iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 6 **Issue:** X **Month of publication:** October 2018

DOI:

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 6 Issue X, Oct 2018- Available at www.ijraset.com

Design and Analysis of a Braking System for Archimedes Wind Turbine

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Abstract: The objective of this paper is to design a braking system that will intend to bring the wind turbine rotors at rest position during the emergency conditions (like over speed or maintenance) at specified time. Braking system represents one of the crucial fundamental safety devices in modern vehicles. It absorbs kinetic energy of the rotating parts and dissipated in the form of heat energy to the surrounding atmosphere. During high guests (or high wind speeds) the turbine will rotate very frequently because of these conditions, the wind turbine will damage or fail. To overcome this problem wind turbine need a braking system.

In this project, it is to design and development of disc brake system by using sensor, control system and an actuator. The disc brake design with disc pads is done by using Creo 2.0 Modelling software and for structural & thermal analysis is done by using FEA Software-ANSYS workbench 16.2 using Gray cast-iron material. Structural analysis and thermal analysis is used to analyze the structural deformation, von-Mises stresses, stains and temperature gradient in both solid and ventilated disc brake and compare the results.

Keywords: Archimedes Wind Turbine, Disc brake, Creo parametric 2.0, ANSYS workbench 16.2.

I. INTRODUCTION

Energy is the major input in economic growth and there is a close relation between the availability of energy and the growth of a nation. A plenty of energy is required to sustain industrial growth and agricultural production. The existing sources of energy such as coal, petroleum, fossil fuels and uranium and so on, may not be adequate to meet the ever increasing energy demands. These conventional sources of energy are also depleting and may be exhausted at the century or beginning of the next century. Consequently, sincere efforts are required to harnessing from several renewable energy sources.

Archimedes spiral wind turbine is a small-scale horizontal axis wind turbine designed based on Archimedean principles. It takes energy from the wind by redirecting its flow 90 degrees relative to the original direction. It is a direct drive wind turbine means the turbine has no gear box [10]. To overcome the damage of any moving or rotating machinery during (high wind speeds) emergency conditions it requires a braking system.

The main design consideration for braking system is that it must be capable of locking the turbine rotor to slowdown or stop the wind turbine during maintenance and emergency conditions to prevent system failure. The brakes usually have a stationary and a rotating surfaces and the contact will be made between these two surfaces. The contact causes a normal force on the surface of the rotating member.

The contacting surfaces have sufficient friction depending on the requirement. The normal force causes frictional resistance or force due to the coefficient of friction. This frictional force causes a moment, which acts in the opposite direction to the turbine rotation and retards the motion of the object. The energy absorbed by brakes is dissipated in the form of heat [18]. This heat is dissipated into the surrounding atmosphere to stop the vehicle, so the brake system should have the following requirements:

Disc brake system has a metal disc instead of a drum. It consists of a flat shoe or pad, mounted on each side of a disc. To slow down or stop the moving machinery, these two brake pads are forced tightly against the rotating disc or rotor. A fluid pressure from the master cylinder forces the piston to move in.

This action pushes the brake pads or shoes tightly against the disc. The friction between the pads and the brake disc slows and stop the disc, which in turn brings the system stationary.

The sensors in a wind turbine indicate the wind speed and send to controller. If the speed of wind is higher than the cut-out speed the controller sends electrical signals to the sensor. And the sensor actuates the actuator to lock the disc brake. This braking system operates either manually or automatically as shown below sketch.

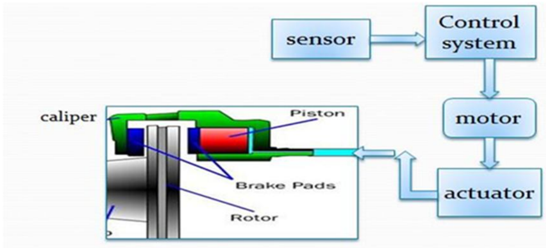

Figure 1: Working of a Braking System

There are some relevant research work is being done on disc brakes related to automobiles. *Rakesh Jaiswal et al* [1] describes the results of design and analysis of a disc brakes using SOLID WORKS 12.0 and carry out the finite element analysis (FEA) on the prepared model using ANSYS CFX and workbench 14.5. For the disc material Aluminium 6262-T9 and take the results of deformation, stress, heat flux and temperature distribution on automobile disc brake. Chengal Reddy et al [2] describes the design, simulation and optimization of solid and ventilated brake disc using Pro-E modeling software, ANSYS-FLUENT.to evaluate the deformations, von-mises stresses was evaluated in the brake disc with the pressure applied on the pads attached to the disc. T.V Manjunath et al [3] explain thermo-mechanical behaviour of disc brake using coupled thermo-structural analysis. S P Jung, et al [4] explains the thermo-elastic instability (TEI) of brake disc by utilizing finite element analysis (FEA) technique. TEI experience was executed by rotating the disc with a constant angular velocity. Contact pressure variation of the brake pad surface was differing as stated by angular direction of the brake disc.

