Design and Analysis of Braking System for SAE car

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Abstract – *The work consists of the processes and parameters involved in design and analysis of the braking system used for cars participating in SUPRA SAEINDIA or any student formula competition. The braking system parameters were calculated by employing the core principles of vehicle statics and dynamics and complying with the templates and envelopes required by SAEINDIA through their rulebook. Softwares namely, SOLIDWORKS and ANSYS were respectively used for the design and analysis of the required components in the braking system for our car. Based upon the data obtained by calculations, a thorough analysis was made to ensure its sustainability during frequent brake testing. The different types of stresses involved in different components of the braking system were duly considered to ensure the proper functioning of the braking system. All the inferences during the design and analysis of our system have been recorded in this work. The core intention is to guide all the important parameters involved during the process of creating an optimal braking system for student formula car.*

Key Words: Structural Analysis, Design Methodology, Brake Disc, Brake Rotor, Clamping Force, Braking Force, Braking Efficiency, Thermal Analysis, Brake Pedal, Pedal Ratio, Structural Analysis, Meshing, Steady State Heat Transfer

1. INTRODUCTION

1.1 BRAKING SYSTEM:

[1] Braking systems is the primary means to reduce the speed of all the road going vehicles, eventually resulting into halting of a car. It is regarded as the most important part of a vehicle influencing the safety of the driver and occupants. When brakes are applied, the fluid under the pressure from master cylinders enters the calliper and applies the pressure on both pistons. Due to the pressure applied on the pistons, the friction pads come in contact with the disc, applying equal and opposite forces. The performance of the braking system is first evaluated when a driver considers a particular car. The braking system must be strong enough to stop the vehicle in the shortest distance possible in case of emergency. The driver must have proper control of the vehicle during braking, this can be ensured by reducing the chances of slipping when brakes are applied.

2. DESIGN OVERVIEW

The brake pedal assembly was designed as a hydraulic system for a one-man performance racing vehicle.

The system was designed based on the following parameters:

1. Total weight of the vehicle affected

2.Forces applied on the brake pedal

3.Comfort and safety of the driver

The design and analysis for this system were carried out on the following three categories/ components:

1. Design of brake pedals
2. Selection of master cylinder and calipers
3. Design of brake discs.

[2][3][4] The design of the brake pedals was made based upon the pedal ratio selected. The pedal ratio determines the amount of potential required to depress the brake pedal to bring about a specific amount of brake force. The design of brake pedal is followed by design of the pedal box which houses the supporting components of the assembly like the master cylinders, stoppers, return spring, clutch and accelerator wires, Brake Over Travel Switch and brake light sensor.

The selection of master cylinder is based upon parameters like the pressure generated and travel required. Based on the master cylinder selection, the pressure generated by master cylinder is calculated followed by the clamping force generated by the brake calipers.

The brake disc is design by considering size of the brake rotor which is based upon the size of tyre rims. The initial design is further optimized by the virtue of holes and slots. The disc is finally analyzed of thermal stress.

2.1 DESIGN OBJECTIVE

The main objective of the brake pedal assembly is to convert the kinetic energy of the vehicle into thermal energy, thus allowing the vehicle to decelerate.

The brake pedal assembly follows the given course: the driver imposes a force on the brake pedal, the brake pedal channels that force to the master cylinders, thus displacing the braking fluid in the master cylinders. A pressure is exerted by the displaced fluid on each of the calipers allowing the callipers pistons to exert a clamping force on the rotors. Therefore, a clamping force is exerted on the callipers, which is the output and the input being, the driver's applied foot force. Based on the competition rules and conditions the designed brake pedal assembly must be able to lock all four tires of the vehicle completely during an emergency stop braking scenario.

The brake pedal assembly consist of:

1.Two Master Cylinders: 1st one is for the braking of the front two tires and 2nd one for the rear two tires.

2.Mounting: The mounting provides a place for accommodating the brake, accelerator and clutch pedals along with the master cylinder.

3.Clutch pedal: It is used to engage and disengage the engine power to the transmission.

4.Accelerator pedal: this pedal provides throttle input to the car.

5.Brake pedal: the deceleration of the car is governed by brake pedals.

