Finite Element Analysis of Solid and Ventilated Disc Brake

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Abstract: ***Braking is a process which converts a vehicle's kinetic energy into mechanical energy which must be dissipated in the form of heat. During the braking phase, the frictional heat generated at the interface of the disc and pads can lead to high temperatures. The frictional heat generated on the rotor surface can influence excessive temperature rise which, in turn, leads to undesirable effects such as thermal elastic instability (TEI), premature wear, brake fluid vaporization (BFV) and thermally excited vibrations (TEV).In this project, solid and ventilated type disc brake rotor of a vehicle, taken an investigation into the usage of various materials is done so as to improve the braking efficiency and provide greater stability to the vehicle. Modelling of the disc brake rotor is done using CATIA V5R18, which facilitates collaborative engineering across various disciplines. The thermal and structural analysis of disc brake rotor is done using ANSYS 14.5, which is a dedicated finite element package used for determining the temperature distribution, variation of the stresses and deformation across the disc brake profile. A comparison is made between three different materials used for both solid and ventilated type disc brakes and the best material for making disc brake and type of disc brake have been suggested based on the magnitude of Vonmises stresses, temperature distribution and deformation.***

Keywords: Disc brake, solid and ventilated disc, thermal and structural analysis

1. Introduction

Brakes are the most important safety parts in the vehicles. Brakes function to slow and stop the rotation of the wheel. To stop the wheel, braking pads are forced mechanically against the rotor or disc on both surfaces. They are compulsory for the safe operation of all vehicles. In short, brakes transform the kinetic energy of the car into heat energy, thus slowing its speed. Brake fade is the reduction in stopping power that can occur after repeated or sustained application of brakes, especially in high load or high speed conditions. Brake fade can be a factor in any vehicle that utilizes a friction braking system including automobiles, trucks, motorcycles, airplanes, and even bicycles. Brake fade is caused by a build-up of heat in the braking surfaces and the subsequent changes and reactions in the brake system components and can be experienced with both drum brakes and disk brakes. Loss of stopping power, or fade, can be caused by friction fade, mechanical fade, or fluid fade. Brake fade can be significantly reduced by appropriate equipment and materials design and selection, as well as good cooling. It is more prevalent in drum brakes due to their configuration. Disc brakes are much more resistant to Brake fade because the heat can be vented away from the rotor and pads more easily, and became a standard feature in front brakes for most vehicles.

1.1 Materials

(a) Aluminium is a most abundantly used light weight metal. It is soft and durable. Aluminum is widely used in several engineering applications. It is non-magnetic and does not easily ignite.

(b) Grey Cast Iron that has a graphic microstructure. It is named after the grey colour of the fracture it forms, which is due to the presence of graphite. It is the most common cast iron and the most widely used cast material based on weight. A typical chemical composition to obtain a graphitic microstructure is 2.5 to 4.0% carbon and 1 to 3% silicon Production of higher strength of Gray Cast Iron is more expensive.

(c) S2 Glass Fibers These are Magnesium alumina silicate glasses which are used for textile substrates or reinforcement in composite structural applications which require high strength, modulus, and stability under extreme temperature and corrosive environments.

1.2 Thermal Considerations

The energy absorbed by brake is converted into heat, which increases the temperature at the rubbing surfaces. When the temperature increases, the coefficient of friction decreases, adversely affecting the torque capacity of the brake. At high temperature, there is rapid wear of the friction lining, which reduce the life of the lining. Therefore, the temperature rise should be kept within permissible range. It is very difficult to precisely calculate temperature rise.

Table 1.2: Material properties

ERTIES	Aluminium	Cast Iron	S-2 Glass Fiber
Density , Kg/m^3	2712	7100	2460
Thermal conductivity w/m-K	250	54	1.45
Young's Modulus , N/m^2	$69X10^9$	$125X10^9$	$87X10^9$
Poisson's Ratio	0.33	0.25	0.28
Specific Heat , J/Kg-K	910	586	737
Coefficient of Linear Expansion , /K	$23X10^{-6}$	$9.9X10^{-6}$	$0.9X10^{-6}$

