TRANSIENT THERMAL AND STRUCTURAL ANALYSIS OF PERIMETRIC DISC BRAKE FOR TWO-WHEELER

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***Abstract**: This paper is to analyze the behavior of brake rotor discs in two-wheelers. The calculations are done for the braking parameters for the bike Hero Passion Pro 2021 model. From the calculations it was found that the braking performance of the perimetric disc is increased when compared with that of the conventional disc. The force, temperature and braking time are taken as the input values for the analysis. In this project, The design tool used is CATIA V5 and analysis tool is ANSYS 2021 R1. Two designs are considered, conventional design and the new design called 'Perimetric Design'. The type of analysis used in this project are Transient Thermal and Static Structural. The analysis inputs are temperature, braking time, force on brake pads, rotational velocity and coupled analysis of Transient thermal, structural analysis is done to check the temperature distribution, stress distribution and the deformation of the disc. Three materials taken were i.e., SS420, GCI, Al 2014 T6. For these materials the two designs are analyzed and studied the behavior. The von-mises stress for conventional discs are 283.4, 121.64, 295.98MPa and for perimetric discs are 234.37, 112.4, 237.88MPa for SS420, GCI, Al2014T6 respectively.*

***Keywords**:* Perimetric Disc rotor, Sketch tracer, Transient thermal analysis, Static Structural analysis

1. INTRODUCTION

An automobile or an automotive system consists of different components like the engine, fuel system, ignition system, exhaust, electrical system, drive train, suspension and steering and the brake system. Among all these systems, the braking system plays an important role. These are one of the safety systems in any automobile. In the 1800s, the first signs of brake-like devices were tested. These early brakes are very different from today's high-tech brakes. Brake systems have come a long way since their inception, reducing the likelihood of accidents and thereby boosting passenger safety.

The initial brake system was made up of nothing more than a block of wood and a lever. When drivers desired to come to a halt, they had to pull the lever to cause the block of wood to rub against the wheels, eventually bringing the car to a stop. When this method of brake technology was prevalent, horse-drawn carriages and steam-powered automobiles used steel-rimmed wheels [10].

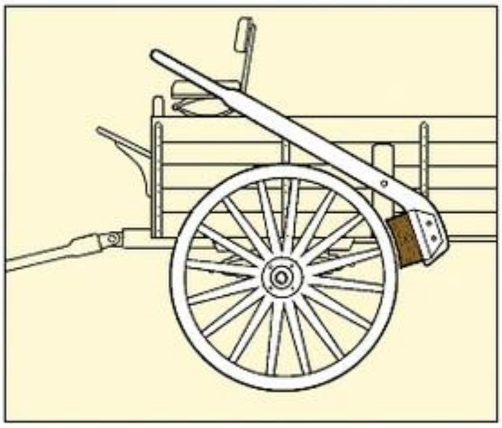

Fig-1. Wooden block and lever

Due to the various forms of brakes that have evolved over the last two centuries, different types of braking system are categorised as:

1.1 Mechanical braking system

The hand brake or emergency brake is controlled by the mechanical braking system. To stop the vehicle, the brake force is transferred to the brake pedal, which is then transmitted to the ultimate brake drum or rotor disc via various mechanical connections such as cylindrical rods, fulcrums, springs, etc.

1.2 Hydraulic braking system

Brake fluid, cylinders, and friction drive this system. Glycol ethers or diethylene glycol create pressure within the brake pads, causing the wheels to cease moving. When compared to the mechanical braking system, the hydraulic braking system generates more force. One of the most essential braking systems for modern automobiles is the hydraulic braking system. In the event of a hydraulic braking system, the chances of a brake failure are extremely low. Braking failure is rare due to the direct connection between the actuator and the brake disc or drum.

1.3 Air braking system

Heavy commercial vehicles and trucks frequently use air/pneumatic brake systems. They necessitate a strong braking effort that can be done solely by the driver's leg. Instead of the foot pressure pushing on the flexible diaphragm in the brake chamber, compressed air pressure is used to activate the air brake. The compressor receives air from the atmosphere, which passes through the air filter and into the reservoir. A specific pressure is maintained in the reservoir. The compressed sir is allowed to move from the reservoir to the foot valve through a supply line when the driver presses the brake pedal. Before the brakes, air is pumped through the delivery lines to the piston and cylinder arrangement. The brake pads are actuated with the help of a cam as a result of the high pressure air, expanding the brake pads and causing the wheel to decelerate.

1.4 Electromagnetic braking system

Many modern and hybrid automobiles include electromagnetic braking systems. Electromagnetism is used in the electromagnetic braking system to create frictionless braking. This extends the life of the brakes and improves their reliability. Furthermore, standard braking systems are prone to slippage, whereas the rapid magnetic brakes are not. This technology is preferred in hybrids since it eliminates friction and the requirement for lubrication. In comparison to standard braking systems, it is also fairly small. It is mostly found in trams and trains.