6.BOT switch: The Brake-Over-Travel-Switch forms part of the shutdown system kills engine and fuel pump.

2.2 PEDAL BOX DESIGN CRITERIA

The final design of the brake pedal assembly was made based upon the following criteria:

1. An inverted layout was selected for the brake pedal assembly as it was the most compatible for an integrated type of master cylinder which was our selected hydraulic cylinder.
2. The pedal ratio 6:1 provided a proper middle ground for the amount of force generated and the pedal travel.
3. As per the rulebook issued by SUPRA SAEINDIA, the distance from the rear most face of the pedal to the hip of the driver must be no less than 915mm [7], the inverted layout offered the lightest and most comfortable design with respect to our chassis.

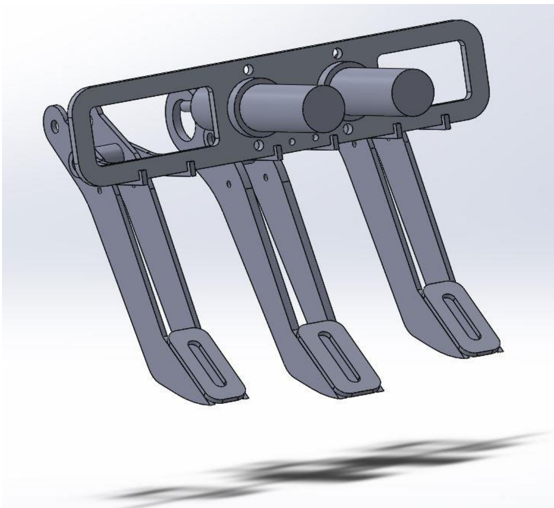

Figure 1: Design of Brake Pedal Assembly

The Figure 1 shows the final design of the pedal box assembly.

3. SELECTION OF COMPONENTS:

Before we proceed with the design of the brake disc, it is necessary to select the appropriate components for ensuring efficient braking of the car. The design of the brake pedal assembly was made on the basis of pedal ratio, where higher the pedal ratio, higher is the pressure generated. Hence it was decided to keep the pedal ratio 6:1. The clamping force of the brake calipers on brake disc depends upon the pressure generated by the master cylinder of the braking system. Hence it is necessary to select the master cylinder specification. The main criteria for selection of master cylinder are based upon its bore size.

Table 1 gives the outcome of selecting a particular bore size in terms of pedal travel and pressure generated by the master cylinder.

Size	Outcome	
	Pedal Travel	Pressure Generated/Force
Small	Large	Large
Large	Small	Low

Table 1: Outcome of selecting a particular bore size in terms of pedal travel and pressure generated by the master cylinder

On making comparison between the two bore sizes, we found the bore size of 0.75 inch to be ideal as the bore size was ideal for generating the large pressure required for braking. The concern related to pedal travel was eliminated by the amount of clearance kept in the chassis of the vehicle.

On conducting market survey, it was found that Willwood offer high performance and integrated reservoir master cylinders which eliminate chances of leakages.

Therefore, the parameters selected are,

1. Bore diameter of master cylinder= 0.75*25.4 mm

   d_m =19.05 mm

2. Pedal ratio: 6:1

4. CALCULATION OF GOVERNING PARAMETERS

4.1 CALULATION OF CLAMPING FORCE

In order to determine the caliper, we first require to determine the required clamping force. Hence, first we determine the clamping force produced during braking. From Reference [8],

The following are some parameters used in calculations:

A. W_f: Front weight (kg)
B. W_r: Rear weight (kg)
C. D: weight distribution on front tyres
D. W: Weight of the car (driver included) (kg)
E. G_{br}: Acceleration produced during braking
F. h: Height of CG (m)
G. w: Wheelbase (m)

It is to be noted that the weight distribution in our case was 40% at front and 80% at rear in our car.

Consider the following figure 2.