2. Literature Review

Before the age of computers, analytical methods were used as engineering tools for determining the integrity of a design. **Dike [1]** illustrated that the mathematical equations for conduction of heat in an isotropic solid could be used to investigate the temperature response of brake disc designs by simplifying complicated parameters such as temperature dependent material properties, real brake disc geometry and complex boundary conditions. However, for real problems involving complex material properties and boundary conditions, a numerical method of analysis is more suitable. The most popular of the various numerical methods that have been developed is the finite element (FE) method. Two types of FE analysis are widely used in brake design: heat transfer analysis to determine transient temperature distributions and thermal stress analysis to determine stresses and strains due to these non-uniform temperature distributions. **Blot [2]** defined several numerical procedures for the temperature analysis of brake discs and revealed that the FE technique was the fastest and most accurate for the investigation of brake disc performance. Furthermore, the time and cost of prototype manufacture and test could be significantly reduced. **Sheridan et al. [3]** reviewed the techniques for modelling the thermal response of brake discs ranging from simple to complex three dimensional analyses including the methods to calculate the thermal boundary conditions. They suggested that more than 90% of all heat dissipated to ambient was transferred by convection for most braking conditions. Furthermore, the accuracy of thermal brake disc models was dependent on how the thermal boundary conditions were determined **Yano and Murata [4]** performed Experimental work to determine the amount of heat now from the frictional interface into the rotor by conduction. The volume or quantity of heat transferring to the pads, the rotor and the ambient air was obtained from the measured temperature gradients and heat transfer coefficients. According to their

Experiments, the heat conduction from the rubbing surfaces to the rotor was approximately 72% of the heat generated .A thermal stress analysis of a brake disc uses nodal temperatures as input that are firstly calculated in a preceding temperature analysis. **Fukano and Matsui [5]** applied this technique in order to investigate elastic thermal stresses in a brake disc with temperature dependent material properties. They found that the maximum calculated tensile stresses in brake discs exceeded the tensile strength of the actual brake disc material, resulting in cracking in the top-hat section close to the attachment holes which had high stress concentration. This prediction of cracking agreed with the experimental results. **Timtner [6]** studied the influence of solid brake disc geometry on brake disc coning using linear elastic FE models. Nodal temperatures, derived from thermal FE analysis, again provided the input to the structural analysis. The effects of changes in the top-hat depth, hat thickness and the undercut depth were investigated. The computational results revealed that increase of the hat depth and the undercut depth both reduced the degree of brake disc coning. However, increase of the hat thickness had the greatest influence. **Medonos [7]** investigated the mechanical and elastic thermal stresses using the FE technique with temperature dependent properties. A full three dimensional model was necessary in order to take the braking drag load and the circumferential variation of thermal stresses into account. The results revealed that the effect of mechanical stresses due to the braking pressure load, deceleration forces and centrifugal forces were minor and could be neglected. However, the friction braking drag load induced significant shear stress in the disc.

3. CATIA V5 Workbench

CATIA V5 serves the design tasks by providing different workbenches. A workbench is defined as a specific environment consisting of a set of tools, which allows the user to perform specific design tasks in a particular area. The basic workbenches in CATIA V5 are Part design workbench, Wireframe and Surface Design workbench, Assembly Design workbench, and Drafting workbench.

3.1SKETCHER WORKBENCH

As CATIA V5 models are created based on B-rep modelling technique, the sketcher workbench enables to create boundary profile of the feature. It is used to draw precise sketches and 2D shapes. Before working on the designs of the sketches, it is essential to invoke the Sketcher workbench.

3.2 Entering Sketcher Workbench

Creating a sketch: To create a sketch, select Start > Mechanical Design > Sketcher from the menu bar. Select the sketcher icon and click the preferred reference plane either in the geometry area or in the specification tree, or select a planar surface. This creates a simple sketch. To edit a sketch Double-click the sketch or an element of the sketch geometry. One can select it in the geometry or in the specification tree. 3D right clicks the sketch in the specification tree, move to (sketch name) object in the contextual menu, select Edit.

3.3 Creating a Positioned Sketch

In positioned sketch, one can decide the reference plane, and the origin and orientation of the absolute axis. Creating a positioned sketch enables to define (later change) explicitly the position of sketch absolute axis. Creating a positioned sketch ensures associativity with the 3D geometry. Select the sketch with Absolute Axis Definition icon. Then the Sketch Positioning Dialog box appears.

