of the vehicle, weight (with driver), front weight ratio, and coefficient of friction for the front and rear tires. From this information, the following parameters were gained.

Total Weight (W)	Length of Wheelbase (L)	Height of CG (Hcg)	Front Weight Ratio (Fwr)	Coefficient of Friction Front Tire (utf)	Coefficient of Friction Rear Tire (utr)
525 lbs	60.2 inches	9 inches	0.49	1.7	1.7

Table 1 Suspension parameters given from Zips Racing

The necessary values for the geometry of the vehicle have been gained, now it is time to take a look to the aerodynamics system, another large source of both force on the tires in the normal direction to the ground in addition to drag force reduced by the airfoils.

2.1.2 Aerodynamics

While the suspension geometry is largely responsible for the stopping abilities of the car, the aerodynamics also affect the deceleration of a vehicle. The aerodynamic forces work in two components, the first one being the opposition of motion and the second is generating normal force that is applied to the front and rear axles. This stopping power due to the aerodynamics is commonly called “Aerodynamic Drag” and it is dependent on the shape of the airfoils that are attached to the vehicle. The aerodynamic drag works as an air brake to slow down the vehicle. The normal force that is generated by the wings is distributed amongst the front and rear axles and affects how much load is being seen on the front and rear tires.

The forces for aerodynamic drag of each major component of the car can be gained from completing CFD analysis (computational fluid dynamics). In order to create a model that is not incredibly cumbersome, aerodynamic values were gained for one speed and that was at 30 mph, which is the average speed for these vehicles while competing on course. To obtain values for our model, we were able to work with Patrick Kruse, the aerodynamics lead for Zips Racing. From the talks had with Mr. Kruse, we had obtained values for the down force produced on the front and rear axle, in addition to the drag forces produced by the front wing, rear wing, and the undertray of the vehicle at 30mph. These values can be seen below.

Front Axle Down Force (Fadf)	Rear Axle Down Force (Radf)	Front Drag (Fdrg)	Rear Drag (Rdrg)	Undertray Drag (Udrg)
48.5587 lbs	33.0469 lbs	7.86831 lbs	19.7832 lbs	1.79847 lbs

Table 2 Aerodynamic parameters given from Zips Racing

With the values being obtained for the aerodynamics of the vehicle, we can now proceed to calculating the weight transfer calculations necessary for the vehicle based on these parameters.

2.1.3 Weight Transfer Calculations

The bulk of the calculations that will be taking place throughout this MATLAB code is that of the weight transfer of the vehicle. To begin, the first variables that need to be determined is the static weight on the front and rear axles of the vehicle. That can be found with the following equations.

$$Weight\ on\ Front\ (Wf) = Front\ Weight\ Ratio(Fwr) * Weight(W)$$

$$Weight\ on\ Rear\ (Wr) = Rear\ Weight\ Ratio(Rwr) * Weight(W)$$

The second step is to calculate the distance of the CG from the front and rear axle.

$$Length\ from\ Front\ Axle\ (Lf) = \frac{Wr * L}{W}$$

$$Length\ from\ Rear\ Axle\ (Lr) = \frac{Wf * L}{W}$$

Once we have found both the front and rear distances for the center of gravity, we can now move onto calculating the weight on the vehicle's axle when under full dive during a braking event. It is important to understand that both of the following values that are being solved for are only concerned with the suspension geometry of the vehicle and does not account for aerodynamics yet.

$$Weight\ on\ Front\ Axle\ (Wfb) = W * \frac{Lr + (utr * Hcg)}{L + (utr - utf) * Hcg}$$

$$Weight\ on\ Rear\ Axle\ (Wrb) = W * \frac{Lf - (utf * Hcg)}{L + (utr - utf) * Hcg}$$

The loads on the front and rear axle during a braking event have been found with respect to suspension geometry. The next step is to add in the aerodynamic forces that will be present during this braking.

$$Weight\ on\ Front\ Axle\ With\ Aero\ (Wfb_{aero}) = Wfb + Fadf$$

$$Weight\ on\ Rear\ Axle\ With\ Aero\ (Wr_{aero}) = Wrb + Radf$$

A simple value can be withdrawn from these calculations to represent the weight being transferred due to this braking event. In addition, we can also solve for the percentage of weight present on the front and rear axle to understand the current weight distribution of the vehicle.

$$Weight\ Transfered\ (Wtf) = Wfb - Wf$$

$$Weight\ on\ Front\ Percentage\ (Wfbp) = \frac{Wfb}{Wfb + Wrb}$$

$$Weight\ on\ Rear\ Percentage\ (Wrbp) = \frac{Wrb}{Wfb + Wrb}$$

2.1.4 Wheel Load & Torque Calculations

The weight transfer calculations have been completed and now we can begin to examine the individual corners in order to further understand the frictional torque that is being created by the rolling radius of the wheel and the frictional force present at the contact patch of the tire. We will begin by finding the friction force present in the front and rear axles.

$$Friction\ Force\ Front\ Axle\ (Ff) = Wfb * utf$$

$$Friction\ Force\ Rear\ Axle\ (Fr) = Wrb * utr$$

From this point we can then begin to calculate the friction torque produced by these axles. This will involve the use of the rolling radius (rr) of the tire which was obtained from Ray Hilbert at a later date.

$$Friction\ Torque\ at\ Front\ Axle\ (Ftfa) = Ff * rr$$

$$Friction\ Torque\ at\ Rear\ Axle\ (Ftra) = Fr * rr$$

It is important to keep in mind that these calculations are for the front and rear axles. We are concerned with the torque that the brake system on a single corner assembly will need to produce to match these tire forces. This can be done by dividing the front and rear axle friction torques by 2 since the vehicle is symmetric left to right.

$$Friction\ Torque\ at\ Front\ Corner\ (Ftf) = \frac{Ftfa}{2}$$

$$Friction\ Torque\ at\ Rear\ Corner\ (Ftr) = \frac{Ftra}{2}$$

Now that we have arrived at a point where we know the torques present at each corner, both front and rear, we can now move to calculating the braking component sizes.

2.1.5 Brake Caliper Calculations

The specifications of the brake caliper that we will be controlling and varying throughout the several iterations will be the following.

$$Safety\ Factor\ to\ Allow\ Lockup\ (Sf)$$

$$Front\ Caliper\ Piston\ Radius\ (Fcpr)$$

$$Rear\ Caliper\ Piston\ Radius\ (Rcpr)$$

$$Number\ of\ Front\ Caliper\ Pistons\ Per\ Caliper\ (Fcpn)$$

$$Number\ of\ Rear\ Caliper\ Pistons\ Per\ Caliper\ (Rcpn)$$

In order to properly continue the calculations, some important parameters needed to be obtained from Zip's Racing. We were able to sit down and have a discussion with David Bartsch, Zip's Racing's Brakes lead to obtain the values that we were after. These parameters can be seen below.

Front Brake Disc Radius (Fdr)	Rear Brake Disc Radius (Rdr)	Front Master Cylinder Bore Dia. (Fmcd)	Rear Master Cylinder Bore Dia. (Rmcd)	Brake Pedal Motion Ratio (Pmr)
3.25 inches	2.75 inches	0.7 inches	0.625 inches	4.7

With these values we can continue the calculations for the brake forces. The first being the relationship between the torque being produced at the contact patch of the tire and the braking system.

$$Front\ Caliper\ Force\ (Fcf) = \frac{Ftf}{Fdr}$$

$$Rear\ Caliper\ Force\ (Rcf) = \frac{Ftr}{Rdr}$$

$$Front\ Caliper\ Force\ With\ Safety\ Factor\ (Fcfsf) = Fcf * Sf$$

$$Rear\ Caliper\ Force\ With\ Safety\ Factor\ (Rcfsf) = Rcf * Sf$$

After this point, we can continue by converting the force needed to be generated by the brake caliper into a brake line pressure.

$$Front\ Caliper\ Piston\ Area\ (Fca) = \pi * Fcpr^2 * Fcpn$$

$$Rear\ Caliper\ Piston\ Area\ (Rca) = \pi * Rcpr^2 * Rcpn$$

$$Front\ Caliper\ Pressure\ (Fcp) = \frac{Fcfsf}{Fca}$$

$$Rear\ Caliper\ Pressure\ (Rcp) = \frac{Rcfsf}{Rca}$$

The front and rea brake pressures have been calculated, now we can relate the line pressure present at the brake caliper to the mechanical input that the driver will need to input in order to achieve the required force.

$$Front\ Master\ Cylinder\ Radius\ (Fmcr) = \frac{Fmcd}{2}$$

$$Rear\ Master\ Cylinder\ Radius\ (Rmcr) = \frac{Rmcd}{2}$$

$$Front\ Master\ Cylinder\ Piston\ Area\ (Fmca) = Fmcr^2 * \pi$$

$$Rear\ Master\ Cylinder\ Piston\ Area\ (Rmca) = Rmcr^2 * \pi$$

$$Front\ Master\ Cylinder\ Force\ (Fmcf) = Fcp * Fmca$$

$$Rear\ Master\ Cylinder\ Force\ (Rmcf) = Rcp * Rmca$$

$$Total\ Master\ Cylinder\ Force\ (Tmcf) = Fmcf + Rmcf$$

$$Pedal\ Force\ Required\ (Pf) = \frac{Tmcf}{Pmr}$$

The completion of these calculations has resulted from us relating the vehicle parameters, such as suspensions and aerodynamics, to the affects that the brake system has on deceleration. With this ground work laid out, we can begin to vary the values previously described for the brake calipers and see what those changes do to the resultant force required by the driver.

2.3 Results

The first scenario that the MATLAB code was run through is the affect that varying number of brake caliper pistons have on the required brake pedal force. In order to properly conduct this study, the size of the pistons had to remain constant in addition to the rear caliper configuration. From this study the following graphs were generated. This was completed for both the front and rear calipers with opposing constants for each.