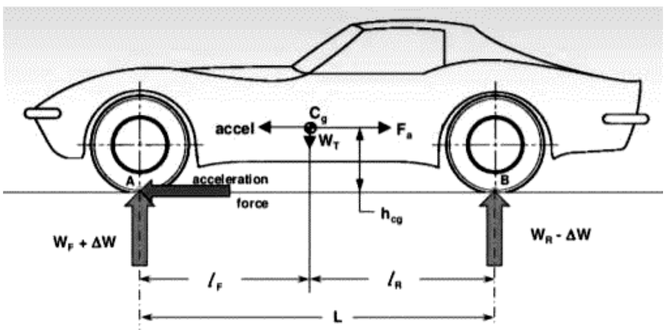

Figure 2: Brake Force distribution in a vehicle

Now we know that sum of moments at a point is equal to zero.

This facilitates the determination of the front and rear axle loads in case of our vehicle which turned out to be,

W_f= 201.94 kg

W_r= 148.056 kg

Forces on tire:

The following are some parameters used in calculations:

F_{ftyre}= Frictional force on front tires (N)

F_{rtyre}= Frictional force on rear tires (N)

μ= Frictional coefficient

g= gravitational acceleration= 9.8 1

We use a simple formula to determine the forces on the tire

F_{tyre}= μ*W*g

Using the above formula, we determined,

F_{ftyre}= 4358.26 N

F_{rtyre}= 3195.34 N

Tire and rotor torque:

F_{rotor}= (F_{tyre}*r_{tyre})/r_{rotor}

Therefore, using the above formula we found,

F_{frotor}= 5860.577 N

F_{rrotor}= 4296.79 N

Clamping force:

Clamping force is the product of F_{rotor} with 0.65

F_{fclamp}= 3809.37 N

F_{rclamp}= 2792.9135 N

On market survey, we considered the need to opt for dual piston calipers and figured out that Vespa KBX calipers offer best price to performance ratio and hence we decided to use the same.

Therefore, dc= 29 mm

Now let us calculate the clamping force generated by the caliper selected.

4.2 METHOD EMPLOYED FOR CALCULATIONS:

The brake pedal:

The brake pedal is used to magnify the force exerted by the driver's foot. From elementary statics, the force increase will be equal to the driver's applied force multiplied by the lever ratio of the brake pedal assembly [8].

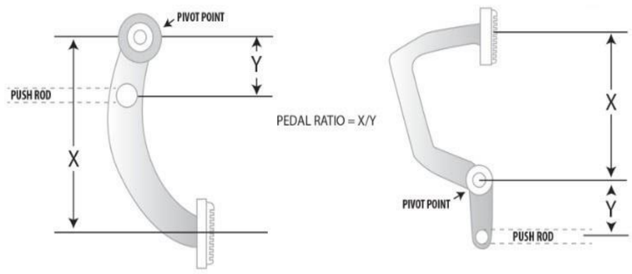

Figure 3: Pedal ratio for different pedal layouts

Figure 3 shows the pedal ratio X/Y. here the value of X and Y changes based upon the layout of the brake pedal, that is, inverted (left) or floor mounted (right).

F_{bp} = F_d*(X/Y)

where,

- F_{bp} =output force of the brake pedal assembly
- F_d = driver's applied force
- X/Y= pedal ratio

Therefore,

F_{bp} = 1500 N

The master cylinder:

We assume incompressible liquids and infinitely rigid hydraulic vessels, using a simple formula for pressure,

P = F /A

P_{MC} = 5.2627 N/mm^2

where,

- P_{MC} = master cylinder hydraulic pressure
- A_{MC} = master cylinder hydraulic piston the effective area

Brake fluid, brake pipes and hoses:

From Reference [8], the pressure transmitted to the calipers assuming no losses in brake lines would be:

$P_{CAL} = P_{MC}$

where,

• P_{CAL}= the hydraulic pressure transmitted to the caliper

The caliper, Part I:

Using the formula for pressure:

F_{CAL} =3476.14 N

where,

• F_{CAL} = the linear mechanical force generated by the caliper on one side

The caliper, Part II:

In theory, the clamping force will be 2 times the linear mechanical force as

follows:

$F_{clamp} = F_{cal} * 2$

F_{clamp} = 6952.2805 N

where,

• F_{clamp} = caliper clamping force

Since the clamping force produced by the selected caliper trumps the required clamping force, the given brake setup can be determined as optimum.

Using the above data, the initial design of the brake was prepared. The design was made using the CAD Design Software: SOLIDWORKS.