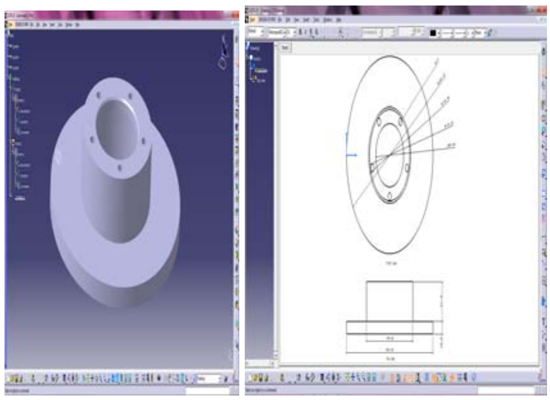


Figure 3.1: Solid model of Solid disc brake& Drafting

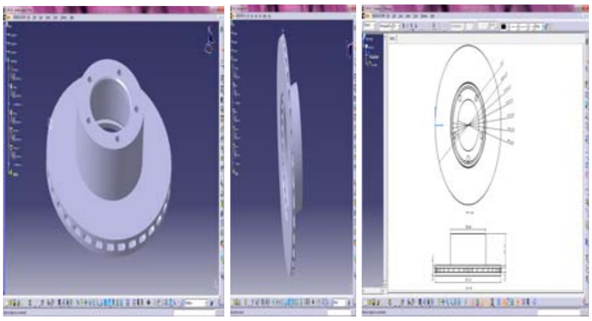
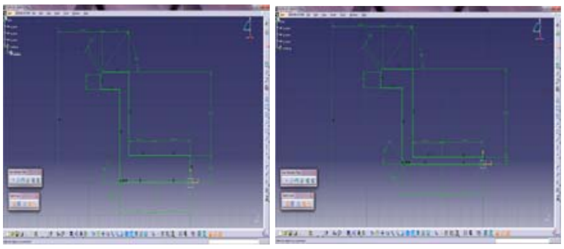


Figure 3.2: (a) and (b) Solid model of Ventilated disc brake and Drafting of Ventilated disc brake



(a) (b)

Figure 3.3: (a) Sketch of Solid type disc brake (b) Sketch of Ventilated type disc brake

4. ANSYS

ANSYS is a general-purpose finite element modelling package for numerically solving a wide variety of mechanical problems. ANSYS simulation software enables organisations to confidently predict how their products will operate in the real world. It expands the use of physics. It gains access to any form of engineering field someone may account in. The ANSYS program has many finite element analysis capabilities, ranging from a simple, linear, static analysis to a complex, nonlinear, transient dynamic analysis. A typical ANSYS analysis has three distinct steps: 1 Build the model, 2 Apply loads and obtain the solution and 3.Review the results.

4.1 Boundary Conditions

In this coupled analysis, the following three types of boundary conditions are applied:

(a) Temperature specified on the surface

S_T : $T = T^*$ …….(4.1) where, S_T is the surface on which temperature is specified, m^2T is the temperature, °C

T^* is the temperature specified on the surface, °C

(b) Heat flux specified on the surface

$S_Q : \{Q\}^T \{n\} = - Q^{*}$ … (4.2)

Where , S_Q is the surface in heat flux, m^2

Q is the heat quantity generated during the friction, J

T is the temperature, °C

n is the unit vector normal to the surface

Q^* is the heat flux specified on the surface, W

(c) Convection specified on the surface

$S_C : \{Q\}^T \{n\} = h (T_p - T_f)$…(4.3) where, S_C is the surface in convection, m^2

h is the Convective heat transfer coefficient, $Wm^{-2}k^{-1}$

T_p is the temperature imposed, °C

T_f is the fluid temperature, °C

4.2 Structural Anaysis

Structural analysis is probably the most common application of the finite element method. The term *structural* (or *structure)* implies not only civil engineering structures such as bridges and buildings, but also naval, aeronautical, and mechanical structures such as ship hulls, aircraft bodies, and machine housings, as well as mechanical components such as pistons, machine parts, and tools.

4.3 Thermal Analysis

A *thermal analysis* calculates the temperature distribution and related thermal quantities in a system or component. Typical thermal quantities of interest are The temperature distributions, The amount of heat lost or gained, Thermal gradients, Thermal fluxes.

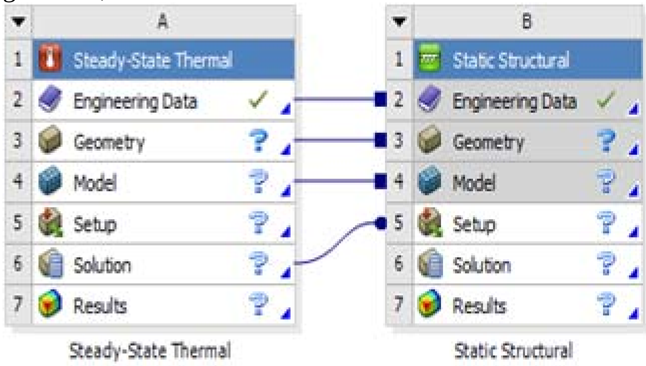


Figure 5.4: Thermal-Structural Coupling (Ref) in ANSYS Workbench

4.4 Coupled-Field Analysis

A *coupled-field analysis* is an analysis that takes into account the interaction (coupling) between two or more disciplines (fields) of engineering. A piezoelectric analysis, for example, handles the interaction between the structural and electric fields: it solves for the voltage distribution due to applied displacements, or vice versa. Other examples of coupled-field analysis are thermal-stress analysis, thermal-electric analysis, and fluid-structure analysis.

