# Design And Analysis of Disc Brake Caliper for Centreless Wheel Assembly of FS vehicle

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***Abstract*—Effective braking is a critical factor determining the performance and drivability of any vehicle. Brake caliper being the heart of a braking system, the whole system is built considering its strength. An optimized design of a brake caliper thereby ensures reduced size of wheel assembly, reduced weight and effective braking. The analysis is further used to identify the critical locations of low stiffness on the brake caliper and also aimed at evaluating the performance of brake caliper under severe braking conditions. Hence best suitable design is suggested based on the performance and strength criteria. This paper studies a conceptual design of a brake caliper for a Formula Student (F.S.) vehicle, primarily focusing on reducing the size and weight without compromising its strength and stiffness. 3D modelling of brake caliper is created in Solidworks and analysed for stress, deformation and temperature distribution in ANSYS Workbench**

***Keywords*—Centerless Assembly, Bore Diameter, Piston Seal, Seal Groove Geometry, Piston Retraction.**

## I. Introduction

A brake system works by converting kinematic energy into thermal energy, which is absorbed by the brake system (mainly rotor) and dissipated into surrounding structures and atmosphere. Upon pressure application with disc rotating, the piston is pushed forward to press the inner pad against the rotor.

Floating and Fixed calipers are the two categories of brake calipers and by extension they determine the categories of disc brake itself.

### *A. How the Floating or Sliding Caliper works*

A caliper bracket is solidly mounted and the caliper itself within that bracket isn't solidly mounted so it can slide left and right via pins and bushings on the bracket.

A piston on the inner side of the disc pushes that brake pad as if to move the disc but because the disc can't slide, the force pulls the sliding caliper with another brake pad unto the other side of the disc.

The advantages of the floating caliper is that it's cheaper and lighter than the fixed caliper as it uses less parts and is more compact.

### *B. Working of Fixed Caliper:*

The fixed caliper comprises two half calipers (flange and cover), each of which have one or two brake pistons). Both parts, firmly screwed together (expansion screws) and connected by the so-called channel bore, make up the "fixed caliper".

This is bolted to the wheel suspension of the vehicle (kingpin, axle flange) or in the case of inboard brakes, to the gearbox.

When the brake is operated (build-up of hydraulic pressure), two or four brake pistons respectively force the pads to simultaneously make contact with the rotating brake discs on each side (braking position). The brake pads are guided and supported in the so-called caliper housing.

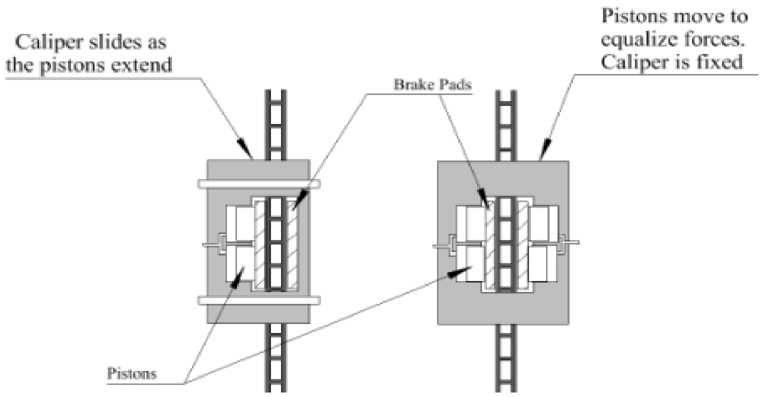
The caliper housing must be clean and undamaged, in order to prevent the brake pads from jamming or seizing up due to rust. If this happened, it would be impossible to press the pads against the brake discs (no braking effect).

When the pressure falls (upon completion of braking) the brake pistons are retracted due to the "rollback" – as described under "Function of the disc brake" – and the brake pads are forced against the piston by the expansion spring. The brake disc can now rotate freely because of the clearance.

To compensate for tapered brake pad wear on the leading edge, some fixed calipers have a "piston shoulder". This piston shoulder must always be in its specified position with respect to the leading edge (observe garage manual instructions).

If this is not the case, it cannot fulfil its function and it can lead to unpleasant brake noise.

If the piston is not aligned correctly, it must be returned to the specified position using piston turning pliers and the prescribed piston gauge.