5. DESIGN AND OPTIMIZATION OF BRAKE DISC

The brake discs need to be structurally sound as they are subjected to immense forces, especially during aggressive or sudden braking.
Hence, the design of the disc brakes is initially made keeping the forces applied on the brake disc in mind.

Parameters that are involved in the design of brake rotor:

1. The size of the rims used.
2. Type of callipers used.
3. The amount of calliper land available to fit the brake rotor into.
4. The thermal stresses that applied during braking.
5. The design of hub and upright from the suspension assembly.

Based on above factors, the initial design of the brake disc was made shown in figure 4:

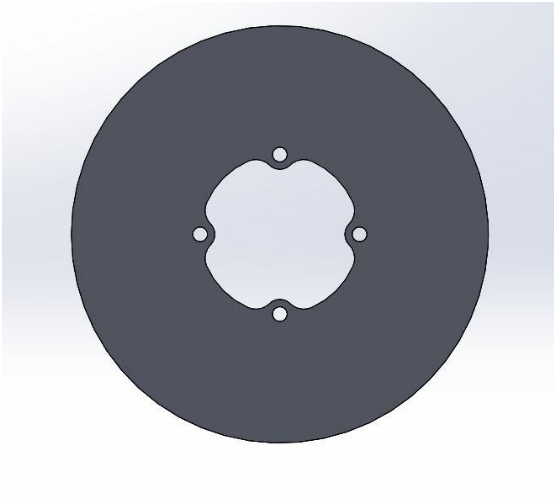

Figure 4: Initial Design of the Brake Disc

5.1 Purpose of holes in design process

The primary function of adding holes is to in fact add boundaries so that you can get rid of heat faster.
Hence the holes and disc brakes are mainly for cooling purposes. A city car consists of a single disc brake on a wheel. However faster cars often need a disc brake with higher braking force and more resistance to fatigue. Hence, high performance car manufacturers usually end up employing multi disc setup.
Weight is another factor that contributes towards adding holes on the brake disc. Hence addition of holes not only result into to a more efficient heat dissipation but also and a producing the overall weight of the vehicle which is the primary focus of the car that we wanted to develop.

5.2 Cooling

When disc brake is clamped, they convert all momentum into heat energy due to frictional forces because of which the disk heats up. If this heating up of the brake discs increases beyond a certain limit that they can handle they will succumb under stress and result in a break fail. Also, it might result to wearing of brake pads which in turn, may end up catching fire and most importantly, the lethal boiling of the brake fluid in the brake lines resulting into its wear. Hence holes are provided in the brake disc to increase the surface area of the disc so that more area can come in contact with the disc to cool them.

5.3 Weight

It might be a surprise on realizing the fact that holes on the brake disc reduced as much as 300 to 500 grams of our car's weight. It might seem quite minuscule but it translates a great length in the performance of the machine. Even as much as 100 grams can make a huge difference in the overall weight, especially considering the fact that the brake disc I've been provided on all four wheels of our vehicle.

Hence it was decided to include holes and slots in the design of the brake discs. Keeping an adequate distance between the two holes, the design of the holes and slots were made.

Thus, the final disc brake design was made which is shown in figure 5. The design was deemed to be effective to counter all the forces applied and would facilitate effective cooling by providing adequate number of holes and slots in a unique pattern.

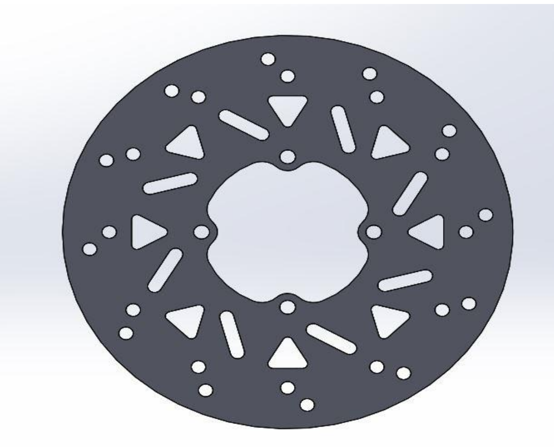

Figure 5: Final Design of the Brake Disc

6. MATERIAL SELECTION

Material selection of Brake disc is important as it is the part where heat generation occurs due to rubbing of Brake pads on the disc because of which the material we are using must not only have good strength but should also stand good against the heat generation.