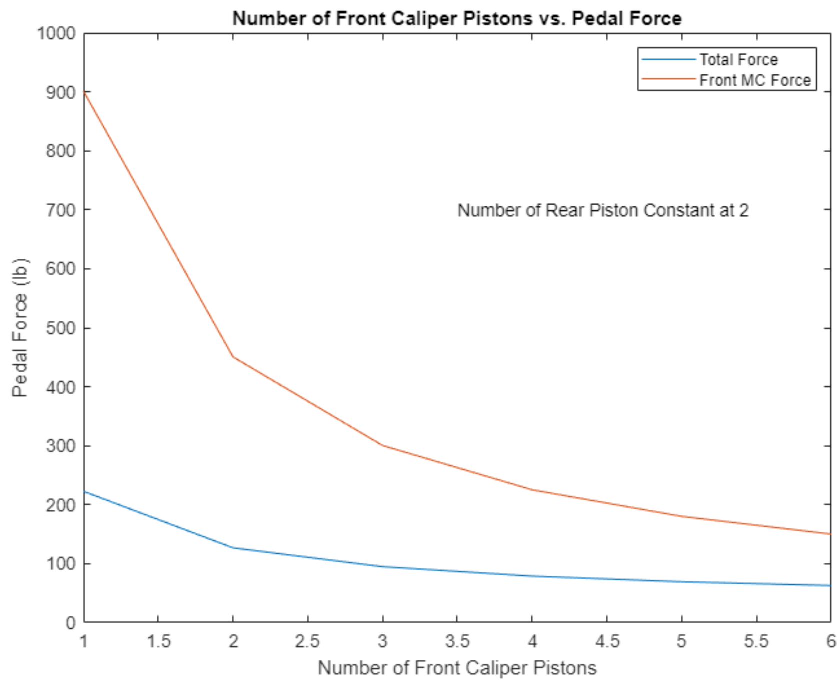


Figure 2 Number of Front Caliper Pistons vs. Brake Pedal Force

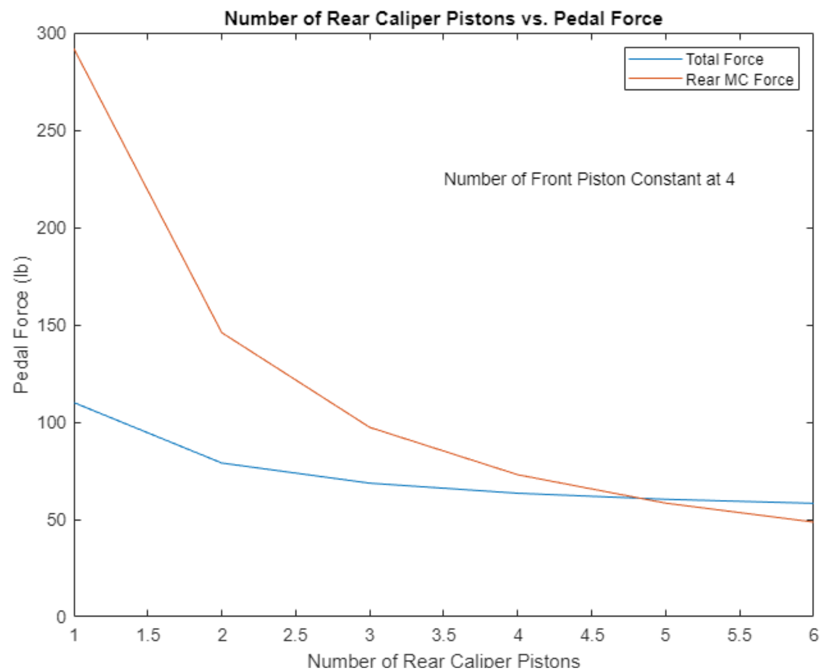


Figure 3 Number of Rear Caliper Pistons vs. Brake Pedal Force

From this study, it can be shown that there is a diminishing return that is present when relating the pedal force vs. the number of pistons in each caliper. It is important for us to keep in mind that while increasing the number of pistons may slightly generate better braking power, it will almost exponentially increase the manufacturing time when producing these parts. The higher to number of pistons, the more post-processing machining would need to take place to hone out each of the cylinders. For this reason, we are trying to keep the number of pistons to a minimum while also generating sufficient stopping power.

The front caliper would be beneficial to produce a caliper with 4 pistons. There seems to still be a generous about of decline for pedal force from 2 to 4 that we can still take advantage of. As for the rear caliper, this decline is still present on the force plot but we feel it would be more advantageous to select 2 pistons for the rear in order to keep manufacturing costs lower. While a 4-piston rear caliper would be ideal, it would almost double the amount of post-processing machining required.

The next step is to sweep values for caliper piston radius to understand how that affects the pedal force required.

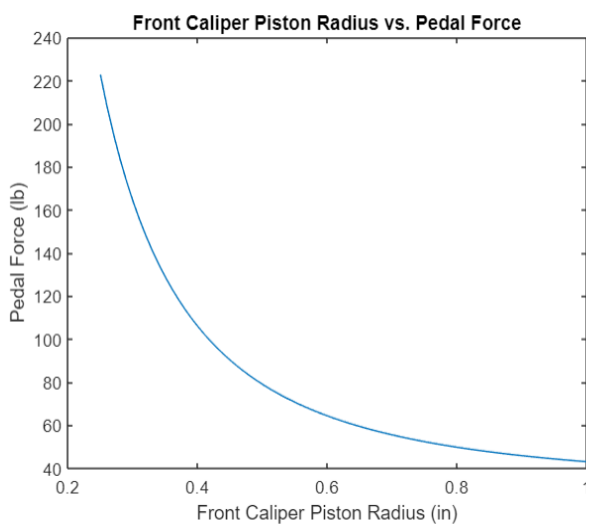


Figure 5 Front Caliper Piston Radius vs. Pedal Force

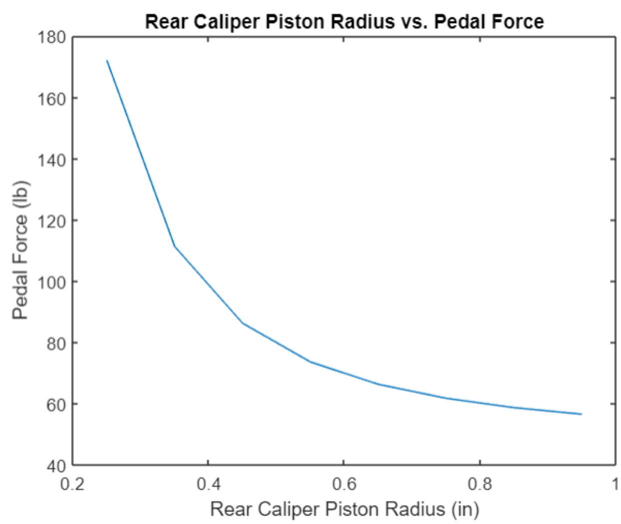


Figure 4 Rear Caliper Piston Radius vs. Pedal Force

With increasing piston radius sizes, we will begin to run into issues with packaging in addition to overall weight of the component. While a deeper analysis can be conducted, for the time permitted we feel that utilizing 0.5-inch radius pistons for both the front and rear would be beneficial. At 0.5 inches on the plot, it is towards the end of the decaying curve. This allows for us to get the most out of a large brake caliper piston while not having too many difficulties with packaging and overall component weight.

3. Seal Research

Preliminary research will be conducted in order to properly understand seals and how they will interact with the piston. MATLAB code will calculate is that of the line pressure that can be found in the brake system. This line pressure will be in direct contact with the seals present in the system and it is imperative that these tolerances between the seals and piston are correct in order to ensure proper operation.

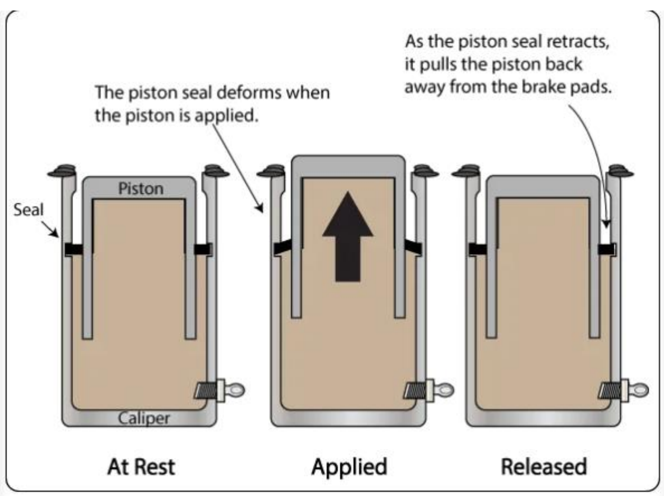
In order to fully understand the seals within the brake caliper, preliminary research has begun to first gain an understanding of what factors are to be taken into account when designing brake caliper seals. System pressure will be one of the largest factors in the design of the piston to caliper seal. The seal we use will need to be capable of holding up in scenarios in which we see the peak pressure of the system. For our preliminary research, a max pressure will be assumed to be around 2500psi. From previous research done, it is known that the system should never exceed 2500psi. Now that a system pressure is obtained, other factors are to be considered. Factors such as caliper to piston tolerance, seal groove design, seal design, seal material and piston surface roughness will all need to be taken into consideration to ensure a functional and successful seal design.