Floating and Fixed Caliper

*C. What are the benefits of opposed-piston fixed calipers?*

A fixed caliper is secured rigidly to the axle assembly and has at least two opposing pistons that force the pads against the disc. A sliding or floating caliper has pistons on only one side of the disc. Therefore, when the caliper acts, it must slide or float in order to bring the pad on the opposite side in contact with the disc. Nearly all original equipment calipers are of the floating type. In a system with fixed calipers, not only is the mounting much more rigid, but the stiffness of the caliper itself is greatly increased. This manifests itself in enhanced braking performance, pedal feel, and pad wear.

*D. Classification of Brake Caliper*

*Depending on number of pistons*:
Number of pistons in a caliper significantly affects its performance. Calipers can be made with single or multiple pistons depending upon torque requirement and space availability. For vehicles requiring less braking torque, single piston can be used. But, with increasing torque requirement the bore diameter becomes considerably large increasing the size of the caliper. Hence, the number of pistons needs to be switched to two or three depending upon the requirement. The only disadvantage of using double or triple piston caliper is added number of leakage sources.

*Depending on Caliper Body*:
Brake caliper can be made as a single body called monoblockcaliper or in two parts called split type caliper. The major problem in a caliper being deflection under the application of clamping force, the caliper is made in two parts and then joined together by bolts. The position of these bolts must be close to the piston centreline so that the deflection is minimal.

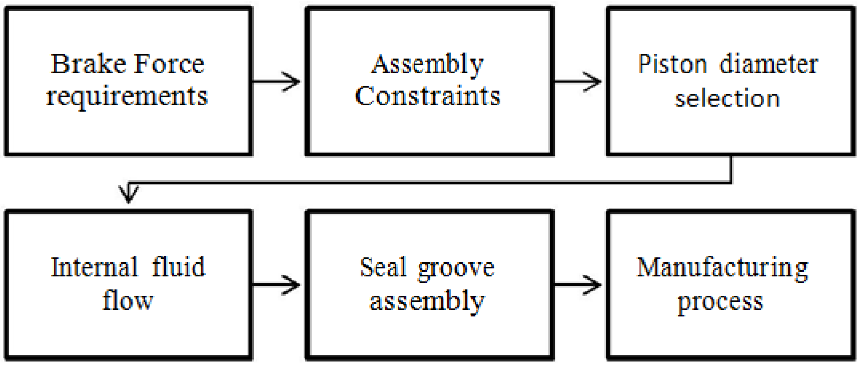
*E. Parts in a Caliper*

The general parts in the caliper are as follows:

- A CALIPER FRAME
- SLIDING PINS (FLOATING CALIPER)
- BRAKE PISTON
- BRAKE PISTON SEAL
- PISTON DUST BOOT
- BRAKE PADS
- PAD RETAINING PIN/S
- BANJO BOLT
- BLEED NIPPLE/SCREW
- MOUNTING BOLTS

## II. LITERATURE REVIEW

The calculation and verification of braking force is a crucial step in the design process of an automobile as the braking system directly factors as a good control and safety feature in the product. While designing, the main objective is to generate more braking force than ideally required to account for inefficiencies in mechanical linkages and hydraulic systems.
The design methodology of brake caliper is as follows:



*A. Bore Diameter calculations*

When the driver applies brakes, the pedal force gets converted into hydraulic pressure in the master cylinder. This pressure, which acts as an actuating force, is transferred through the brake fluid to the caliper mounted on the disc. Here the actuating force gets converted into the clamping force. Magnitude of this force depends upon the bore diameter and number of pistons in the caliper. The clamping force pushes the friction pads against brake rotor thereby generating a frictional force between them which is responsible for braking torque. The generated braking torque must be greater than the required braking torque to stop the vehicle. Required braking torque on a particular wheel is calculated from the load on the $F_{c =}$
The above equation gives us the magnitude of clamping force which is applied on the rotor by the piston. The diameter and number of pistons can be decided by performing iterations based on the above equation and depending upon space availability. The piston diameter is nothing but the bore diameter of caliper. A clearance fit has to be provided between the piston and the caliper bore in the absence of any seals. A step is also provided at the bottom of the bore to prevent the piston from touching the bottom surface of the caliper and to increase the space for the brake fluid to apply the required pressure.