Some of the applications in which coupled-field analysis may be required are pressure vessels (thermal-stress analysis), fluid flow constrictions (fluid-structure analysis), induction heating (magnetic-thermal analysis), ultrasonic transducers (piezoelectric analysis), and magnetic forming (magneto-structural analysis).

4.5. Methods

The procedure for a coupled-field analysis depends on which fields are being coupled, but two distinct methods can be identified: sequential and direct.

5. Thermal Structural Coupling

The governing equations for the frictional heat analysis, and stress analysis while employing two different material hardening models will be described below.

(a)Heat Transfer analysis
Frictional heat power generated at the contact interface of a disc-pad system can be expressed as

$q_{gen} = \mu p_n \omega r$, ..(5.1)

Where, μ is the coefficient of friction, r is the distance of a contact pair from the center of the disc, p_n is the normal component of the contact traction vector, and ω is the angular velocity of the disc. The frictional heat generated at the contact interface flows into the disc and the pad. Heat conduction for each body is governed by the classical heat equation,

$$\rho c \dot{T} = k \sum_{i=1}^{3} \frac{\partial^2 T}{\partial x_i^2}, \quad (5.2)$$

Where, ρ is the density, c is the specific heat capacity and k is the thermal conductivity.

(b)Stress analysis
Stress –strain relations used to describe deformation of a material are different for the elastic and plastic domain. Consequently, it is important to know if the stress state is in the elastic or plastic domain. For this purpose a yield criterion is used to suggest the limit of elasticity and the initiation of yielding in a material under any combination of stresses. There are several yield criterion used in practice. Some of these are: the maximum shear stress criterion, the maximum principal stress criterion and the Vonmises stress criterion. These criterion could be expressed in terms of material constants obtained from different physical tests e.g. a shear or a uniaxial tensile test.

According to the Vonmises stress criterion, yielding depends on the deviatoric stress and not the hydrostatic stress. It is expressed as,

$\sqrt{3J_2} - \sigma_y = 0$ ... (.5.3)
for plastic deformation

$\sqrt{3J_2} - \sigma_y < 0$ .. (5.4)
for elastic deformation

Where, σ_y is the stress at yield in a uniaxial test and J_2 is the second invariant of the deviatoric stress,
i.e.

$J_2 = \frac{1}{2} s : s$, …..(5.5)

Where, s is the deviatoric stress, given by

$s = \sigma - \frac{tr(\sigma)}{3} I$ ..(5.6)