The material selection process of the pedal box was based around the initial constraints of the design mentioned prior along with the brake pedal, which is the component on which most of force would be subjected upon.

Based on the type of loading the pedal box would be subjected to it was modelled as a beam in bending and was decided that the desired material needed to have the following mechanical properties:

1. High Strength
2. Stiffness
3. Good toughness
4. Machinability

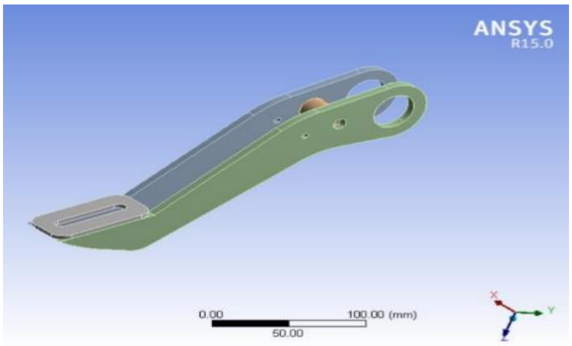

Figure 6: Design of the Brake Pedal imported in ANSYS

As like Brake Pedal we here did a comparison of materials. The materials which we compared are AISI 1020, EN24T, Stainless Steel 410. We compared the mechanical properties of these material as follows:

Properties	Stainless Steel 410 (SS410)	AISI 1020 (Carbon Steel)	EN24T
Density (g/cm^3)	7.8	7.85	7.9-8
Young's Modulus (Mpa)	210000	200000	200000
Poisson's Ratio	0.285	0.29	0.25
Bulk Modulus (Mpa)	150000	140000	140000
Shear Modulus (Mpa)	83000	80000	80000
Tensile Yield Strength (Mpa)	415	294.74	350
Tensile Ultimate Strength (Mpa)	450	294.74	420
Machinability (%)	55	50	50

Table 2: Properties of SS410, AISI 1020 and EN24T

After comparing the materials, we decided to go with the Stainless Steel 410 (SS410) as:

A. Density of Stainless Steel is less than other two elements so it will result in less weight of our disc.
B. By seeing the chart, you will think there is not much difference in densities of them but if you are designing something small things also matters a lot.
C. Shear & Bulk Modulus of SS410 is better than rest of two.
D. Tensile Yield Strength & Tensile Ultimate Strength is also good than these two.
E. Machinability of the SS410 is better.
F. Heat Resistance of SS410 is appropriate against the heat generation occurs due to rubbing of brake pads.

Let's discuss about some points of Stainless Steel:

A. Stainless Steel 410 is Made up of 0.15% C, 11.5-13.5% Cr,0.75 % Ni, 1%Mn, 1% Si, 0.04% P, 0.03% S.
B. SS410 is used for better heat resistance & high strength. Heat resistance of SS410 have good scaling at temperature upto 650^{0}c
C. Processes such as tempering, hardening, annealing & polishing enhance the mechanical properties of SS410. After of hardening & oil quenching the grade 410 steels can be performed at 925 to 1010^{0}c

7. ANALYSIS

7.1 ANALYSIS OF BRAKE PEDAL:

Before manufacturing we must have to check or verify our design. We must verify that our design is sustainable under the forces acting on it, the stresses acting on it should not cross the limit of its ultimate stress, its Factor of Safety (FOS). All these values can be calculated with the help of Structural and Thermal Analysis. Here we use ANSYS Workbench R 15.0 here are some processes which we did while analysis in ANSYS.

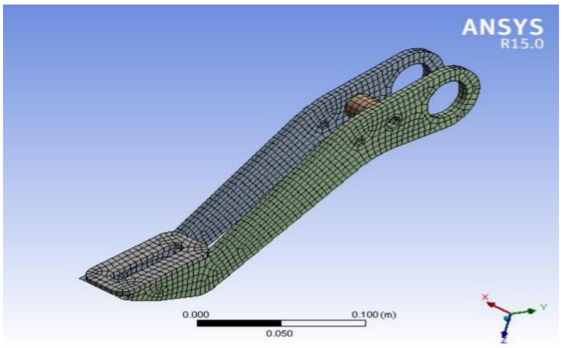

Figure 7: Meshing of the Brake Pedal

According to the rule book provided by SAEINDIA for SUPRA 2020, the brakes pedals must be able to sustain a force of 2000N. [7]

Hence, the design and analysis of the brake pedal assembly was made considering the above factors.