*B. Material Selection*

The material of a brake caliper body must be rigid to allow less deflection, and should be light to reduce the final weight of assembly. But, most important property considered for selection of the material is the modulus of elasticity as, for a caliper, stiffness is more important than strength. Most of the commercial vehicles use brake calipers made of cast iron because of low cost, high modulus of elasticity (200-210 GPa) and good machinability. The only disadvantage of cast iron is its density, which is much higher than other materials. Aluminum can also be used for the manufacturing of caliper considering its lower weight, but modulus of elasticity in this case is less (72-80 GPa).

Also, metal matrix composite (MMCs), with base material as Aluminum or Beryllium, reinforced with ceramic fibers which are aligned in proper direction to obtain required strength and stiffness along that particular direction. These MMCs have modulus of elasticity of about 180 GPa and lower density as compared to all other materials, but are most costly. Pistons can be made of Aluminum alloys. But, thermal conductivity of Aluminum is high, around 200-250 W/mK, which causes the heat generated due to the friction between rotor and friction pads to be transmitted through piston. This leads to decrease in disc temperature, but as the heat is transmitted to the brake fluid, it may increase the temperature of fluid.

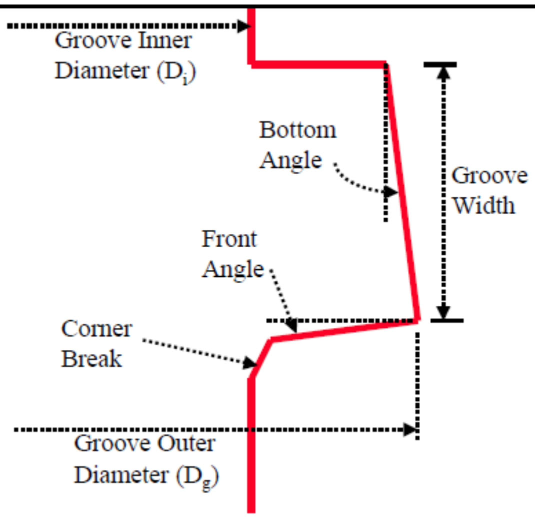
Higher fluid temperatures may cause changes in compressibility and evaporation of the brake fluid. To overcome this problem, small titanium blocks can be used in between the backing plate of friction pad and the piston surface. Along with this, the contact surface between backing plate and piston surface can be reduced by making a hole at the center of the piston. Pistons can also be made of Titanium or Phenol formaldehyde, but are avoided due to their high cost as compared to Aluminum.

*C. Seal Groove Geometry*

A seal groove assembly has three main components - rubber seal, piston and caliper groove. By design, the seal outer diameter is larger than the groove outer diameter. Hence the rubber seal is squeezed between the groove and the caliper piston when assembled. Rubber squeeze in the seal groove assembly and its deformation during brake apply are critical parameters for evaluating seal performance and piston retraction.

With the actuation of brakes, piston moves out, which needs to be retracted from the brake rotor surface after releasing the brake pedal so that there will not be any piston drag. Also, the brake fluid must not leak. The distance between the brake rotor and the friction pad is around 0.006 inch after the application of brakes. The seal performs both the functions of piston retraction and leakage prevention. Retraction seal deforms and stores energy as the piston moves out. With release of the pedal, it pulls piston back, releasing the energy. It indicates that the amount of retraction depends upon the deformation of seal, and should be considered while selecting the seal groove. Piston drag and piston displacement are directly dependent on the piston retraction. If the piston retraction is small, piston drag is induced. Piston drag is the residual torque on brake rotor even after releasing the brakes. Greater the piston drag, greater is the energy loss and fuel consumption. Larger piston retraction causes larger piston displacement which in turn increases braking time and stopping distance due to larger pedal travel. This also disturbs the brake pedal response (feel). Considering these factors, the deformation of the seal and hence the groove geometry must be optimized. Deciding a groove geometry depends on the experience of prototype testing. General groove geometry is as shown in figure.

In figure, groove denoted by 1 shows the piston retraction seal groove in which front taper angle allows deformation of the seal, while the bottom taper angle ensures easy insertion of the piston. After the installation of seal, inner diameter of the groove is less than outer diameter of seal which provides the necessary radial squeeze. At the front corner, a chamfer is given, called corner break, to allow excessive deformation of seal. One more groove is provided in the front, given by 2 in above figure for scrapper seal, which prevents the dirt from entering into the bore. A radial squeeze of around 12%-18% is provided in the seal for the prevention of leakage.