These braking systems are responsible to activate the actual braking mechanism like cams and pistons. According to the type of mechanism used and geometry of the brake lining material brakes are divided into:

1.4.1 Drum brakes

Fig-2. Drum Brakes

A drum brake is a type of classic brake in which friction is created by a set of shoes or pads pressing against a rotating braking drum. These brakes are typically employed in vehicles with modest braking force, such as light automobiles. There are two types of drum brakes in use.

a. Internal expanding brakes, widely used in light weight vehicles like 2-wheeler, auto rickshaw, cars, etc.

b. External contracting brakes

1.4.2 Disc brakes

The first portion of a disc braking system is the disc/rotor, and the second part is the brake caliper assembly. The caliper assembly contains one or more hydraulic action pistons that push against the back of the brake pad, clamping it around the spinning or turning Disc/rotor from both sides.

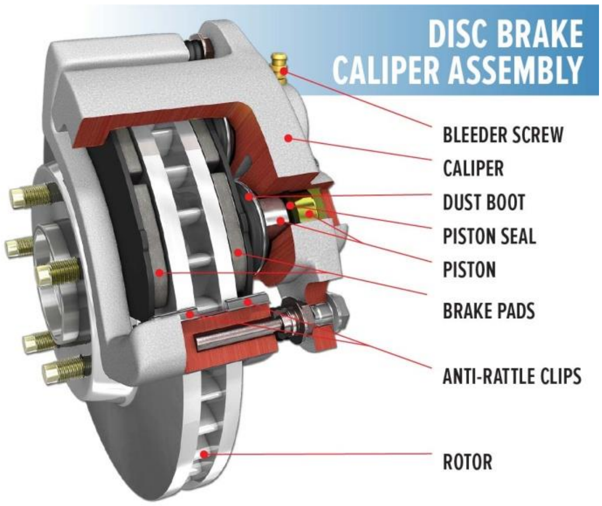

Fig-3. Disc Brake (ventilated type)

Naturally, the greater the clamping force, the greater the magnitude of frictional force, the formation of friction, the generation of heat, and, in turn, the transfer of kinetic energy. As a result, the design of disc brake rotors is primarily dependent on critical elements such as heat generation, heat dissipation, and the amount of force supplied by the operator/driver.

The main components of a Disc brake assembly are:

a. Brake pads

b. Calipers, containing piston(s)

c. Disc brake rotor

Along with the wheel, the brake pads squeeze the rotor fixed to the brake hub. The rotor spins or rotates in lockstep with the wheel at the same rotational velocity (rpm). The hydraulic action of a fluid called as braking fluid is used to transfer force from the pads to the rotor in this case. Friction is formed between the rotors and the pad, causing the vehicle to slow down and eventually come to stop.

2. LITERATURE REVIEW

Mahmood Hasan Dakhil et al. [1] studied the performance of disc brake using FEA method under severe braking conditions. The material taken in this study are Cast Iron and Stainless Steel. ANSYS 12.0 was used to carry out the analysis process for determination of the temperature distribution, variation of stresses and deformation across the disc brake. Two thickness values for the discs were taken to check the behavior i.e., 10mm and 12mm. The cast iron discs results in the greater maximum stress values than that of disc made with stainless steel material and further the factor of safety for cast iron (both 10 and 12mm) were 1.106 and 1.89 respectively and for stainless steel 3.316 and 4.636 respectively. It was concluded that using 12mm thick disc possess better performance than that of 10mm disc as well the use of stainless steel usage gives better results than that off cast iron discs for the given loading conditions.

Belhocine Ali et al. [2] carried out the project on a 4 wheeler disc brake unit. In this study the designs of full disc and ventilated disc were made and transient thermal analysis is done. Considered the disc is symmetry in design, only a quarter part of the disc is utilized to perform the analysis process. ANSYS was used as the analysis tool and were able to study the thermal behavior of gray cast iron (FG15). CFD analysis along with transient thermal analysis is carried out after the designing process. The inputs given to the system are pressure inlet, pressure outlet and domain edges - symmetry as boundary conditions. The disc wall temperature was taken as 800K and the thermal properties of the Gray Cast Iron. Temperature distribution, total heat flux are calculated for both the designs. The results were compared to verify the better performing design.

M. Boniardi et al. [3] studies the failure regions of two rotor discs made of martensitic stainless steel of dimensions Ø180mm and 8mm thick. The idea of the project is to chose a different kind of steel, characterized by a greater resistance to the tempering processes. In their study they observed that cracks were mainly located nearby the holes placed on flange to ventilate and refresh pads. In visual and chemical analyses they observed that the two discs are of two different compositions. First disc contains the major portion of Molybdenum and Vanadium and second disc has higher manganese percentage. Then the discs were cut into pieces for several small studies and used polishing and chemical etching process to reveal their microstructure Hardness values were taken on the entire flange and spokes area. Micrographic analysis also been done. It was concluded that second disc was still not resistant to tempering process and suggested to replace all the other components of the same material to avoid the problem. The first type disc is suitable because of the higher percentages of Vanadium and Molybdenum which gave the material resistance to tempering.