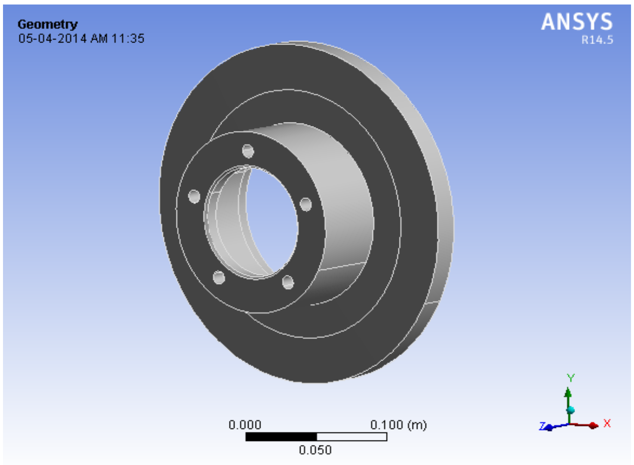


Figure 5.7: (a) Solid type disc brake imported in ANSYS

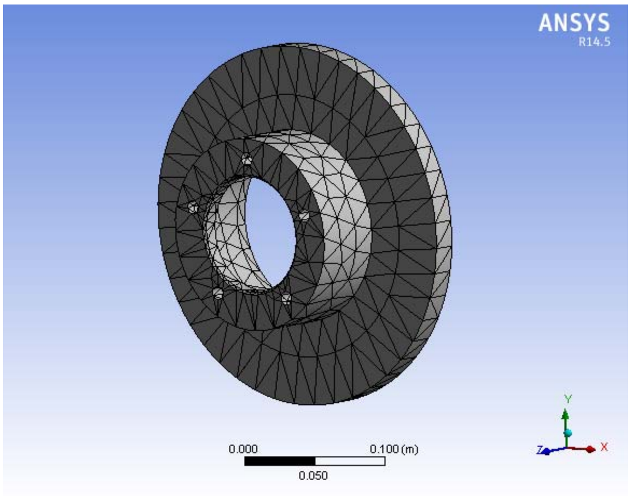


Figure 5.7: (b) Meshing of Solid type disc brake

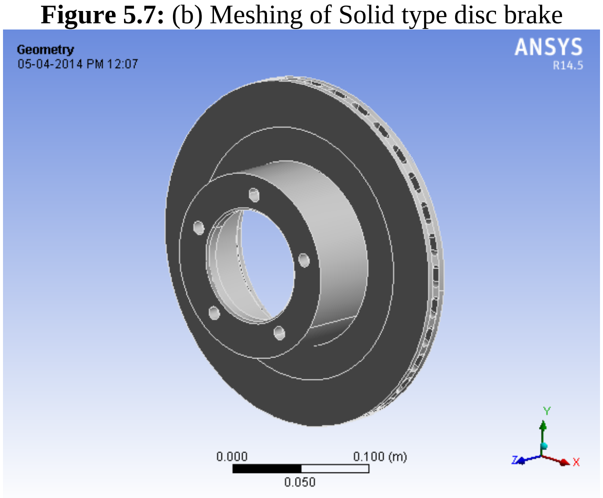


Figure 5.8: (a) Ventilated type disc brake imported in ANSYS

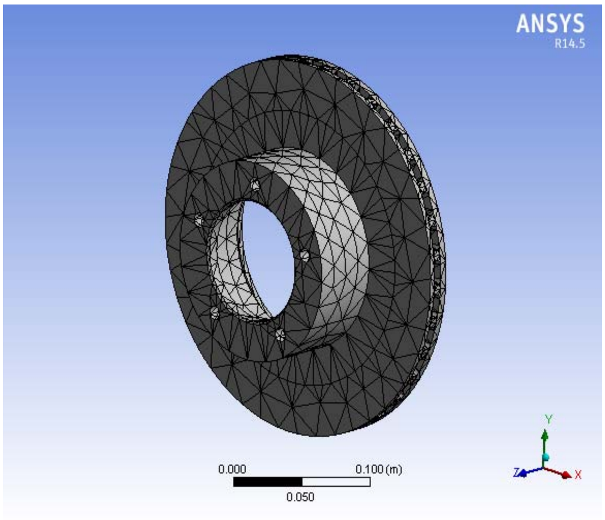


Figure 5.8: (b) Meshing of Ventilated type disc brake

5.1 Heat Flux Calculation

Velocity of vehicle = 120kmph = 33.33m/s
Time for stopping the vehicle = 4 sec
Mass of the vehicle = 1800kg

Kinetic energy (K.E.) = $\frac{1}{2} \times m \times v^2$........(5.11)

$= \frac{1}{2} \times 1800 \times 33.33^2$

= 999800.01 J

The above value is the total kinetic energy developed, when the vehicle is in motion.

Total Kinetic Energy = Heat Generated

Hence , Heat generated = 999800.01 J

Heat Generated per wheel = $\frac{999800.01}{4}$

= 249950.0025 J

Area of the rubbing faces = 2 X 3.14 ($130.01^2 - 95^2$)

= 0.0494 m^2

Heat flux = Heat Generated/time/Twice the Projected area……….(5.12)

= 249950.0025 / 4 / 2 X 0.0494

= 632464.5812 w/m^2

The analysis is done by taking the Brake Efficiency as 30% and hence the distribution between the front and the rear axle is 70:30 and the heat flow is taken as 0.

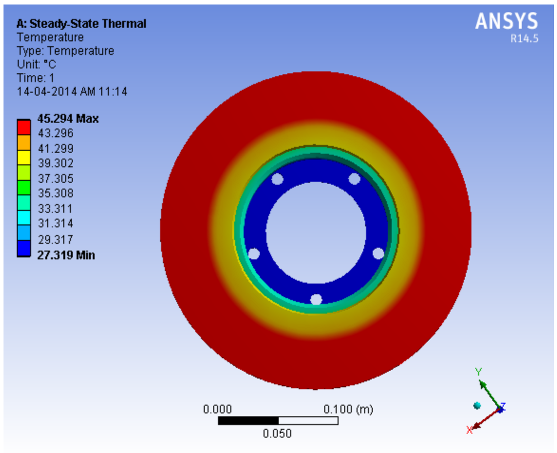
Thus, flux = 632464.5812 X 0.7 = 442725.2069 w/m^2

6. Results and Discussion

The results shown below are of ventilated and solid type disc brake made of Aluminium, Cast Iron, S-2 Glass Fiber. These results are obtained after applying the thermal and structural boundary conditions and performing the Coupled Thermal-Structural Analysis. The minimum and maximum values of Temperature, Total Heat Flux, Total Deformation, Equivalent (von-Mises) Stress are interpreted in the form of colours such as blue being the minimum, green being the intermediate temperature and red being the maximum.