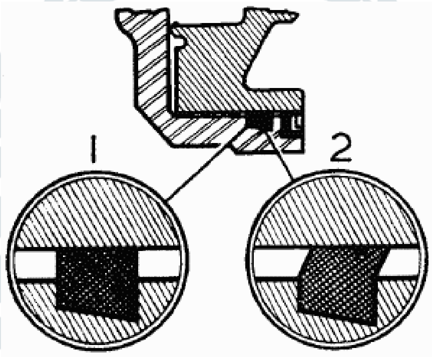



Details of Groove Geometry

*D. Disc Brake Piston Arrangement*

The brake fluid enters the cylinder and pushes the piston along with the brake padagainst the rotor when the brake pedal is applied. When the brake is disengaged the brakepads retract from the rotor surface by virtue of pistons seals. There is no specialpiston retracting mechanism for this operation. The rotor rotates very close to the brakepads almost touching the brake pads. The distance between the rotor and the brake pads isabout 0.2 mm in a disengaged position. The seal is designed in such a way that; theseal distorts the same amount as the piston moves. The piston seals pull back the pistonwhen the brake force is removed

If the distance between the pad and rotor increases due to pad wear, the piston moves adistance greater than 0.2 mm. Due to this piston seal overload is overcome, pushingthe piston closer to the rotor. The retracting motion of the piston depends on how muchthe seal distorts during braking action.




Working of Seal

*E. Brake Pad Material*

Brake pads material is very important for safe and consistent working of a vehiclebraking system. Brake pad material is generally classified into two categories asbestosand metallic. Asbestos dust is proved to be a cancer causing agent therefore federalregulations prohibited their use in the 90s. Metallic brake pad materials are classified aslow metallic and semi-metallic. All pad material begins to disintegrate at the frictionsurface due to high heat generation process between the rotor and pad. Due to non-uniform pressure distribution between the pad and rotor, pad surface temperature will benon-uniform and the areas of higher temperature will have low friction level than that ofthe lower temperatures. An exact analytical value of coefficient of friction between rotorand brake pads is difficult to set [1]. SAE J661 procedure is used to determine the frictioncoefficient for hot and cold surfaces. Disc brake pads should have certain amount ofporosity to minimize the effect of water on coefficient of friction. Important characteristics of brake pads are friction coefficient, wear rate, thermal conductivity andstrength and durability. These porous contents should not store contaminating agentslike salts and wear particles. Materials like aluminium boron carbide are found to be best suited for automobile brake pad application. It has high toughness and thermalconductivity relative to other ceramics with better thermal shock absorbing capacity.

Types of Brake Pads

*F. Thermal Study of Brake Caliper*

During braking action, the kinetic energy and the potential energy of the vehicle is converted to thermal energy through friction between the brake pads and the rotor. This temperature rise depends on various conditions such as frequency of brake application. Overheating of brakes can cause brake fading. The heat developed is dissipated to the cool air flowing over the brake by means of convection. This convection factor was considered for thermal analysis. Race cars travel at much higher speed than normal passenger cars. The kinetic energy goes up as the square of the speed. Kinetic energy is expressed as
$KE=1/2\ mv^2$
Where, m is the mass of an object and v is its speed. Going at twice the speed means four times the kinetic energy because velocity gets squared. This large amount of KE gets converted into large amount of heat energy. This tremendous amount of heat can damage the brake components. This heat can affect the hydraulic fluid which operates the pistons in the brakes. Therefore, proper measures need to be taken for isolating the heat from some parts of the brake caliper such as pistons. Ti inserts were inserted between piston and the backing plate to isolate the heat from the pistons.