The analysis was done using the following parameters:

1. Material: AL 7075 T6
2. Fixed geometry: The 10mm diameter hole provided for the bolts which in turn attach to the gusset plates.
3. Forces: 2000N (per item) Applied on the Foot Pad of the brake pedal.
4. Meshing: Fine Mesh

7.1.1 Meshing:

Ansys is based on the Finite Element Method, there are finite no. of meshing. Meshing is important as there are different stresses acting at different points, for example a truck passing over a bridge gives a different amount of bending stress at different point so it's important to have different element at that point These nodes are point where load is applied & stresses are calculated. Figure 7 shows the meshing of the brake pedal while figure 8 shows the properties of the mesh selected in ANSYS.

Object Name	footpad	BRAKE PEDAL	BRAKE PEDAL	pedal tube
State	Meshed			
Graphics Properties				
Visible	Yes			
Transparency	1			
Definition				
Suppressed	No			
Stiffness Behavior	Flexible			
Coordinate System	Default Coordinate System			
Reference Temperature	By Environment			
Material				
Assignment	Aluminium 7075 T6			
Nonlinear Effects	Yes			
Thermal Strain Effects	Yes			
Bounding Box				
Length X	38. mm	6.5 mm		25. mm
Length Y	70.306 mm	253.75 mm		20. mm
Length Z	33.749 mm	172.55 mm		20. mm
Properties				
Volume	8942.5 mm³	61072 mm³		5890.5 mm³

Figure 8: Mesh Properties in ANSYS

7.1.2 Structural:

[5] Structural Analysis is determination of the effects of loads on physical structures & the component structures subject to this type of analysis includes all that must withstand loads. Structural Analysis makes use of applied mathematics to compute a structures deformation, internal forces, stresses, support reactions, accelerations & stability. The results of the analysis are often precluding physical tests. Here we fixed point A at a frictionless support i.e., the pedal will give moment about point A. The force acting at point A is zero, whereas the force acting at point B is -2000 N as it is mention in rulebook of SAE Supra [7]. The force is compressive therefore its negative. Figure 9 shows the faces and elements which were selected and the constraints which were applied to check for their sustainability.

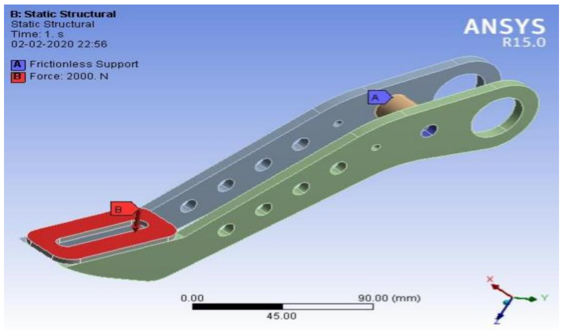

Figure 9: Selection of force constraints

7.1.3 Total Deformation:

Deformation is considered to be the total deformation or directional deformation both of them are used to obtain displacements from stresses.

The directional deformation is the main difference which calculated for the deformations in X, Y & Z Planes for a given system. Total deformation gives a square root of the summation of the square of X-direction, Y-direction & Z-direction.

Total Deformation = square root of (X2+Y2+Z2)

Conclusion:

Factor of Safety (FOS) = Ultimate Tensile strength /Design Stress

= 572 / 147.04 = 2.420

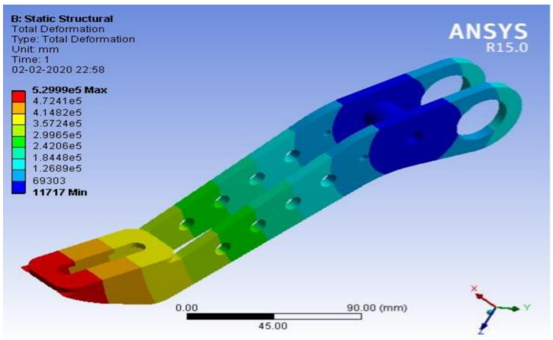

Figure 10: Total Deformation in the Brake Pedal

From the result, we can see that the design stress or the stress which we obtained is within the Tensile Ultimate Stress of the material so we can say that our design is safe. As we also did the topology optimization, we remove the excessive material from low stress region which directly results into reduction of weight of our Brake Pedal Assembly.