3.1 Seal Material

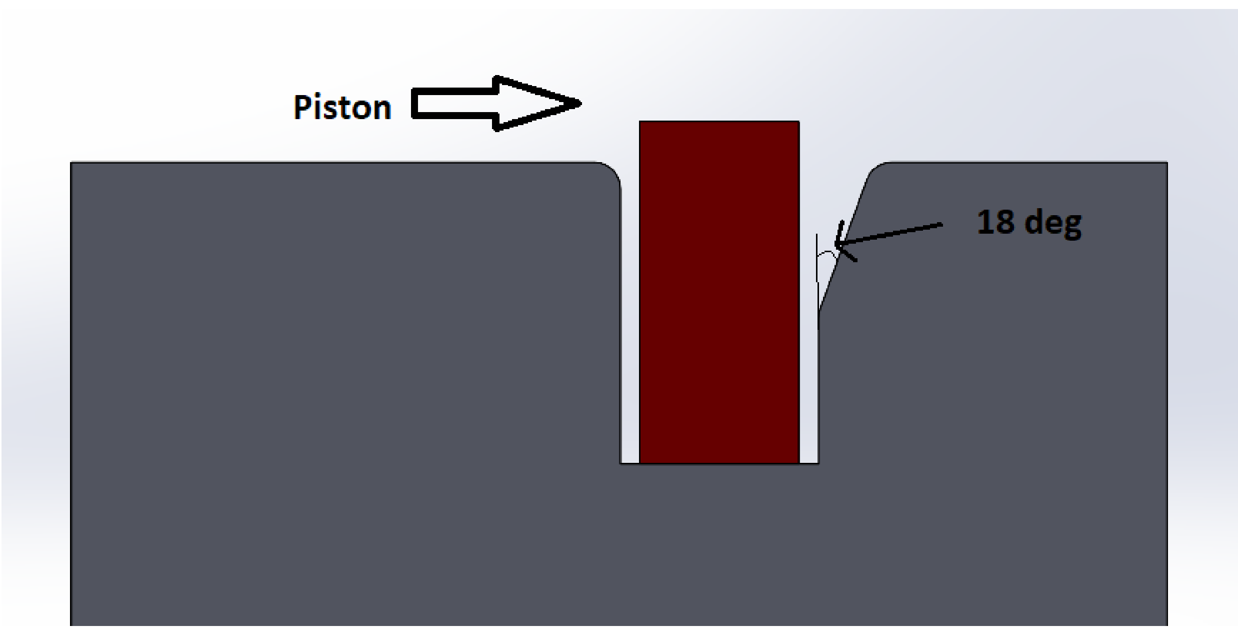
The first step taken in the actual design of the seal was to determine the material in which the seal could be made out of. The seal used in our application will be a O-ring type seal. Whether or not this is a round O-ring, square O-ring or some sort of different geometry has yet to be decided and will most likely depend on the design of our seal groove. To select the proper seal material two design properties were to be analyzed. These two properties are the temperature of caliper and brake fluid used. There are two main materials used in brake caliper seals, these are EPDM (ethylene propylene diene monomer rubber) and FKM (Fluorocarbon or Viton). EPDM is a very common material used for braking systems with resistance to almost any brake fluid on the market. The downfall of EPDM is its temperature resistance, being it can only withstand around 300 degrees Fahrenheit. Due to high temperature expected in our system, it is clear that FKM will need to be the material used for the brake caliper seal because it has a temperature resistance of around 400 degrees Fahrenheit consistently and it can also withstand much higher temperature for short periods of time. The downfall of FKM is that it is not resistant to any glycol-based brake fluid therefore a silicone-based brake fluid would need to be used. Now that a seal material is selected, the next steps to be taken will be designing the seal groove as well as seal geometry.

3.2 Seal and Groove Geometry

The seal geometry along with the seal groove geometry are very important design factors in a brake caliper. To design this portion of the brake caliper we must consider and analyze the three main components, the piston, the seal, and the seal groove. While these may seem like very simple parts, there is a lot that needs to be considered when designing the seal geometry and most importantly the geometry of the groove for which the seal will be sitting in. The brake caliper seal in our system will perform two functions. The first and most important function is to seal and prevent leakage along the piston when the caliper is seeing peak fluid pressure. Another function our seal will perform is retracting the piston when the brake pedal is released. The idea behind this is that the seal will be stretched when the piston extends and the elastic material of the seal will return to its original position when the pressure is released. This is illustrated in the figure below. Another reason to design the seal in this way is to prolong the life of the seal. If the piston is simply just stretching the seal slightly rather than sliding across the seal the amount of friction and wear on the seal will be greatly reduced. In order to allow the seal to deform in such a way, the seal groove must be designed in such a fashion that allows for this movement while still ensuring a tight fit.



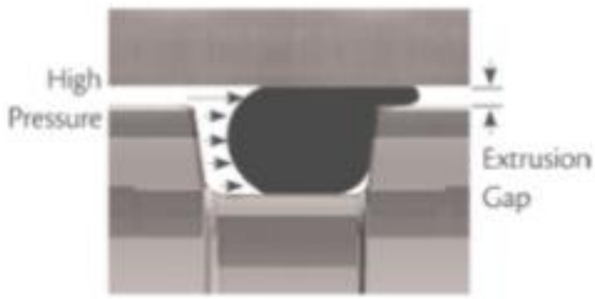
Before the seal groove is designed, a seal geometry must be determined. Due to its large surface area contact to the piston, and wide availability, a square seal will be used. For this brake caliper we will be designing the seal groove to be embedded into the caliper body rather than in the piston. The geometry and tolerances of the groove will be very crucial to the functionality and reliability of the system. Before the groove geometry is designed, the size of the square O-ring needs to be determined. Since the pistons have been determined to have best functionality at a size of 1 inch in diameter, the inside diameter of the seal is to be smaller to ensure a tight seal. With that in mind a Fluorocarbon seal with an od of 1.121", an id of 0.989" and a thickness of 0.066" was selected. As a general rule of thumb, the seal should be squeezed by 1% to 2% of its diameter in order to maintain a proper seal. Since the piston is 1 inch and this will stretch the seal about 1%, the inside diameter of the seal groove will be designed to be 1.120" which accounts for just a little over 1% squeeze. To account for the bulging of the seal, the bottom of the seal grove will be 0.080" wide. To allow the movement of the seal which in return will retract the piston when the brakes are released, the seal groove will have an 18-degree angle toward the direction of piston travel. A rough model of this is shown below.



Depending on material properties of the seal, the 18 degrees should allow the piston to be extended anywhere from 0.010" to 0.020" and retract to its home position without breaking the static seal with the square O-ring being used.

3.2.1 Piston to Bore Tolerance

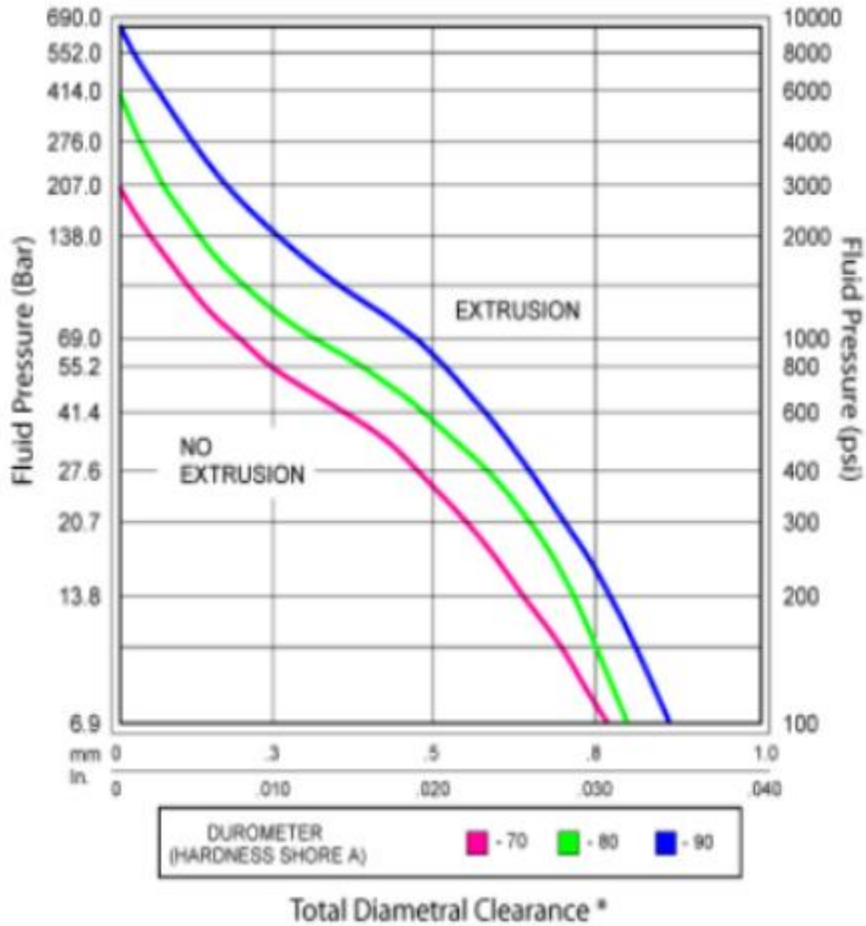
Now that the seal material, seal geometry, and seal groove geometry has been determined, it is very crucial that the proper piston to bore tolerances are maintained for this system to perform at a



Extrusion

high standard. The main failure that will be seen if proper tolerances are not held is seal extrusion. Seal extrusion is a phenomenon that is seen when the piston to bore gap is too large and the seal actually begins to enter the large gap due to the fluid pressure. An illustration of this is shown below.

In order to avoid this, there is a chart that shows the maximum diametral clearance between the piston and bore for any given pressure. This chart is shown below.



Reduce the clearance shown by 60% when using silicone or fluorosilicone elastomers.

From the previous section it is known that this system could see up to 2500 psi. The material of the seal being used is fluorocarbon with a hardness of Shore A 90. From this chart, it is determined that the maximum diametral clearance to avoid seal extrusion in our situation is about 0.007”. For better functionality and higher performance, the piston to bore clearance will be designed to be 0.003” with a tolerance of 0.0002".