6.1 Thermal Analysis:

(a) Ventilated disc brake S-2 Glass Fiber



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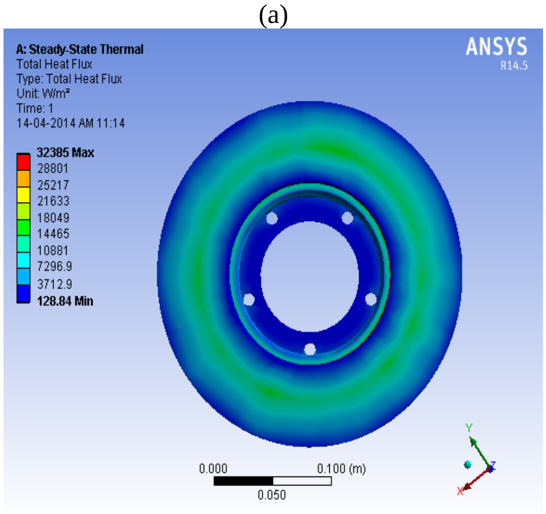
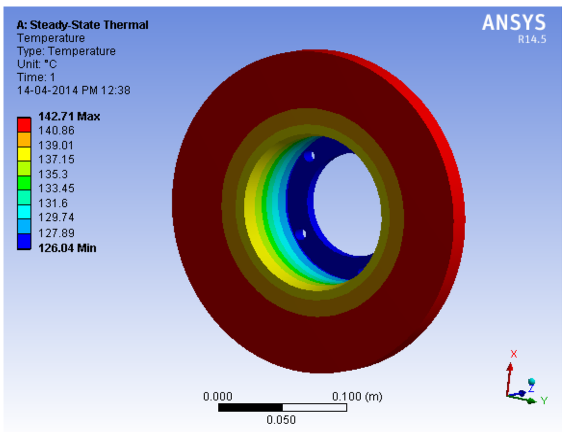


(b)

Figure 6.1: (a) & (b) Ventilated disc brake S-2 Glass Fiber

The above figures display the Temperature and Total heat flux of Ventilated disc brake made of S-2 Glass Fiber. As it is evident from the figures, the maximum temperature and the maximum total heat flux are represented by red colour and the values being, 45.29 °C and 32385 w/m^2 respectively.

6.1 (b) Solid disc brake S-2 Glass Fiber



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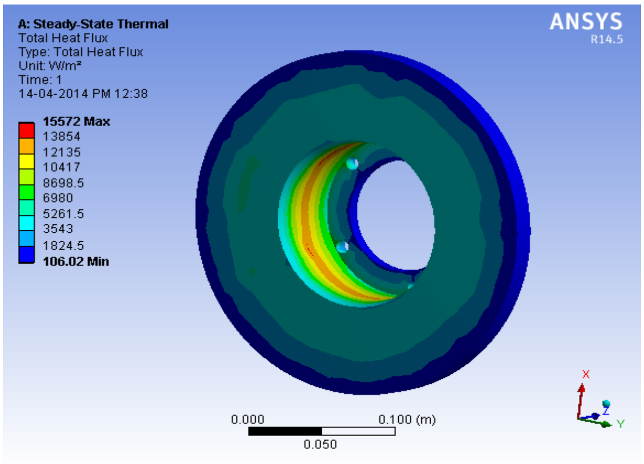


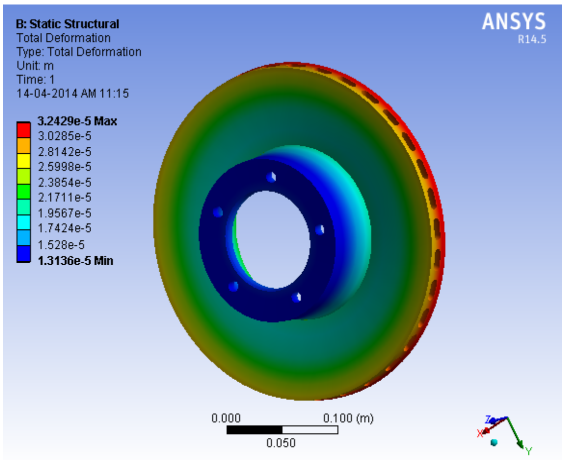
(b)

Figure 6.2: (a) & (b) Solid disc brake S-2 Glass Fiber

The above figures display the Temperature and Total heat flux of Solid disc brake made of S-2 Glass Fiber. As it is evident from the figures, the maximum temperature and the maximum total heat flux are represented by red colour and the values being, 142.71 °C and 15572 w/m^2 respectively.