1. Design is satisfied as the design stress is within the Tensile Ultimate Strength

2. Weight reduction is done very accurately.

As compared to our previous year's assembly, the team managed to reduce the weight by 50%, thus making the assembly weight only about 980grams.

7.2 ANALYSIS OF BRAKE DISCS

The thermal analysis of the brake disc is crucial for ensuring optimum braking performance and adequate heat dissipation while keeping the weight under control.

Software Used: ANSYS WORKBENCH R15.0

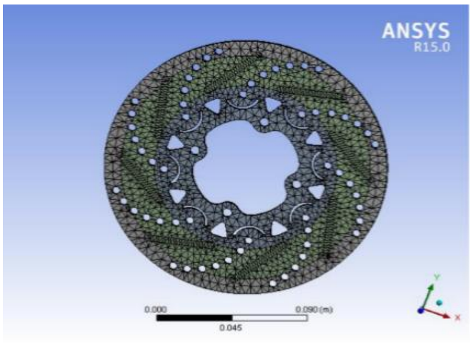

Figure 11: Brake Disc imported in ANSYS

FOR CONDUCTIVITY (K):

Since the constant of conductivity depends upon material selected and the selected material is SS410. We get,

k= 24.9 W/mK

FOR HEAT FLUX (Q):

Calculation of Heat Flux

Parameters required:

W= Mass of vehicle (driver included)

U= Initial velocity

V= Final velocity

W= Weight of the car

D: weight distribution on front tires

For KE,

$KE= d*k*m*(u-v)^2/2$

Thus,

KE= 10416.83 J

Consider, ideal deceleration time during braking (t): 5sec

Braking power= P_b= KE/t

Thus, P_b= 2083.36 W

Heat flux= Q= P_b/A

Q=46635.538 W/m^2K

7.2.1 MESHING

Object Name	brake disc 3 (AP203)	brake disc 3 (AP203)	brake disc 3 (AP203)
State	Meshed		
Graphics Properties			
Visible	Yes		
Transparency	1		
Definition			
Suppressed	No		
Stiffness Behavior	Flexible		
Coordinate System	Default Coordinate System		
Reference Temperature	By Environment		
Material			
Assignment	Structural Steel		
Nonlinear Effects	Yes		
Thermal Strain Effects	Yes		
Bounding Box			
Length X	0.17 m	0.11 m	0.14999 m
Length Y	0.17 m	0.11 m	0.14999 m
Length Z	4.e-003 m		
Properties			
Volume	1.8629e-005 m³	2.1148e-005 m³	2.7983e-005 m³

Figure 12: Mesh Properties for Brake Disc

7.2.1.1 Thermal Analysis:

Any technique for the study of the materials which involves thermal control is known as thermal analysis. Measurements are usually made with increasing temperature whereas you can also take measurements with decreasing temperatures are also possible. It is an application of a precision-controlled temperature program that allows quantification of a change in a material. Figure 13 shows the constraints applied for thermal analysis of the rotor.

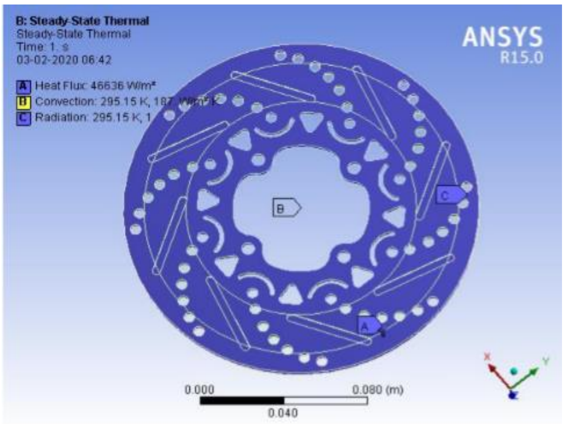

Figure 13: Thermal constraints on the Disc

7.2.2 Steady State Heat Transfer:

[6] A state which remains constant over given time period is called as steady state. In heat transfer for convection or conduction, a steady state heat transfer if there is specific rate of heat transfer through medium if it remains constant at any time.