4. Modeling Introduction

The next step is to model a brake caliper with the base geometry that can be used to run finite element analysis studies in addition to topology studies. This model was created with close detail on the interior geometry that we felt needed to remain in the finished product to ensure proper operation. In addition, further research and design time has been spent on the seal-piston interaction. Not only has geometry been looked further into but also the materials that both the seal and piston will be made out of have been analyzed.

4.1 Modeling Background

To create a part that can operate correctly when put into operation, it is important that the persons designing it fully understand the forces and constraints that the part require. While most people see a brake caliper as another mundane component on a car that doesn't serve any "special" purpose, it is more interesting than most think. The team had to take a step back from the nitty gritty calculation analysis that was happening previous and take a 10,000 ft view at the operations of a brake caliper. This allowed for a big picture understanding of what the we would be dealing with when designing a primitive 3D model that we would later build off of. The biggest focus for this part of the design is to create a 3D model using Solidworks that we could use for the topology study. This model will then need to be ran through multiple variations of FEA in addition to topology studies to create a part that is 75% complete.

5. CAD Modeling

The first step to take is creating the 3D model that the remainder of the work will be completed off of. This model must have the locating geometry defined and constraining geometry modeled in order to locate the position of the part onto the vehicle. It must also have a complete system of fluid passages that will deliver the fluid from the brake lines of the vehicle to the pistons of the brake caliper. In addition, the number of pistons and piston bore diameters must match that of what was decided from the last analysis that was completed using the MATLAB model. Generally speaking, this part must be able to operate as a brake caliper without any further studies being complete. This will be the billet of material that the topology study will then remove the appropriate pieces from to create a lighter part that performs the same function as original. A picture of this initial model can be seen below in the figure.

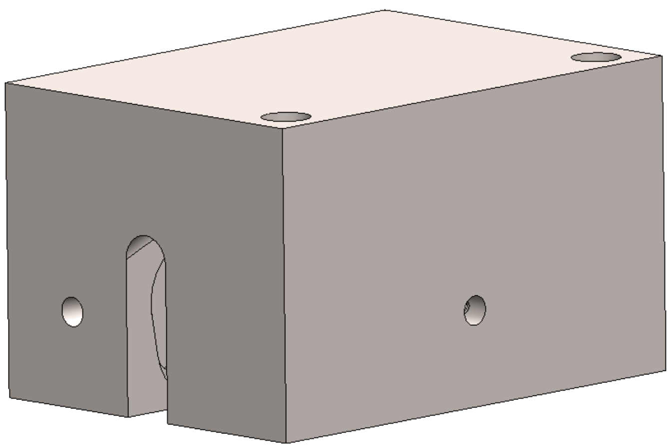


Figure 6: Isometric view of initial brake caliper model

While this part does not seem like it contains many features, it is still a critical part of the process. If one were to look at the transparent view of the part, they would see all of the inner workings that the caliper contains. A closer look into this "simple" part can be seen below in the following figures. The lines are set to full fill instead of the typical dotted lines in order to show the complexity of the interior design more easily.

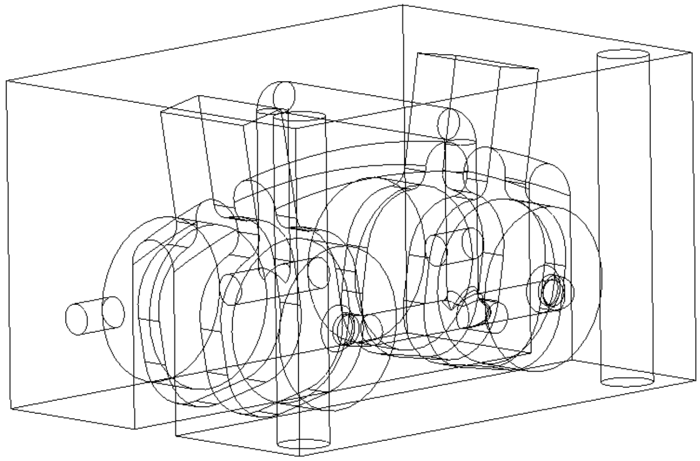


Figure 7: Transparent isometric view of initial brake caliper model

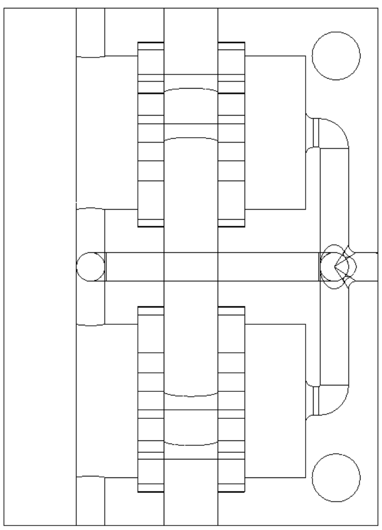


Figure 8: Transparent aerial view of caliper

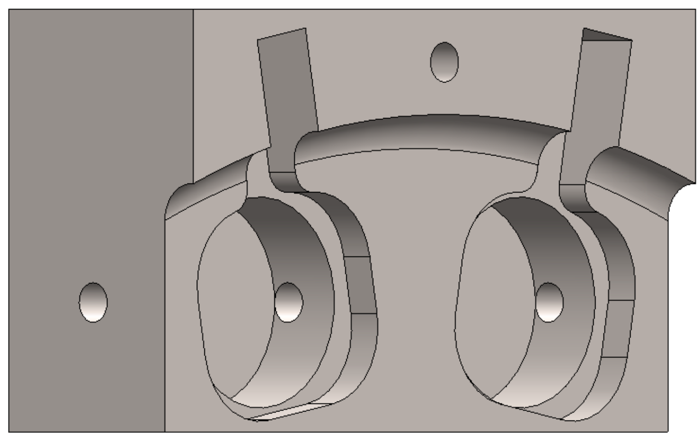


Figure 9: Cut section of brake caliper model

From these figures displayed, some interesting features can be seen. These figures range from items like the fluid passage ways, brake pad fixtures, piston bores, to outlet and inlet ports for the movement of fluid. Each of these will be talked about in further detail.

5.1 Fluid Passage Ways

The purpose of the fluid passage ways that run through the body of the caliper is to efficiently transport the pressure created by the driver through the brake line, into the caliper body, and finally ending up at a motion in the brake caliper piston. The Formula SAE team uses 3/16" brake line that leads into the caliper. In order to keep the line size consistent throughout the system, the fluid passage ways that are seen are also 3/16" in size. In addition to the sizing of the cut outs, it was important to keep the inlet to the brake caliper located as centered as possible. While the system should be pressurized evenly when in operation, it has proven that the calipers that featured feed lines that are centered often had more even pad wear than the caliper with offset feed lines. This information was relayed to us from the Brake System lead at Zips Racing.

5.2 Brake Pad Cut-Outs

The brake pad cut-outs are integrated to allow for the given brake pad to fit into the caliper body. For this iteration, the previous style of brake pad that the Zips Racing team used is what was designed.

The purpose of the brake pad cut outs is to provide adequate space for the brake pad to recede into the caliper body in order to clear the thickness of the brake disc. They must also be reinforced enough to resist the braking torque that is acted directly onto the brake pad from a braking event. While these cut-outs may not seem necessary, they are the primary structure that hold the brake pad into the body of the caliper so it is crucial that they are significant in regards to strength.

5.3 Piston Bores

The piston bores are positioned in way that it will distribute a centralized force onto the brake pad. This creates an even braking surface that will aid in efficiency. The fluid passage ways enter the piston bores as low as possible without choking the flow present in the channels. This is done in hopes that the fluid will make a somewhat smooth transition from the passage ways to the cylinder bores.

6. FEA Analysis

With the completed interior geometry being designed onto a base part, we can begin Finite Element Analysis on the part in order to understand the load paths traveling through the component. FEA analysis is focused on ensuring that the part is properly constrained and the forces are applied in a way that will represent an operational case.

6.1 Constraints & Forces

The first step is to understand the forces that will be traveling through the part. The forces and constraints that will be applied are as follows; interior line pressure, braking torque, piston force acting outwards on the caliper body, fixed hinged at caliper bolts, fixed face where the caliper mounts to upright.

6.1.1 Interior Line Pressure

From the calculations that were preformed previously using values provided by the Formula SAE team, it was shown that the maximum operational pressure they see in their data is ~1250 psi. While this is during operation, there are certain events where they will see spikes in the line pressures when large amounts of force are being inputted into the brake pedal such as the braking event in tech inspection. Due to these occasional spikes in pressure the caliper will see, the FEA is ran at the overall maximum value that the part will see in its lifetime. The pressure of the internal passage ways in addition to the brake piston bores is set to a value of 2000 psi. In the figure below, the internal forces can be seen acting on the part.

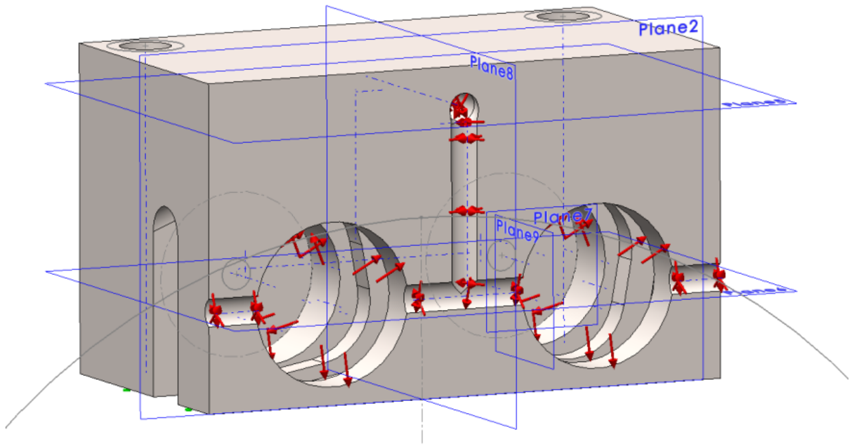


Figure 10: Picture of pressure forces being applied to internal passages of part

The red lines shown in the figure is where the pressure force is defined. It spans throughout the entire passage way as well as the bores of the pistons. It is located wherever the fluid inside of the caliper will be pressurized.