Ali Belhocine et al. [4] aims to determine disc temperature and to examine stress concentration, structural deformation and contact pressure of brake disc and pads during single braking stop event by ANSYS. Two discs were designed, a solid disc and a ventilated disc. The static structural, transient thermal analysis were performed on the disc and disc pad contact region. Took only one quarter of the disc for the fluid field analysis considering the symmetry of the disc. It was concluded that the ventilated disc is best for the application as all the analysis value were less than the allowable values. The total stress and deformation in the disc increase in a notable way. When the system is thermo-mechanical coupling and there is no significant change in disc-pad deformation with respect to the variation of friction coefficient.

The use of disc brakes are gradually increasing in normal performing vehicles. As the engine capacity and weight of the vehicle increase, the brakes need to be more effective and strong enough to stop the vehicle as the heavy moving vehicle possess higher kinetic energy. Some two-wheelers are designed with a larger disc or two brake disc set-ups. In order to decrease the excess material used in these braking systems, a disc design called perimetric disc brake can be used. The perimetric design satisfy the braking conditions and also saves the amount of material used.

3. METHODOLOGY

The designing process is carried out in a design tool CATIA V5R20. The analysis of the model is done using analysis tool ANSYS 2021 R1. The type of analysis carried out is coupled analysis of Transient Thermal and Transient Structural. As the disc is first subjected to thermal loads thermal analysis have to be done to study the temperature distribution. The structural analysis is done to check the reaction of the disc physical loads like Von-Mises stress and Total deformation. The design of the disc is considered safe only when the maximum stresses induced in the disc material should not exceed the yield strength of the material.

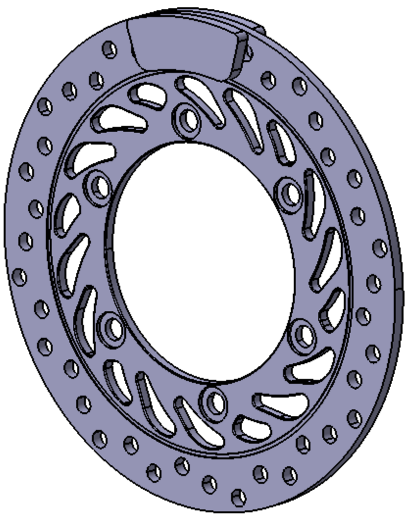

Fig-4. Convention Disc Design

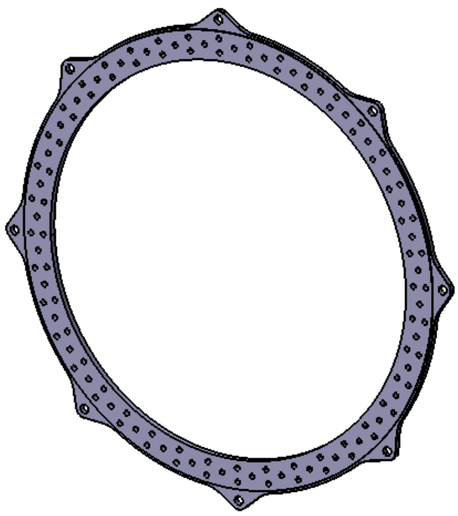

Fig-5. Perimetric Disc Design

In order to get the accurate results the assembly design of Disc and the brake pads is been done. So that we can apply the force on the brake pads and thermal loads can be applied between the contact region of the disc and brake pad.

4. DESIGN CALCULATIONS OF BRAKE ROTOR

For this study, Passion Pro model bike is chosen as it is easily available and one of the most used bikes in India. The below table shows the specifications of the vehicle parameters and performance for calculating the total braking force and time required to stop the vehicle. These will be same for the conventional brake disc and perimetric brake disc design.

Braking Specifications

Table-1. Specifications of the vehicle.

	Front	Rear
M/C Diameter(d_m)	11mm	12.7mm
MC motion ratio factor	0.8	0.8
Caliper diameter (d_c)	25.4mm	32mm
Caliper motion ratio factor	0.7	0.7
Pedal Ratio (P_r)	5:1	5:1
Pedal Force (F_p)	90N	100N
Tire diameter (D_{tire})	607.97mm	633.44mm
Wheelbase	1300mm	
Curb weight of the vehicle	120kg	
Driver + Passenger weight	120kg	

Conventional disc brakes

Disc diameter = 240/188mm (front)

= 130mm (rear)

Perimetric disc brakes

Disc diameter = 400/348mm (front)

= 130mm (rear)