## III. Design Calculations

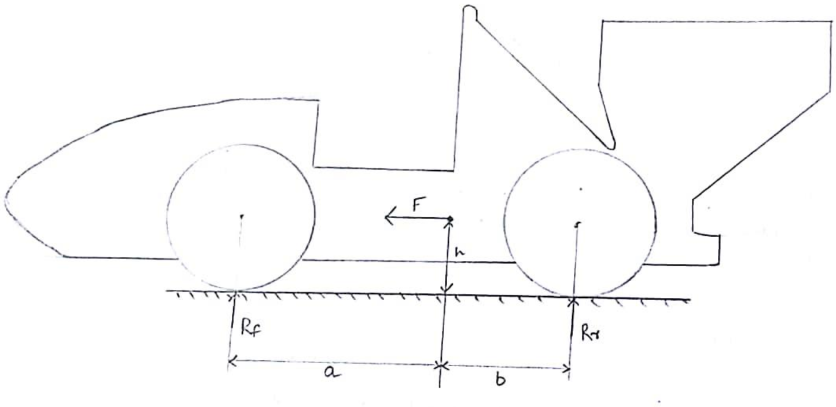
*A. Considerations and inputs*

*Considerations:*
1) Drivers force on pedal = 40 kg
2) Mass of vehicle (Including driver) m = 270 kg

*Inputs:*
1) Pedal ratio = 5.4:1
2) Front MC Bore = 15.875 mm
3) Rear MC Bore = 19.05 mm
4) Balance bar biasing = 50:50
5) Rear Caliper piston bore = 28.45 mm
6) Disc Diameter: Front = 180 mm Rear = 170 mm
7) Disc Effective radius: Front = 71 mm Rear = 72.3 mm
8) Tire Effective radius = 203.2 mm
9) Co-efficient of friction between pads and disc = 0.40
10) Co-efficient of friction between road and tire = 1.2

*B. Loads Transfer Calculations*

*Design Considerations:*
CG Height = 0.28 mm
Wheel base = 1545 mm
Mass of vehicle = 270 kg
Braking g = 1.2
Static Weight Distributions = 40:60




*C. Load Transfer*

LT = $\frac{a}{g} * \frac{h}{l} * w$

= 1.2 * 0.28 * 270 / 1.545

= 58.7184 kg

Weight on front axle while braking = Static weight + load transfer

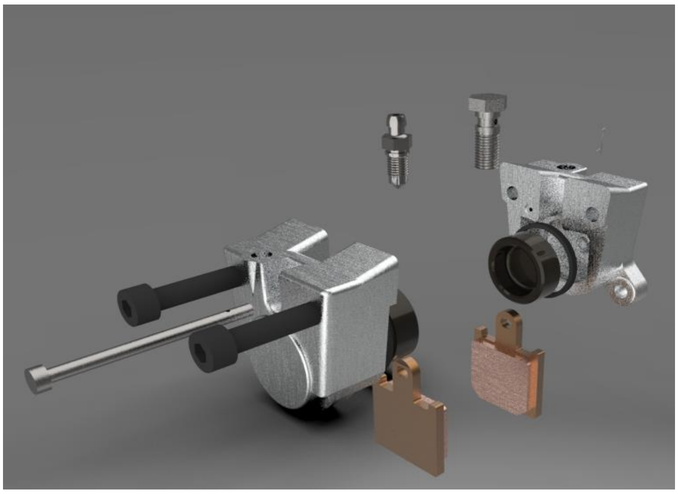
= 102 + 58.7184kg

= 166.718 kg

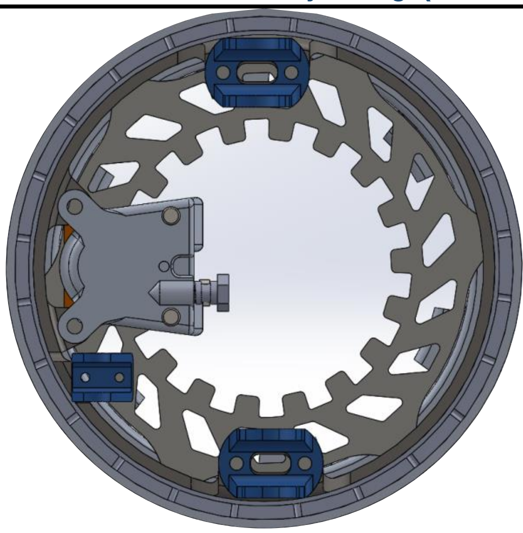
Weight on front tire while braking = 83.359 kg