6.1.2 Braking Torque

The brake torque is applied normal to the brake pad holding surfaces. The reason for this is because that is the only caliper geometry that opposes the forces generated between the brake pad and the brake disc. The force value used for this is found by dividing the brake torque generate by a front corner assembly by the center swept radius of the brake disc. This force is defined in the direction of the disc as it would be seen on the car. The value used is 2300 lbf after a safety factor of 1.5 is applied to the original force calculated. This force can be seen in the figure below.

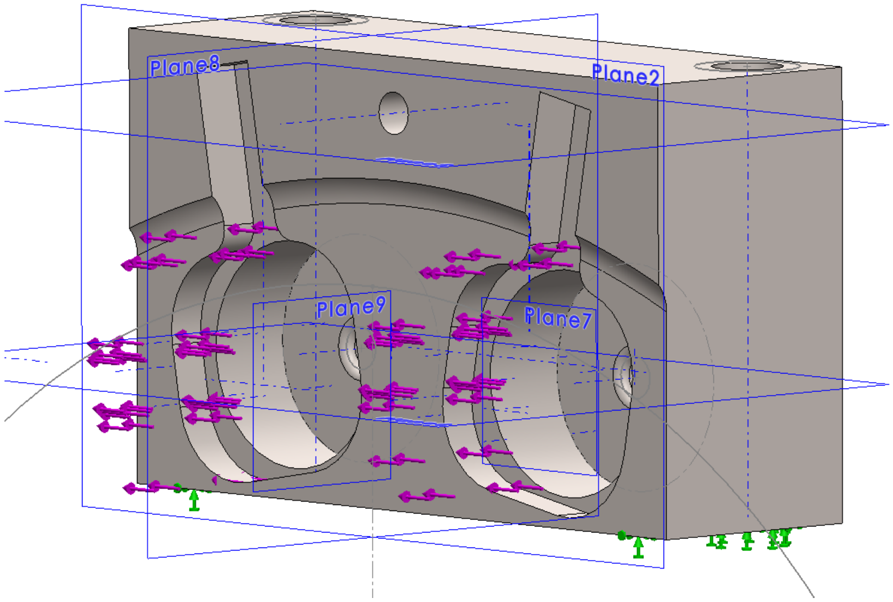


Figure 11: Cut section of caliper body with braking forces applied

The figure above shows the braking torque as pink arrows acting in the direction of rotation of the brake disc. Only the front half of the geometry is selected because only these faces will see load from this braking event due to direction of rotation.

6.1.3 Outward Piston Force

The next force being applied is the outward force that exerted by the pistons due to the reaction for at the brake disc. This is the reaction force of the internal pressure acting on the brake caliper piston so the magnitudes will be the same. The force being applied in total is 1800 lbf of “clamping” load. This force will act at each piston individually and can be visualized below.

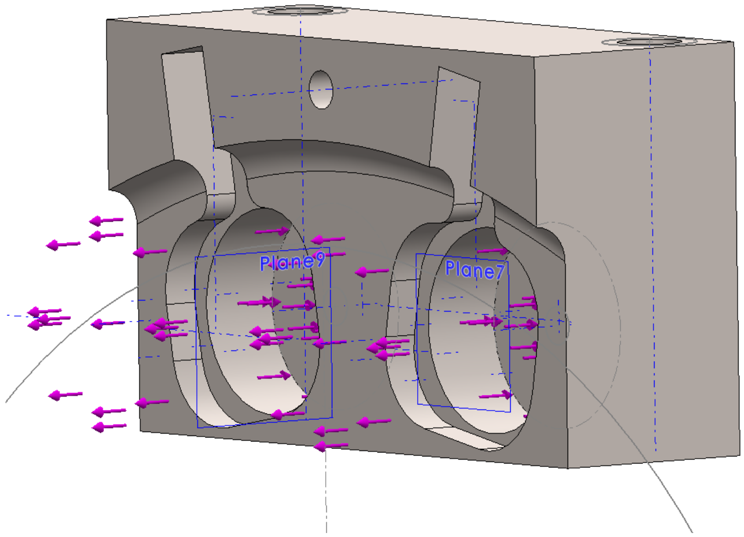


Figure 12: Cut view of outward force on caliper body

6.2 FEA Results

After each of the constraints and forces are applied to the part, it can proceed to be meshed and have the analysis ran. This FEA is ran to ensure that the correct forces are being applied and the deformation of the part is as expected. Below are the results that have been generated from the study.