Calculations

For conventional disc,

Force on the master cylinder,

$$F_{mc} = F_p \times P_r \times 0.8$$

$$= 90 \times 5 \times 0.8$$

$$= 360 \text{ N}$$

Area of master cylinder piston,

$$A_{mc} = \frac{\pi}{4} \times {d_m}^2$$

$$= \frac{\pi}{4} \times 0.011^2$$

$$= 9.5 \times 10^{-5} \text{ m}^2$$

Pressure developed in brake fluid,

$$P_{mc} = \frac{F_{mc}}{A_{mc}}$$

$$= \frac{360}{9.5 \times 10^{-5}}$$

$$= 3786626.597 \text{ N/m}^2$$

Area of caliper piston,

$$A_{cal} = 2\frac{\pi}{4}{d_c}^2$$

$$= 2 \times \frac{\pi}{4} \times 0.0254^2$$

$$= 1.0138 \times 10^{-3}\ m^2$$

Force at the caliper piston,

$$F_{cal} = P_{mc} \times A_{cal} \times 0.7$$

$$= 3786626.597 \times 1.0138 \times 10^{-3} \times 0.7$$

$$= 2687.27\ N$$

$$F_{clamp} = 2 \times F_{cal} \qquad \text{(2 pads)}$$

$$= 2 \times 2687.27$$

$$= 5374.55\ N$$

Friction force,

$$F_{friction} = \mu \times F_{clamp}$$

$$= 0.35 \times 5374.55$$

$$= 1881.1\ N$$

Braking torque,

$$T_B = F_{friction} \times R_{disc}$$

$$= 1881.1 \times 0.107$$

$$= 201.28\ Nm$$

Braking Force,

$$F_{B_f} = \frac{T_B}{R_{tire}}$$

$$= \frac{201.28}{0.304}$$

$$= 662.13\ N$$

Similarly, the braking force is calculated for the rear wheel

$$F_{B_r} = 255.38\ N$$

Total braking force,

$$F_B = F_{B_f} + F_{B_r}$$

$$= 662.13 + 255.38$$

$$= 917.51N$$

Deceleration,

$$a = \frac{Force}{Mass}$$

$$= \frac{917.51}{240}$$

$$= -3.82 \text{ m/s}^2$$

Stopping time (100-0kmph),

$$\text{Initial velocity} = 27.78\text{m/s}$$

$$v = u + at_s$$

$$0 = 27.78 + (-3.82 \times t_s)$$

$$t_s = 7.27 \text{ s}$$

Stopping Distance,

$$s = ut_s + \frac{1}{2}at_s^2$$

$$= (27.78 \times 7.27) + \left(\frac{1}{2} \times -3.82 \times 7.27\right)$$

$$s = 100.9 \text{ m}$$

The values for the conventional and perimetric disc are calculated and tabulated in the below table.

Table-2. Results

	Conventional	Perimetric
Braking Force, N	917.51	1412.6
Deceleration, m/s²	3.82	5.88
Stopping time (100-0), s	7.26	4.72
Stopping distance (100-0), m	100.92	65.55
Stopping time (50-0), s	3.63	2.35
Stopping distance (50-0), m	25.23	16.39

The above table shows that the stopping time and distance are lesser in perimetric disc than that of the conventional disc. The deceleration of the vehicle is decreased by almost 54%, that implies the vehicle with perimetric disc stops before the vehicle with conventional one. The stopping time and distance for the perimetric disc is decreased by 35% and the vehicle comes to stop within 66meters. So, by replacing the conventional disc with the perimetric disc may show a good change in the vehicle performance.

Heat Energy generated

Due to the rubbing action between Brake pad and the disc rotor there will be friction generated and temperature raise will be noticed. The temperature rise in the disc-pad contact is calculated by the energy conservation equation.

Table-3. Mass of respective design for respective material, kg

Material	Conventional	Perimetric
SS420	1.238	1.553
GCI	1.151	1.443
Al	0.443	0.555

$$\text{Kinetic Energy} = \text{Heat Energy}$$

$$\frac{1}{2}mv^2 = mC\Delta T$$

$$\frac{1}{2} \times 240 \times 27.78^2 = 1.238 \times 460 \times (t_2 - 28)$$

$$t_2 = 121.5°C$$

The calculations shown above are for the final temperature (t_2) for the SS420 material and the conventional design. All the other results are tabulated below.

Table-4. Final temperatures, °C

Material	Conventional	Perimetric 01
SS420	121.5	102.5
GCI	133.0	111.7
Al	171.0	142.4

Rotational Velocity

Assuming the maximum speed at which the vehicle goes is 100kmph

$$100\text{kmph} = 1666666.67 \text{ mm/minute}$$

The circumference of the tire is noted as 1990mm

So, rotational velocity of the wheel @100kmph $= \frac{1666666.67}{1990}$

$$= 838$$

$$\approx 840\text{rpm}$$

Materials

Material used in the manufacture of the disc brakes should possess mechanical properties like good wear resistance, compressive strength, friction coefficient, density, thermal properties and should be available economically.

For this experiment three materials have been chosen which are widely used in manufacturing industry. They are

a. Gray Cast Iron

b. Al2014T6

c. Stainless steel SS420

Material Properties of rotor disc

Table-5. Material Properties of GCI, AL & SS420 respectively.