6.2 Structural Analysis

(a) Ventilated disc brakeS-2 Glass Fiber



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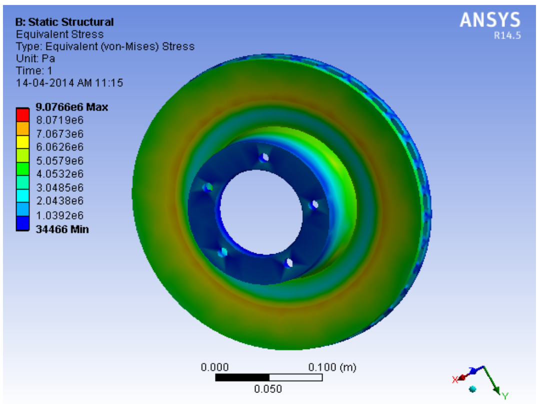
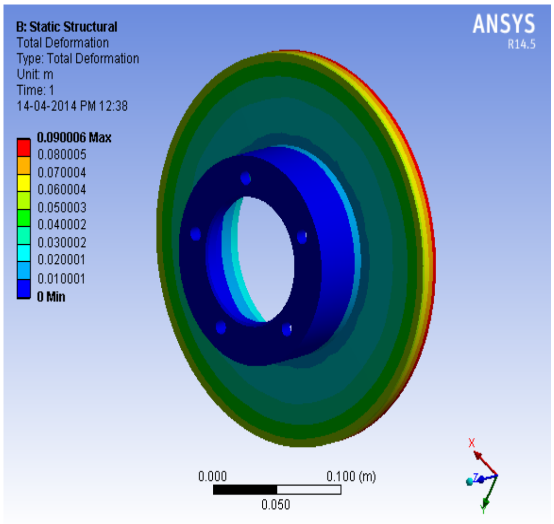


(b)

Figure 6.3: (a) & (b) Ventilated disc brake S-2 Glass Fiber

The above figures display the Total deformation and Equivalent (Vonmises) stress of Ventilated disc brake made of S-2 Glass Fiber. As it is evident from the figures, the maximum total deformation and equivalent stress are represented by red colour and the values being, 3.24e-5 m and 9.07e6 Pa respectively.

(b) Solid disc brake S-2 Glass Fiber



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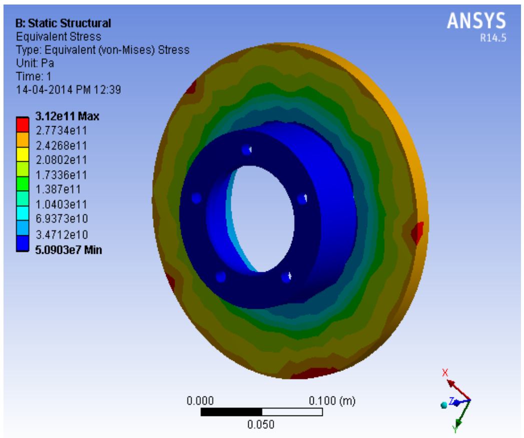
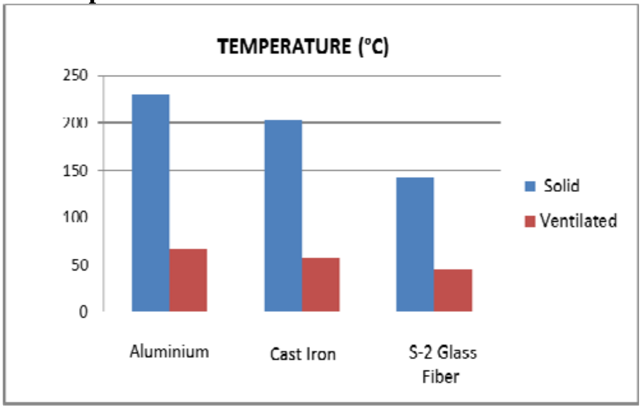


(b)

Figure 6.4: (a)&(b) Ventilated disc brake S-2 Glass Fiber

The above figures display the Total deformation and Equivalent (von-Mises) stress of Solid disc brake made of S-2 Glass Fiber. As it is evident from the figures, the maximum total deformation and equivalent (vonmises) stress are represented by red colour and the values being, 0.09 m and 3.12e11 Pa respectively.