*For caliper piston Diameter*

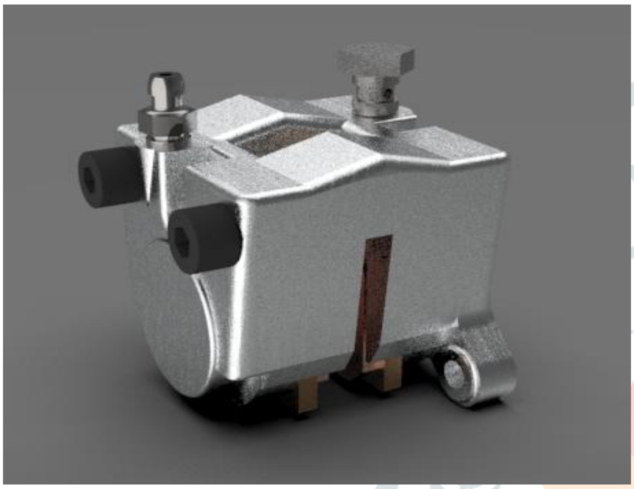
1) Force on Master cylinder = Driver's force * Pedal ratio
   = 35 * 9.81 * 5.4
   = 1854.09 N
2) Force on Front Master Cylinder = Max Front Bias * Force on MC
   = 0.5 * 1854.09 N
   = 927.045 N
3) Diameter of front MC piston = 15.875 mm
   Area of front MC piston = $\frac{\pi d^2}{4}$ = 197.83 mm$^2$
   Pressure created by front MC = Force on front MC/ Area of Front MC
   = 927.045 / 197.83
   = 4.686 N/mm$^2$
4) By Pascal's Law
   Pressure exerted by front MC = Pressure in front caliper
5) Let us assume that max. possible braking g required for vehicle is = 1.2g
6) By Newton's law
   F= m * a = 270 * 1.2 * 9.81= 3178.44 N
7) Dynamic weight ratio = 62:38
8) Front Braking force required = 1970.6328 N
9) Front Braking force per tire = 985.3146 N
10) Braking torque on front tire= Front Braking force per tire*Tire effective radius = 985.3146 * 203.6 = 200610.41 N-mm
11) Braking torque on tire= braking torque on disc
12) Frictional force on disc= $\frac{\text{Braking torque on disc}}{disc\ effective\ radius} = \frac{200610.41}{71}$= 2825.49 N
13) Clamping force = $\frac{frictional\ force\ on\ disc}{\mu\ between\ pad\ and\ disc} = \frac{2825.49}{0.40}$ = 7063.725 N
14) Front caliper piston area = $\frac{clamping\ force}{pressure\ from\ MC}$
    $\frac{\pi}{4}d^2 = \frac{3531.8625}{4.686}$
    d = 30.983



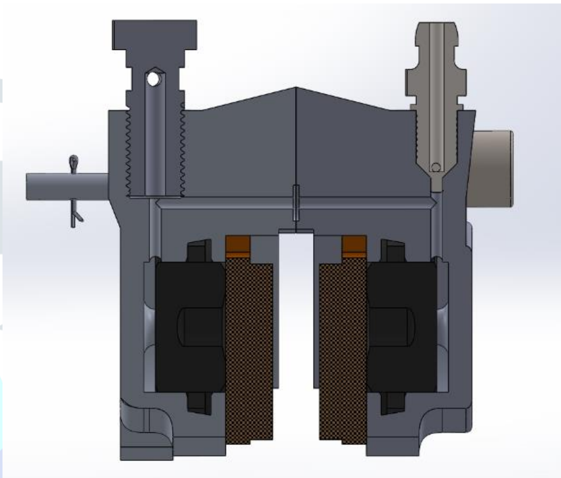
Caliper Assembly Exploded View



Caliper placement in wheel assembly

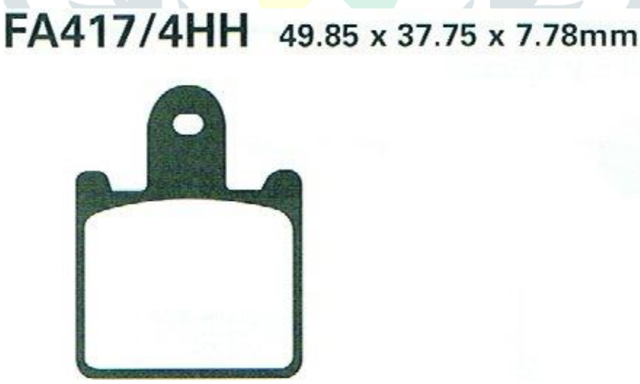


Caliper CAD model



Brake Caliper Plumbing Cross-section view

*Brake pads:*
The brake pads were selected on the basis of height of pad which covers the maximum area on disc and also fit in the caliper. The best fitting brake pads were the sintered HH pads from EBC Brakes.