Property	GCI	Al	SS420
Density, kg/m³	7200	2770	7750
Young's Modulus, GPa	125	71	200
Poisson's Ratio	0.28	0.33	0.31
Tensile Yield Strength, MPa	0	280	207
Compressive Yield Strength, MPa	0	280	207
Tensile Ultimate Strength, MPa	240	310	586
Compressive Ultimate Strength, MPa	1290	0	0
Isotropic Thermal conductivity, W/m°C	54	-	40
Specific Heat Constant,C, J/kg°C	460	875	480

Material properties of brake pad

Table-6. Material Properties of Brake pad

Property	Brake pad
Young's modulus (GPa)	28
Poisson's ratio	0.29
Density (kg/m³)	2700
Conductivity	2.36
Specific heat	4000

5. ANALYSIS

ANSYS is the mostly used analysis software because the results obtained by ANSYS are close to accurate values. In ANSYS we can perform different kind of engineering problems. The different kinds are Static-Structural Analysis, Steady State Thermal Analysis, Transient Structural, Transient Thermal, Modal, Harmonic, Buckling, Fatigue, Computational Fluid Dynamics, etc. the modeling of the disc brake rotors are done using a CAD tool CATIA V5 R20. A special module called "Sketch Tracer" is used to transfer the dimensions from an image to the CAD tool. In order to use this module at least one dimension of the part to be designed has to be known so that we can scale the image. In this paper, for the conventional design the known dimension is outer diameter i.e., 240mm. after setting the image to correct scale the modeling process can be started. The ventilation holes, structural holes and the mounting holes can be incorporated in the solid disc. For the perimetric design, the known dimension is the pitch circle diameter of the mounting holes. Number of mounts for perimetric disc are taken as 8 and the same thickness is taken as for conventional design that is 6mm. The design process of ventilation holes are carried out later. After the designing of the disc rotors the files saved as .CATpart and .stp file formats. The .CATpart file is used to open and re-edit in CATIA and the .stp file is used to import the model into the ANSYS software, as ANSYS requires .stp and .iges file formats to read.

A coupled analysis of Transient Thermal and Static Structural Analysis is done with calculated loading conditions. The material properties are to be changed in material library section in ANSYS. We can create a new material if it is not available in the library or can edit the existing material's properties. As we take three materials for every analysis and addition to with that a common brake pad material "Asbestos" is taken. Then the part model is imported into ANSYS workbench as .stp format using geometry tab in ANSYS standalone system. Here we can edit any feature using Spaceclaim. As the analysis type is Transient we have to give the analysis settings for the analysis preferences. The analysis time is set to 7.26s for conventional and 4.72s for the perimetric model. Number of steps are 8 and 5 respectively with 0.5s sub-step time interval. After the geometry is ready the mesh can be generated. The mesh set for conventional and perimetric model are 3.1 and 3.2mm respectively.

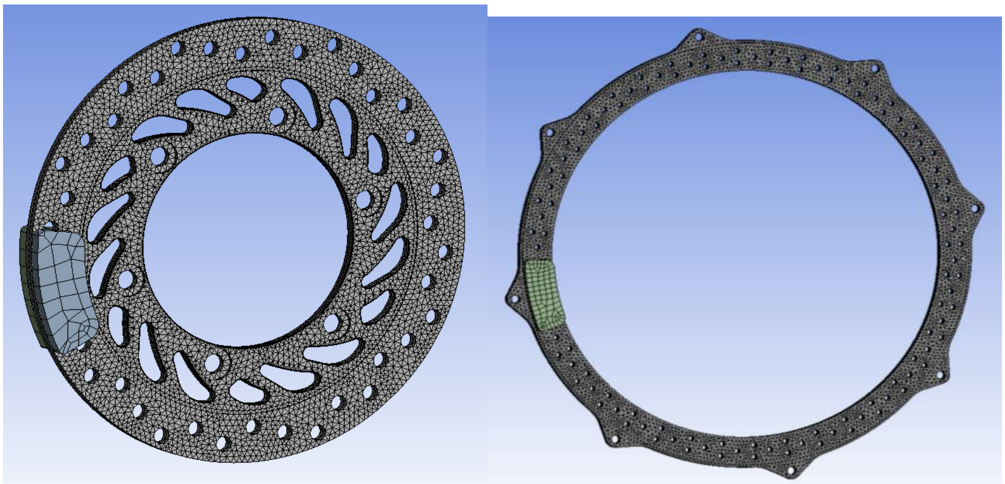

Fig-6. Mesh of Conventional and Perimetric Designs

After meshing the thermal boundary conditions have to be given. Those conditions are temperature generated at the contact of the pad and disc face for the respective design and model as the values obtained from the calculation. For convection coefficient we can take the standard values from ANSYS database. So, the heat transfer coefficient value is a simplified case of ANSYS 2021 R1 which is temperature dependent (stagnant air - horizontal cycle).