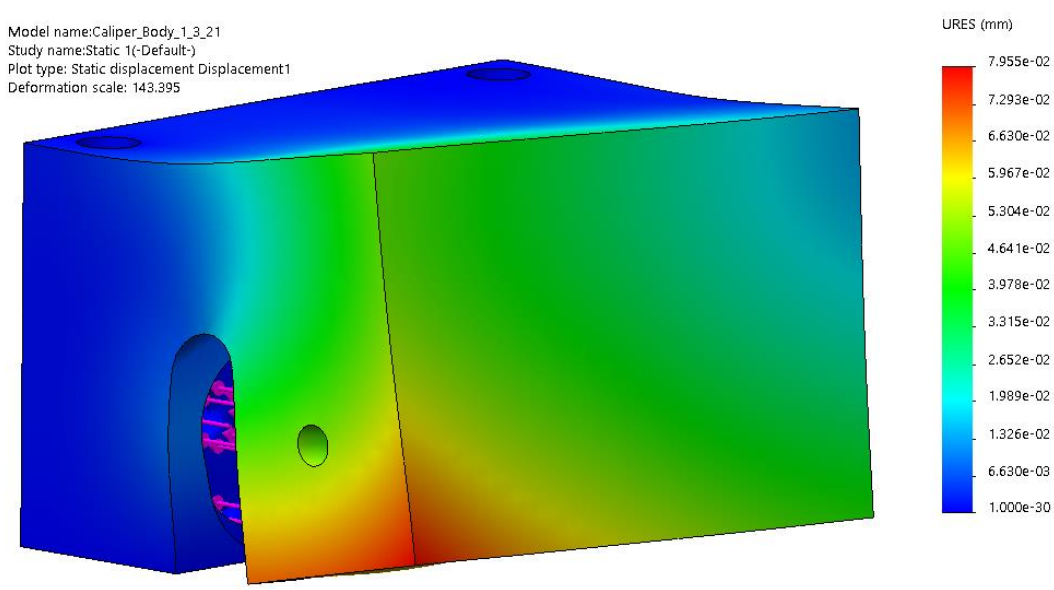


Figure 13: Displacement results from FEA study

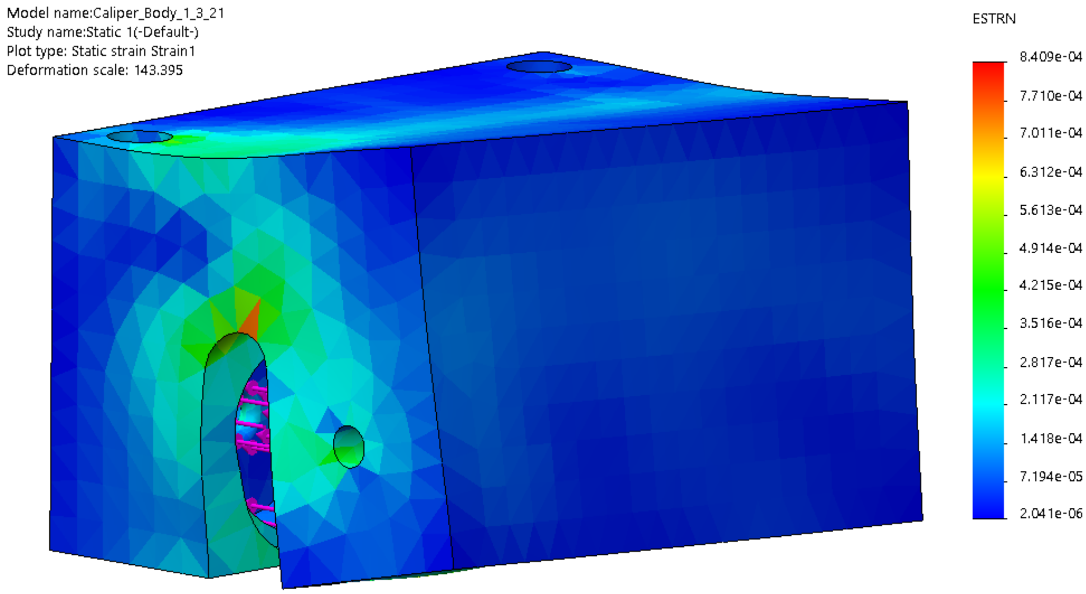


Figure 14: Strain results from the FEA study

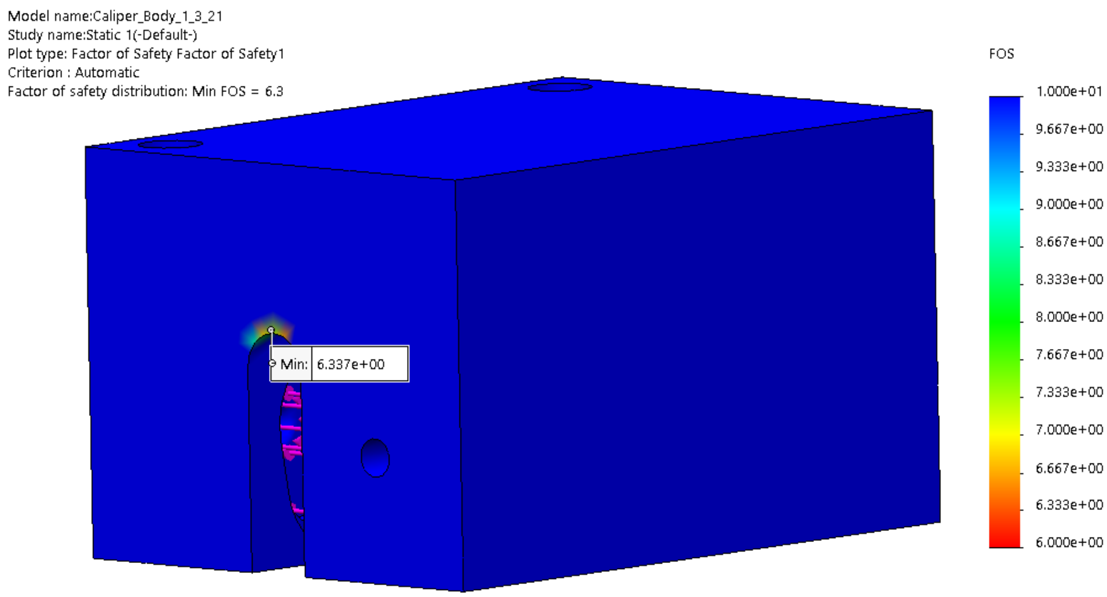


Figure 15: Factor of Safety results from the FEA study

7. Topology Background

In order to have a part that utilizes the modern technology of additive manufacturing, the means of component design are vastly different than what is considered traditional. In most instances, the engineer would go through an iterative process of running revised components through the FEA analysis and understanding where material can be removed based off of those results. With topology, this iterative process is automated and will continue until the criteria set by the user are met. While this seems straight forward, it is much like a calculator. It is only efficient if the user is inputting the correct information. The way the topology software analyzed the part caused use to take a step back and redesign our base model that we were using for this analysis. Certain geometry had to be modified in order to properly constrain the study and leave material in certain sections where we would later need to post-process machine features.

7.1 Model Modification

After gaining more experience with the topology software in the SolidWorks software package, it was apparent that we would need to modify the model that was created in the previous steps. The reason for this is because we needed to add the additional access holes that would be used for post-processing the bores of the calipers after print. These features had to be integrated into the part prior to

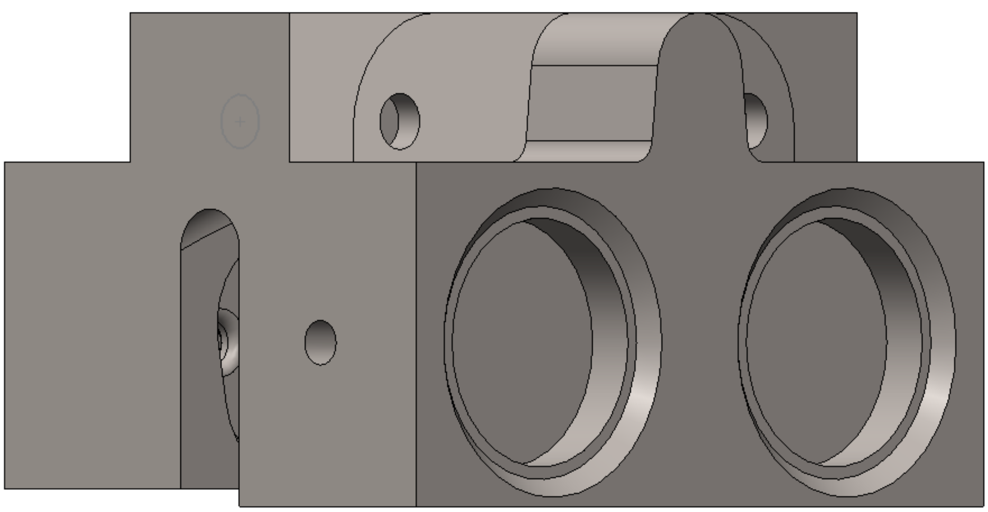


Figure 16: Modified part model with additional cut-outs for post-processing

analysis because after the topology study is complete, the geometry that is left is difficult to modify. Below is the picture of the modified model that would be used for the topology study.

7.1.1 Bore Machining Holes

The portion of the caliper that received the most reworking is the outboard section of the caliper that can be seen in *Figure 16.* This features holes that have faux walls modeled into them to allow for outward forces to be applied to replicate the extension forces of the brake caliper pistons. These walls are purely for FEA and loading reasons. The "complete" feature can be seen in the figure below.

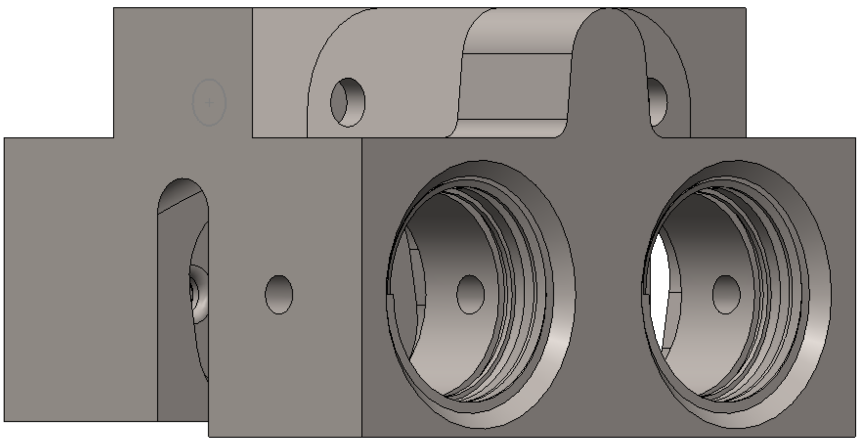


Figure 17: "Complete" post-processing feature on base brake caliper

These holes that are present in this base part will allow for a student to post-process machine the bores of the brake caliper pistons. The reason for this is because when the part is printed, the surface that is created inside of these bores will not be capable of creating an efficient seal. Since this portion of the print will have 100% infill density, it will be able to be machined after the print is completed by traditional milling techniques. This will create a surface that will allow for a tight fit between our seal and our brake caliper piston.

7.1.2 Bore Plugs

In order to fill these holes, custom plugs needed to be modeled. These plugs are able to be machined by traditional processes and will be created in-house using The University of Akron's machine shop. These plugs must be able to thread into the body of the brake caliper and create a seal that will not allow for pressurized brake fluid to escape. The plugs that were modeled for this purpose are shown below. There are currently no fastening features modeled into the part due to time constraints but they will be added prior to production.

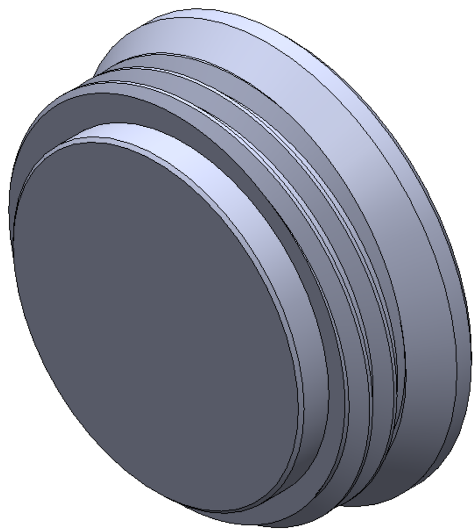


Figure 18: Bore plug that will be used to close access holes

8. Simulation

After the modifications above were added to the caliper, the rounds of simulations could begin. The simulation would have the same loads and constraints as the finite element analysis that was described in the previous report. The only additional items that are added to the study are the criteria needed for the topology study. These criteria can be understood in the following sections.

8.1 Topology Constraints & Goals

The constraints and goals used in the topology will determine the part that is outputted by the study. These constraints will be different from part to part but it is important to understand the operation of each feature on the part and apply the necessary constraints to each. The following sections will highlight the varying types of constraints & goals and how they were applied to the model.

8.1.1 Preserved Regions

The first criteria to include in the topology study are the preserved regions. These are sections of the part that the user can define and they will be neglected to change during the analysis. The purpose of this is to have geometry remain the same before and after the study. This is primarily used on the surfaces that will be coming in contact with the brake fluid and must maintain a fluid tight seal. The other features that are selected are the holes that will be used to mount the caliper, the features used to retain the brake pad, the seal surfaces for the post-processing features, the holes used to secure the brake pads in the caliper, and the fitting inlet for the caliper. These features will remain untouched in the part after the simulation is completed.

8.1.2 Symmetry Control

The symmetry control will allow for the user to define a plane that the part will remain symmetric across. This can be used to ensure the part is both visually appealing and ensures the functional operation if the part was to be used for the opposite side of the vehicle. For this study the symmetric plane was defined at the mid-point of the caliper. This can be seen in the figure below.