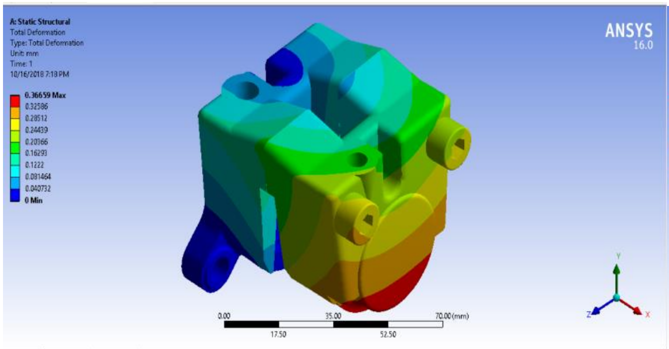



Brake Pad

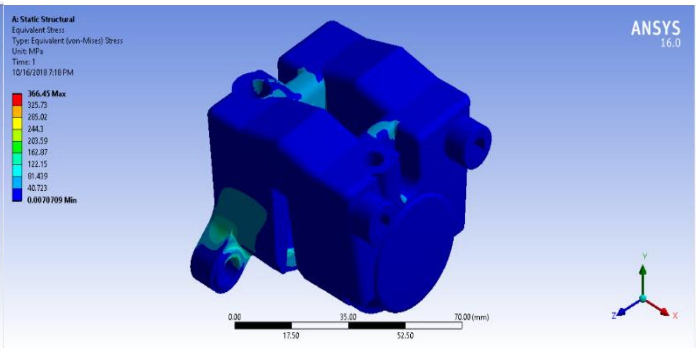
## IV. Analysis of Caliper

*A. Material Properties*
Material: Al 7075-T6
Density: 2810 kg/m3
Young’s Modulus: 72GPa
Yield Tensile Strength: 450 MPa
Ultimate Tensile Strength: 550 MPa

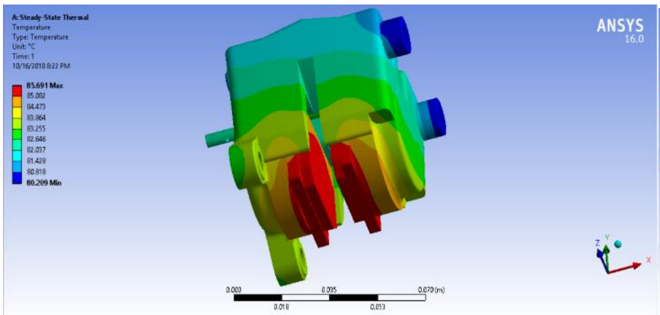
*B. Figures*



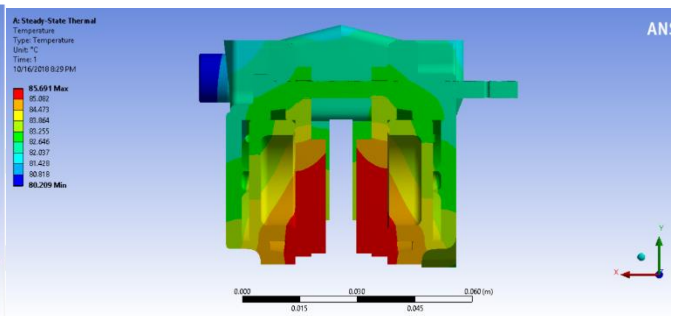

Deformation




Equivalent Stress




Temperature



Temperature Cross Section

The analysis was done using standard ANSYS Static Structural module and the respective forces were applied as per the calculations done. For the temperature analysis, the heat flux was calculated for 4 stops from 40 kmph to 0 kmph with maximum possible friction i.e. the wheel not 'just' locking, and then applied on the pads.

## V. Conclusions

- Determination of braking force is the most crucial aspect while designing the braking system as all other calculations and design analysis depend on these values.
- The generated braking force should always be greater than the required braking force
- The calculations of required clamping force helps us to decide the diameter and number of pistons to be used.
- Space and assembly constraints are important factors while designing the caliper body
- Shape and size of brake pad is also crucial while designing as temperature analysis depends on it.
- The seal groove geometry is important to the operation of caliper as it controls the retraction of piston.

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