Tabular Data

	Temperature [°C]	Convection Coefficient [W/mm²·°C]
1	1.	1.24e-006
2	10.	2.67e-006
3	100.	5.76e-006
4	200.	7.25e-006
5	300.	8.3e-006
6	500.	9.84e-006
7	700.	1.101e-005
8	1000.	1.24e-005
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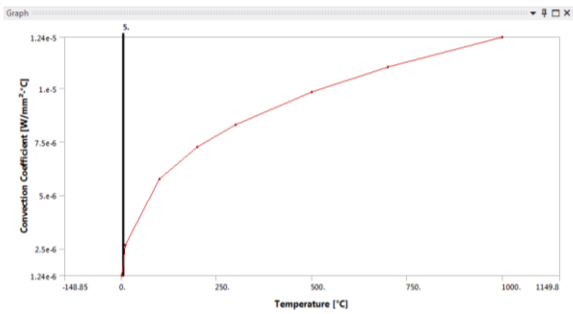

Fig- 7. (a) & (b) Tabular data and Graphical representation of the Convection coefficient [W/mm² °C]

6. RESULTS

With these inputs we can generate the solution for temperature distribution to check how the temperature is distributed along the disc surface.

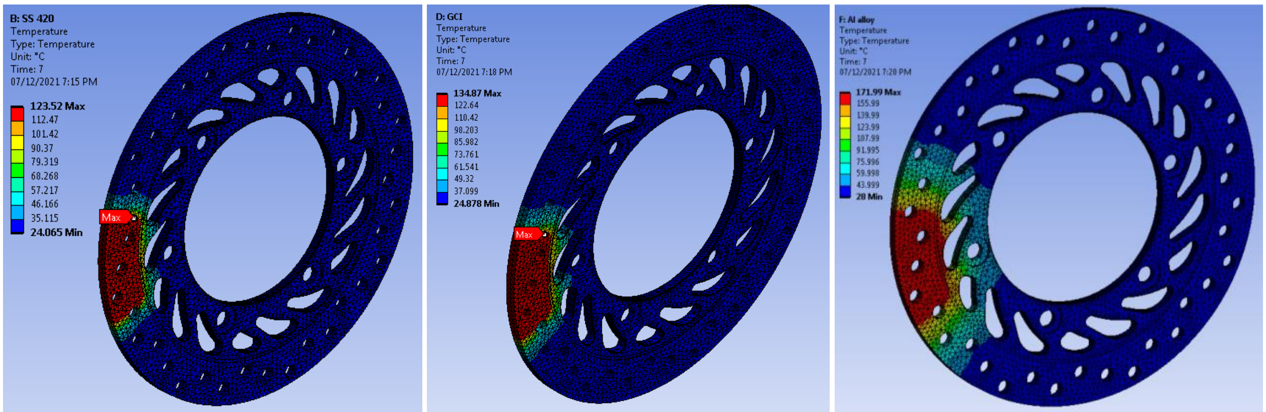

Fig-8. (a), (b) & (c) Temperature Distributions in Conventional discs for 3 materials

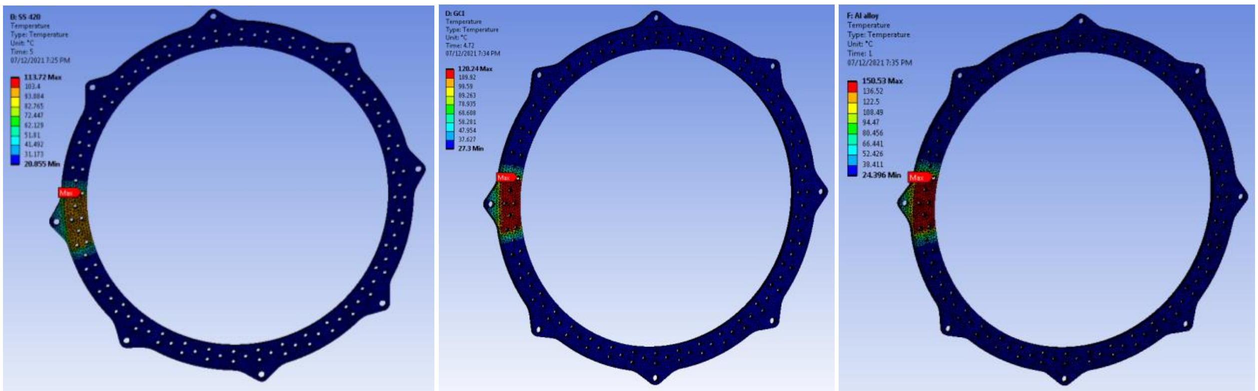

Fig-9. (a), (b) & (c) Temperature Distributions in Perimetric Discs for 3 materials

In Static Structural analysis there is no need to change the analysis settings. The thermal loads from Thermal analysis has to be imported. The rotational velocity of the rotor disc is taken as 840rpm clockwise from the calculations for all the analyses. The mounting holes' surfaces of the disc pads are fixed. Two forces are applied on either side of the disc pads of magnitudes 917.51N for conventional and 1412.6N for the perimetric model.