6.3 Graphs



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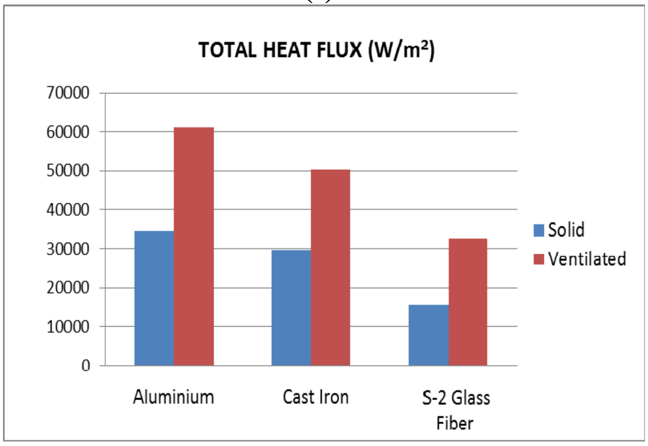
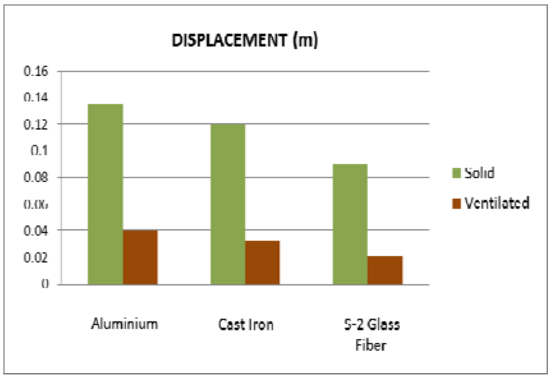


(b)

Figure 6.1: (a) & (b) Thermal analysis of solid and ventilated disc brake for different materials



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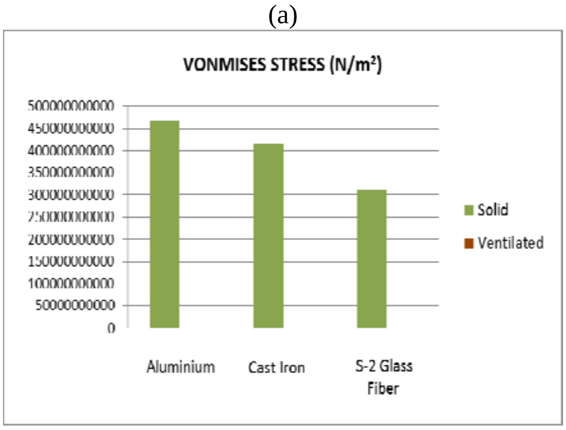

(b)

Figure 6.2: (a) & (b) Structural analysis of solid and ventilated disc brake for different materials.

6.4 Comparison of Results

Table 6.1: Thermal Analysis

Material	*Temperature (°C)*		*Total Heat Flux (W/m²)*	
	Solid	Ventilated	Solid	Ventilated
Aluminium	230.05	65.63	34496	61178
Cast Iron	203.09	58.15	29636	50211
S-2 Glass Fiber	142.71	45.29	15572	32385

The Table 6.1 gives the results of the three materials: Aluminium, Cast Iron, S-2 Glass Fiber and shows that Ventilated type disc brake made of S-2 Glass Fiber gives less temperature value when the loads are applied. Therefore, Ventilated type disc brake made of S-2 Glass Fiber material is preferred.

Table 6.2: Structural Analysis

Material	*Displacement (m)*		*Vonmises Stress (N/m²)*	
	Solid	*Ventilated*	*Solid*	*Ventilated*
Aluminium	0.135	0.040	$4.68e^{11}$	$1.695e^{7}$
Cast Iron	0.120	0.033	$4.16e^{11}$	$1.406e^{7}$
S-2 Glass Fiber	0.090	0.021	$3.12e^{11}$	$9.076e^{6}$

The Table 6.2 gives the results of the three materials: Aluminium, Cast Iron, S-2 Glass Fiber and shows that Ventilated type disc brake made of S-2 Glass Fiber gives less deformation and stress when the loads are applied. Therefore, Ventilated type disc brake made of S-2 Glass Fiber material is preferred.

7. Conclusion

In order to improve the braking efficiency and provide greater stability to the vehicle, an investigation is carried out into the usage of materials. The ventilation system plays an important role in cooling the discs and provides a good high temperature resistance. The analysis results showed that, temperature field and stress filed in the process of braking phase were fully coupled .Static structural analysis is carried out by coupling the thermal solution to the structural analysis. All the values obtained from the analysis are less than their allowable values. Hence the brake disc design is safe,based on the strength and rigidity criteria. Comparing the different results obtained from analysis, it is concluded that **ventilated type disc brake** is the best possible for the present application. From the results of the analysis, it is concluded that **S-2 Glass Fiber** is the best material for Disc brake.

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