Thermal Analysis not simply a sample composition technique and can be used in characterizing the physical properties of a system used to simulate conditions involved in real world application.

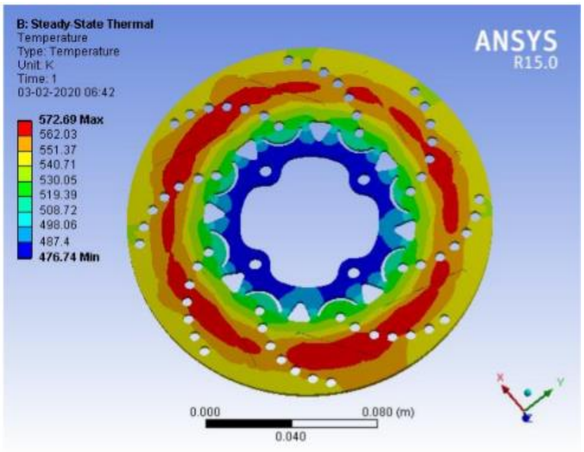

Figure 14: Temperature distribution from the result

Here we fixed the three points in the disc which are:

1. Point C (At the outermost boundary section)
2. Point A (At the middle layer of the disc)
3. Point B (At the centre of the disc)

Here the heat flux dissipation is done in middle layer of the disc & it is at the rate of 46636 W/m² through the holes & slots which we made on disc as well as it helps us to reduce the weight, whereas the middle section is of convection as heat transfer changes the medium from material to air.

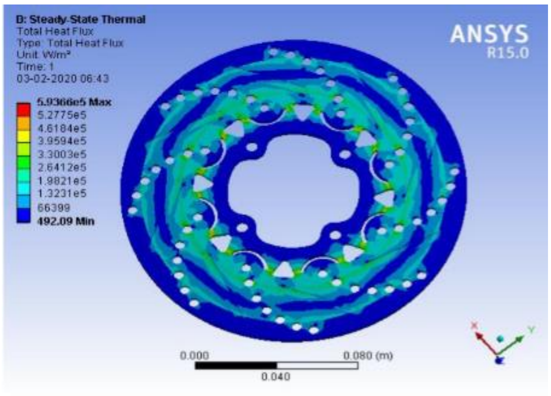

Figure 15: Heat Flux distribution

7.3 FINAL CONCLUSION FROM THE ANALYSIS

Figure 14 shows the temperature distribution while the figure 15 denotes the distribution of Heat Flux on the brake disc from the results interpolated from the Steady State Thermal Analysis.

1. Melting point temperature of SS410 is 1497^{0}C.
2. Upon thermal analysis of the brake disc, the temperature at braking turned out to be 572.69^{0}C which is less than melting point at given boundary conditions.
3. By observing the values of the above analysis, we came to know that:
4. After thermal analysis we see the temperature rise occurs in disc its reasons are rubbing of pads on disc & its continuous rotation with wheel.
5. By observing value of heat flux distribution for the profiles, we come to conclusion that heat flux dissipation is good in design with SS410 material so, the life of the disc is also going to be good.

8. CONCLUSIONS

The following comments can be concluded:

1. The objective of the pedal box design was to enhance comfort, to secure from the forces applied and reduce the overall weight of the assembly.
2. A braking system is deemed to be optimal if the clamping force is greater than the required stopping force.
3. The parameter that determines the effectiveness of a braking system also included the size, material and thickness of the brake disc along with components like master cylinder and callipers.
4. The design of the brake disc is made most importantly by keeping the forces involved in mind.
5. Holes and slots play a significant role in cooling the brake disc during sudden or aggressive braking.
6. Proper analysis of all components is crucial to ensure proper function during testing as well as regular use.

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