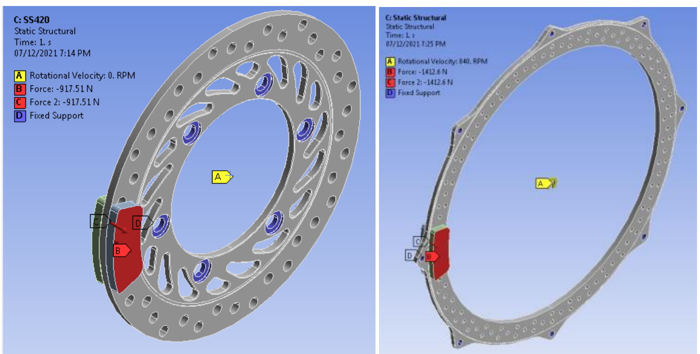

Fig-10. (a) & (b) Structural Loading Conditions

In the solution tab we insert the Von-Mises stress and total deformation and click on **Solve.**

Von-Mises stress & Total deformation of Conventional Disc:

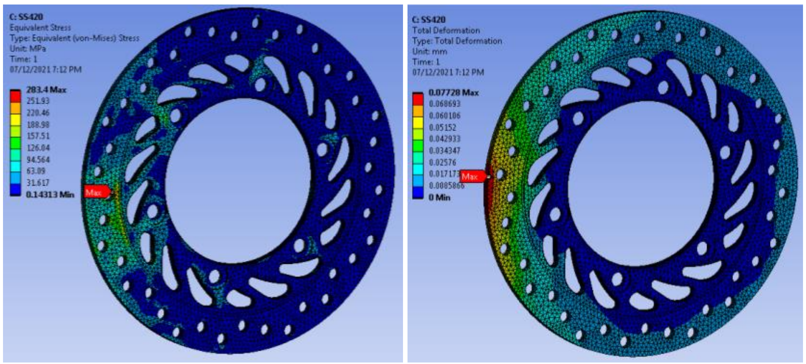

Fig-11 (a) & (b) SS420

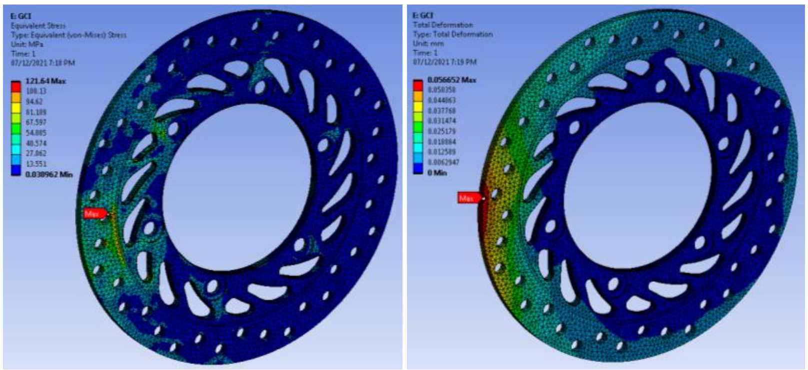

Fig-12. (a) & (b) Gray Cast Iron

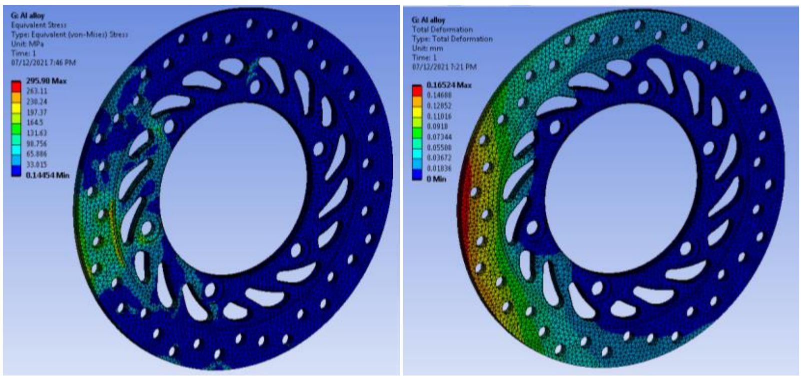

Fig-13. (a) & (b) Al2014T6

Von-Mises stress & Total deformation of Perimetric Disc:

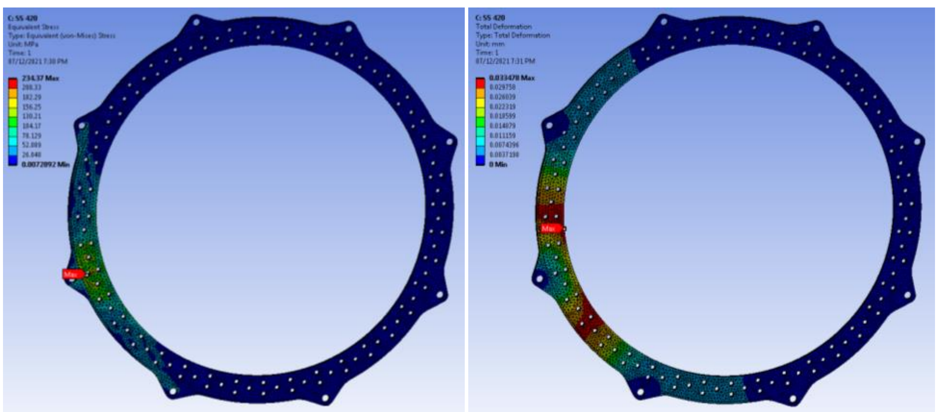

Fig-14. (a) & (b) SS420

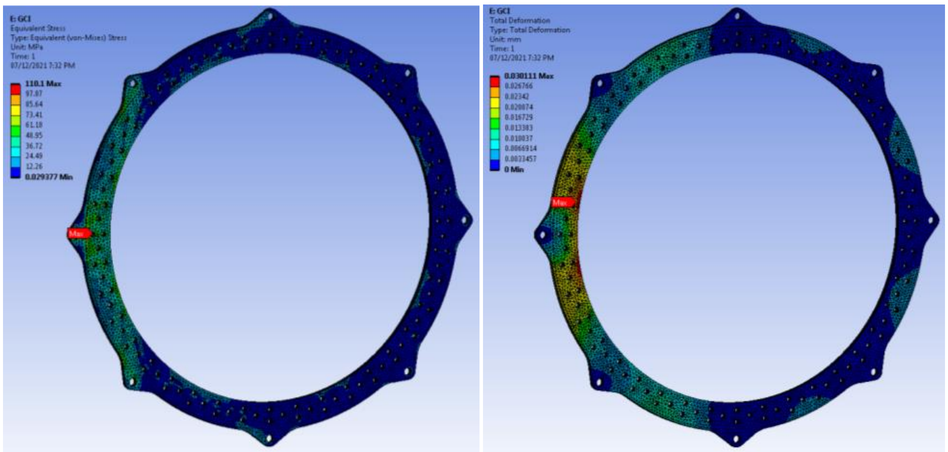

Fig-15. (a) &(b) GCI

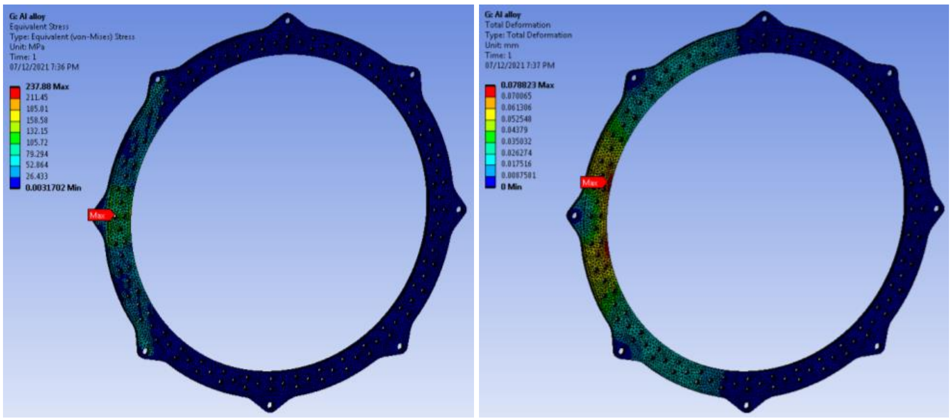

Fig-16. (a) &(b) Al2014T6

The Von-Mises Stress and Deformation results for two designs and three different materials are tabulated below.

Table-7. Von-mises and deformation results.

Material	Conventional		Perimetric		Yield Stress, MPa
	MPa	mm	MPa	mm	MPa
SS 420	283.40	0.077	234.37	0.033	600
GCI	121.64	0.056	112.4	0.030	200
Al2014T6	295.98	0.165	237.88	0.079	414

7. CONCLUSION

The transient thermal and static structural analysis is done on two designs i.e., conventional and perimetric designs with three materials (SS 420, GCI, Al 2014 T6). The temperature distribution, Von-Mises stresses induced in the disc rotors and the total deformation is analyzed. It is noted that the Von-Mises or equivalent stresses induced in the Conventional design in much lower than the yield stress of the each material, so the conventional disc gives more than enough resistance to the rough braking conditions of the motorcycle.

In the analysis of the perimetric disc, it is noted that the equivalent stress values are decreased by 17.3% in stainless steel, 9% in Gray Cast Iron and 19.6% in Al2014T6. There is also reasonable decrease in deformation in perimetric design when compared with the conventional design.

From the result it is noticed that both the designs are within the limits. So the design considered to be safe. By using perimetric disc design we can say that:

a. The vehicle stopping distance is decreased
b. The vehicle stopping time is decreased
c. The design is structurally and thermally safe

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