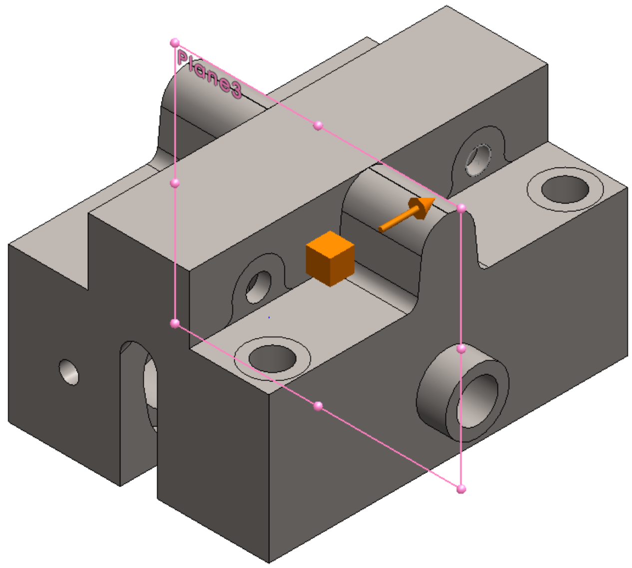


Figure 19: Mid-plane used to define the symmetric control in the topology study

8.1.3 Topology Goals

The next necessary step is to define the goals that the topology study must meet. These goals vary from stiffness to weight ratio, maximum displacement, factory of safety, and percentage of weight lost. For this particular study, we chose to drive the study with 60% weight reduction while maintaining a factor of safety of 2. We felt that these goals would drive the software to optimize the part in a way that created the lightest possible component while keeping it reliable. In our eyes, this is the ideal way to utilize the topology software.

8.2 Topology Results

Due to restrictions to the simulation computers that were initially going to run the topology studies, we had to exercise our back-up plan which was running these simulations on our laptops. While this wasn't an ideal situation, we made the best of what we had available to us. Each topology study took roughly 4-6 hours while using a mesh that wasn't unnecessarily fine but would also provide an accurate component once the study was complete. Each study generated ~75 gigabytes of result file data and had to be ran on a dedicated external hard drive. Often times we had to go back and tweak the model to generate results that were visibly promising which led to many iterations of the study needing to be ran. Shown below are the current results from the iteration we have most recently completed. The resulting part is 56.1% lighter than the current traditional caliper counterpart.

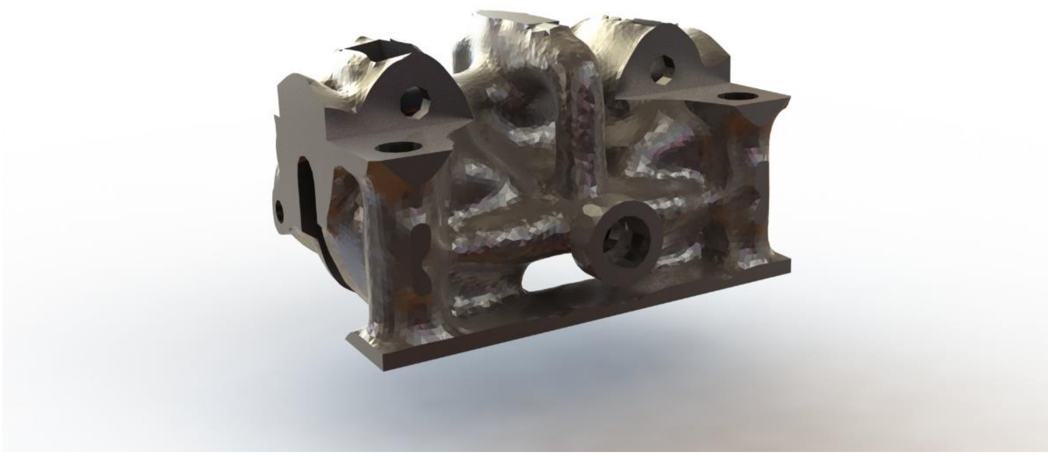


Figure 20: Side profile of brake caliper after topology study

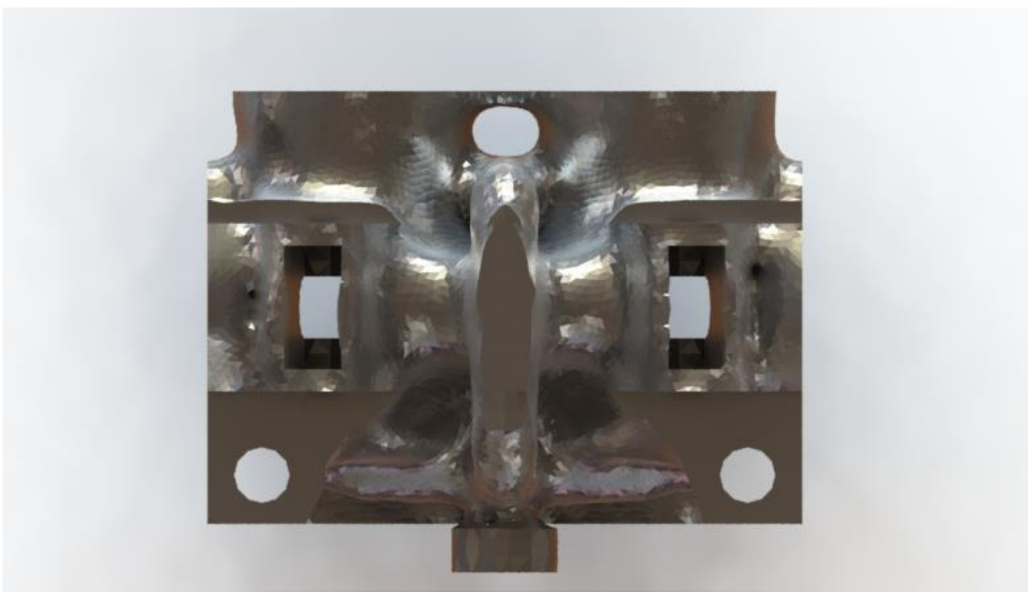


Figure 21: Top profile of brake caliper after topology study

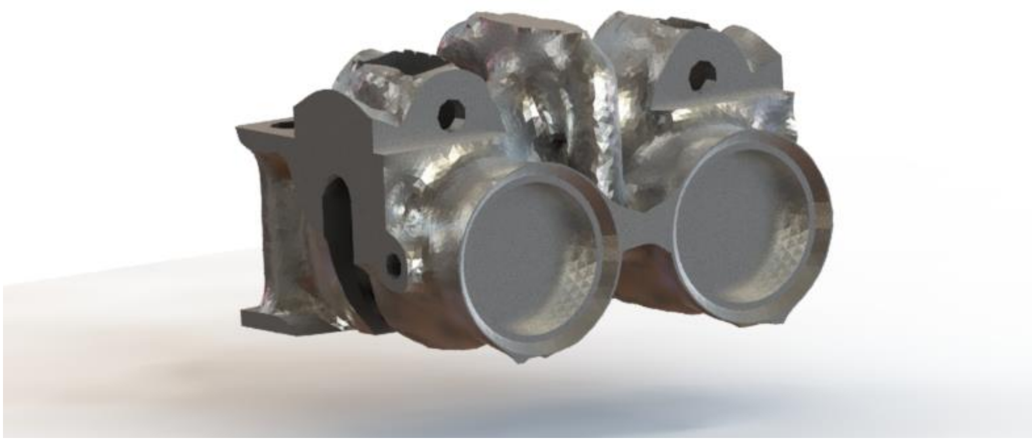


Figure 22: Outboard side of brake caliper after the topology study

9. Engineering Standards

When designing and manufacturing a brake caliper of this nature there are several engineering standards set in place by organizations such as SAE and ASME that referenced and followed to ensure the finished product will meet all requirements and be safe for use. An example of one of these standard J1603_201412 from SAE International. The title of this standard is Rubber Seals for Hydraulic Disc Brake Cylinders. The importance of this standard is to make sure the proper material and geometry is being used for the seal to prevent failure in extreme situations. The documentation on this standard includes required specifications such as temperature resistance, fluid resistance, corrosion resistance and seal geometries that are allowed. During the design of this brake caliper, this standard was followed carefully.

Another engineering standard published by ASME that is of important for this project is code Y14.46. The title of this standard is Product Definition for Additive Manufacturing Draft Standard. This was a standard that was crucial to follow at the end of the design process as it provides the proper terminologies and definitions unique to additive manufacturing that are a crucial part of a drawing that is going to be sent to a professional additive manufacturing facility. This standard also gives guidelines on geometric tolerances and dimensions for an additive manufactured part. It is also important to note that the ASME guidelines for validation of a finite element analysis were closely followed to ensure proper loading and mesh sizing.

10. Conclusion

The goal of this project was to take advantage of modern additive manufacturing technologies to design a lightweight brake caliper that is not commercially available for use on the formula SAE combustion car. Throughout the length of this project, we have endured many adversities that required alternative solutions to continue making progress. To achieve this goal, we made use of finite element analysis and topology optimization with Solidworks. While this project was a learning curve for everyone, we were able to successfully design a brake caliper that meet all the requirements. The requirements and calculations carried out for the design were all based on known parameters obtained from the past year's formula SAE car. Overall, we feel as if we have successfully met the goal and laid down excellent groundwork for future formula SAE teams to manufacture and use this brake caliper to obtain a competitive edge in competition.

10.1 Future Work

This section will cover the future work that needs to be completed on this part in order to create an operational prototype. While we faced many adversities throughout this senior design time frame, we feel that what we were able to walk away with is a great accomplishment. The goal of this project was to design and optimize an additive manufactured brake caliper that can be used on the formula SAE design team and that is exactly what we did. While we were not able to manufacture an operational prototype, we did complete a design that we are confident with which provides the formula SAE design team with what they need to manufacture and test this brake caliper on the car in years to come.

In the future a few things will need to take place to bring this brake caliper to life. First thing that needs to be done is to develop drawings of the caliper that can be sent to the additive manufacturing facility. This is a very crucial task as it is necessary to closely follow all the engineering standards to ensure proper tolerancing and dimensioning. Once a caliper housing is printed, the next steps will be the most crucial part of the manufacturing process. The next steps include the cnc machining of seal grooves and piston bores. It is of utmost importance that the correct tolerances are stated clearly and followed in this post processing step or the brake caliper will not function properly. Another critical component that will need manufactured is the pistons. The pistons will be manufactured on a cnc lathe to meet proper tolerances, surface roughness and geometry to maximize performance of this caliper.

Once the brake caliper is manufactured and goes through all the proper post processing, the next steps will include purchasing of seals and fitting per design requirements. With all the components in hand the brake caliper will then be assembled. Once a set of two calipers are manufactured it will be necessary for the formula SAE design team to mount the calipers and run them through vigorous testing.

10.1.1 Fittings

A final selection has not been made for the bleeder fittings that will be used on the newly designed brake caliper. Fittings are a small factor when looking at the big picture of the entire unit, but they must be considered as an essential part of the unit. Bleed fittings are necessary to purge air out of the brake system to maintain proper function of the unit. If there is air in the lines, the brakes will not function correctly because the air will compress in the lines and not activate the pistons. The non-compressible brake fluid should be the only substance in the brake lines and calipers at the times of operation.

The primary focus of creating a titanium brake caliper was to create a stronger unit which is also lighter. Weight reduction is very important to the team, and every opportunity to reduce unnecessary weight should be considered. Currently, a fitting using a ¼-28 thread is being used. This size was selected because it is the smallest size that is easily available. Some fittings are smaller, but this size was selected primarily for its availability.

In the future, smaller fittings could be a viable option for a refined design. The smaller the fitting can be would mean the more weight saved even if it is just a few grams. Other fitting designs could also be considered as well. Although the Zips Racing Formula car is inspected and maintained, corrosion of parts will still occur. A potential fitting could be designed to be made out of titanium to reduce the corrosion effect from the elements while saving a few more grams of weight overall. From a cost analysis standpoint, the titanium fitting route may not be the best investment when considering how much it is actually saving in weight and corrosion replacements. However, the idea of a titanium fitting should be considered for future work.

10.1.2 Post Processing

Our model will need to processed post the printing phase. This means the 3D printed part will undergo a machining process before it is complete. The specific area that needs attention is the cylinder housing. This housing needs to have a fluid tight seal to prevent the hydraulic from leaking out or from having environmental factors getting in. This section of the caliber will be infilled at 100% density to be machined out via a CNC machine. The reason for this section of the part to be machined out and not just printed is because printing will not provide the overall consistent diameter size. Without a consistent diameter size, the housing will not be fluid tight.

With the level of accuracy that modern 3D printer can obtain, many more avenues of innovation and application have been discovered. However, for the tight tolerances needed to have a fully functional brake caliber, metal 3D printing falls short. The average tolerance of a metal 3D printer is +/- 0.5 mm. This seems like a very tight tolerance however compared to the tolerance obtained using a CNC machine the difference is drastic. The average tolerance for CNC machining on titanium is +/-.0127mm. This is difference is why we chose to infill then process after printing.

Once the full-scale model is printed the post processing will be done at the University of Akron, in the machine shop. There is also the option of us sending it to a profession machine shop and getting the part processed there. The main deciding factors of this money and accessibility. Using the resources of the University of Akron will allow for cheap, if not free labor to have the post processing down. The drawback of this is twofold: graduation and COVID-19. As this group is fully consisted of fifth year engineering students that plan to graduate at the end of this semester, spring of 2021. With the current timeline we cannot get a full-scale part made before graduation, thus as graduates we will not have the same accesses to the University’s resources that we did as students. Even if we are allowed access, to finish the part, due to COVID-19 we may not be allowed on campus until summer classes start or the University re-opens. This will be some months away and by this time all of us will have started our careers. We will have extremely limited schedules or even be in different parts of the country at that time.

This leaves the option of sending the full-scale model to a third-party machine shop. Here, the second problem of money emerges. Using the University's resources there would be barely any, if not zero, cost of labor. Whereas the machine shop will pose a rather large price due to the high tolerance and the material of the part.

Along with boring out the cylinder housing, custom caps need to be made. These plugs will thread into the body of the break caliber to prevent excessive brake fluid from leaking out. The plugs can be machined via CNC. The caps will either be made at the University of Akron or through a third part machine shop. The same problems that were faced with the cylinder housing also apply here.

The way the post processing will work all depends on when we obtain a full-scale model. In the future, when that happens, we will then evaluate the current social climate and determine the best course of action. Whether that may be through a third party or through the University of Akron. No matter what is chosen, it will be the safest and most effective way to complete or design.

Appendix A Base MATLAB Code

Givens

All numbers are based off of Zips Racing 2019 FSAE car

```
clear
clc
close all

G = 32.2;
% Geometry
W = 525;                  % Weight w/ driver: Lbs
L = 60.2;                 % Length of Wheelbase: Inches
Hcg = 9;                  % Height of CG: Inches
Fwr = 0.49;               % Front Weight Ratio
Rwr = 1-Fwr;
% Tire Info
utf = 1.7;                % Coefficient of Friction Front
utr = 1.7;                % Coefficient of Friction Rear
% Aerodynamic Loads at 30mph
Fadf = 48.5587;           % Aero Load on Front Axle: Lbs
Radf = 33.0469;           % Aero Load on Rear Axle: Lbs
Fdrg = 7.86831;           % Drag from Front Wing: Lbs
Rdrg = 19.7832;           % Drag from Rear Wing: Lbs
Udrg = 1.79847;           % Drag from Undertray: Lbs
```

Weight Transfer Calculations

```
Wf = Fwr*W;               % Static Weight on Front Axle: Lbs
Wr = Rwr*W;               % Static Weight on Rear Axle: Lbs
Lf = Wr*L/W;              % CG Distance from Front Axle: Inches
Lr = Wf*L/W;              % CG Distance from Rear Axle: Inches
Wfb = W*((Lr+(utr*Hcg))/(L+(utr-utf)*Hcg));                                %
 Weight on Front Axle after Transfer: Lbs
Wrb = W*((Lf-(utf*Hcg))/(L+(utr-utf)*Hcg));                                %
 Weight on Rear Axle after Transfer: Lbs
Wfb_aero = (W*((Lr+(utr*Hcg))/(L+(utr-utf)*Hcg))) + Fadf;                  %
 Weight on Front Axle With Aero: Lbs
```

1

```
Wrb_aero = (W*((Lf-(utf*Hcg))/(L+(utr-utf)*Hcg))) + Radf;        %
 Weight on Rear Axle with Aero: Lbs
Wtf = Wfb - Wf;     % Total Weight Transferred: Lbs
Wfbp = Wfb/(Wfb+Wrb);        % Percentage of Weight on Front Axle
Wrbp = Wrb/(Wfb+Wrb);        % Percentage of Weight on Rear Axle
```

Wheel Load/Torque Calculations

```
Ff = Wfb*utf;    % Friction Front Axle: Lbs
rr = 9;          % Rolling Radius of Tire: Inches
Ftfa = rr*Ff;    % Friction Torque at CP Front Axle: Lb*in
Ftf = Ftfa/2;    % Friction Torque at CP Front Corner: Lb*in
Fr = Wrb*utr;    % Friction Rear Axle: Lbs
Ftra = rr*Fr;    % Friction Torque at CP Rear Axle: Lb*in
Ftr = Ftra/2;    % Friction Torque at CP Rear Corner: Lb*in
```

Brake Caliper Inputs to Change

```
Sf = 2.0;        % Safety Factor to Allow Lockup
Fcpr = 0.5;      % Front Caliper Piston Radius: Inches
Rcpr = 0.5;      % Rear Caliper Piston Radius: Inches
Fcpn = 4;        % Number of Front Pistons Per Caliper
Rcpn = 2;        % Number of Rear Pistons Per Caliper
```

Brake Caliper Calculations

```
Fdr = 3.25;      % Front Brake Disc Radius: Inches
Rdr = 2.75;      % Rear Brake Disc Radius: Inches

Fcf = Ftf/Fdr;   % Front Caliper Force: Lbs
Rcf = Ftr/Rdr;   % Rear Caliper Force: Lbs
Fcfsf = Fcf*Sf;  % Front Caliper Force W Sf: Lbs
Rcfsf = Rcf*Sf;  % Rear Caliper Force W Sf: Lbs

Fca = (Fcpr^2)*pi*Fcpn;          % Front Caliper Piston Area: In^2
Rca = (Rcpr^2)*pi*Rcpn;          % Rear Caliper Piston Area: In^2
Fcp = Fcfsf./Fca;      % Front Caliper Pressure: Psi
Rcp = Rcfsf./Rca;      % Rear Caliper Pressure: Psi
```

Brake Master Cylinder Calculations

```
Fmcd = 0.7;      % Front Master Cylinder Bore Dia: Inches
Rmcd = 0.625;    % Rear Master Cylinder Bore Dia: Inches
Fmcr = Fmcd/2;   % Front Master Cylinder Bore Radius: Inches
Rmcr = Rmcd/2;   % Rear Master Cylinder Bore Radius: Inches
Fmca = (Fmcr^2)*pi;       % Front Master Cylinder Piston Area: In^2
Rmca = (Rmcr^2)*pi;       % Rear Master Cyldiner Piston Area: In^2

Fmcf = Fcp*Fmca;          % Front Master Cylinder Force: Lb
Rmcf = Rcp*Rmca;          % Rear Master Cylinder Force: Lb
Tmcf = Fmcf+Rmcf;         % Total Master Cylinder Force: Lb
```

```
Pmr = 4.7;       % Pedal Motion Ratio
Pf = Tmcf/Pmr;   % Pedal Force Required: Lb
```

References

J1603A: Rubber Seals for Hydraulic Disc Brake Cylinders - SAE International, www.sae.org/standards/content/j1603_201412/.

"Y14.46 - Product Definition for Additive Manufacturing [Draft Standard for Trial Use]." *ASME*, www.asme.org/codes-standards/find-codes-standards/y14-46-product-definition-additive-manufacturing.