Disc brake design and numerical simulation is carried out for different materials and compare the results obtained from analysis such as deformation, thermal stresses, and temperature distribution with in a disc brake rotor under hard braking conditions [5-7]. Cueva.G, et al. explains wear characteristics of three dissimilar grades of grey cast iron materials (grey iron grade 250, high-carbon grey iron and titanium alloyed grey iron), utilized in brake rotors. The wear experiment of materials was done using a pin-on-disc wear-testing instrument. The wear was detected on brake disc and brake pads before and after the experiment. The values convey that for given applied pressures the pins wear was experimentally the same, irrespective of the grade of iron [14].

H. Mazidi et al discusses the problem of heat conduction for disc brake (rotor and pad) and time dependent equations are taken into consideration for implicit method using ANSYS. Results shows, that there is a thermal resistance which causes heat accumulation and wear resistance occurs between two contact surfaces [8].

The controlling of a braking torque in a disc brake is developed by the rotation of wind turbine. In this he also implemented a pressure controlled prototype system to check the disturbances arrived from the disc brake operated on hydraulic pressure which is based on the speed of the shaft and the alignment of the brake pads on the brake disc. An estimator is designed, to demonstrate and estimating the amplitude of this disturbance and rejection of disturbances from the possible equivalent disturbances [12].

In this study, Design of disc brake is done by CREO 2.0 and simulation has done by ANSYS workbench 16.2 to analyze structural deformation, von-mises stresses and temperature distribution on disc brake.

II. DESIGN CALCULATIONS OF A DISC BRAKE

The design calculations of a new braking system is based on the uniform pressure theory and some standard formula to find braking force, torque, temperature and heat flux as written below.

Table 1: Geometrical dimensions and application parameters of braking

Parameter	Values	Units
Outer diameter of disc	260	mm
Inner diameter of disc	120	mm
Center hole diameter	40	mm
Overall height of disc	54	mm
Thickness of disc	24	mm
Disc pad size	115*72.5*13	mm
Weight of the wind turbine (M)	120	kg
Wind cut-out speed (V)	15	ms^{-1}
Time required for braking	5	Sec
Mass of the disc (m)	6	kg

1) Nomenclature

R_0 = Outer radius of the disc pad
R_i = Inner radius of the disc pad
r_0 = Outer radius of the disc
r_i = Inner radius of the disc
R_e = Effective radius of rotor
α = Angular acceleration
θ = Angle turned by the disc
t = Time required for braking

2) Angular Velocity Of Rotor (Ω)

$$V = r_0\omega \Rightarrow \omega = 115.38 \text{ rad/sec}$$

Total energy (ΔE) = $K.E_T + K.E_R = \frac{1}{2}MV^2 + \frac{1}{2}I\omega^2$ = 13875.5 joules

Braking torque (T_f) = $\frac{\Delta E}{\theta}$ = 48.1086 N-m

Where, $\theta = \omega_1 t + \frac{1}{2}\alpha t^2$ and $I = \frac{mr_0^2}{2}$

3) By Using Uniform Pressure Theory

Braking torque (T_f) = $\mu F R_e$

Where, $Re = \frac{2(r_o^3 - r_i^3)}{3(r_o^2 - r_i^2)}$ = 0.09929 mm

$\mu \rightarrow$ Coefficient of friction in dry condition (μ = 0.3-0.5)

Braking force (F) = $\frac{\text{Braking torque}}{2\mu R_e}$ = 538.26 N (on each disc pad)

Braking pressure (P) = $\frac{Total\ braking\ force}{\pi(r_o^2 - r_i^2)}$ = 25764.432 Pa

4) Thermal Calculations

Energy absorbed by the disc (ΔE) = Heat generated (Q)

$$\Delta E = mc_p\Delta T$$

Heat flux (q) = $\frac{\text{Rate of heat transfer}}{\text{area of the disc}} = \frac{2775}{0.4178}$ = 66.4 kW/m^2

Where, Rate of heat transfer = $\frac{Q}{t}$ = 2775 joule/sec

A. *Materials Properties*

For analysis we have to consider Gray Cast-iron ASTM A48 class 40 for brake disc and Semi-metallic material for brake pads. The properties of gray cast-iron have good hardness and wear resistance. The mechanical properties of grey cast-iron as listed below.

Table 1: Material properties of grey cast-iron

Property	Values	Units
Density	$(7.06\text{-}7.34)*10^3$	Kg/m^3
Young's modules	124	GPa
Thermal expansion	$9.0*10^{-6}$	$°C^{-1}$
Poisons ratio	0.24-0.33	-
Specific heat capacity	490	J/Kg-K
Ultimate tensile strength	>=276	MPa
Thermal conductivity	52	W/m-K

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III. DESIGN OF A DISC BRAKE WITH PADS

The design of a solid and ventilated brake discs with brake pads is done by using CREO 2.0 software. The dimensions of the center bore of a brake disc is based on the diameter of wind turbine shaft and other dimensions of disc and brake pads as shown in below figures.

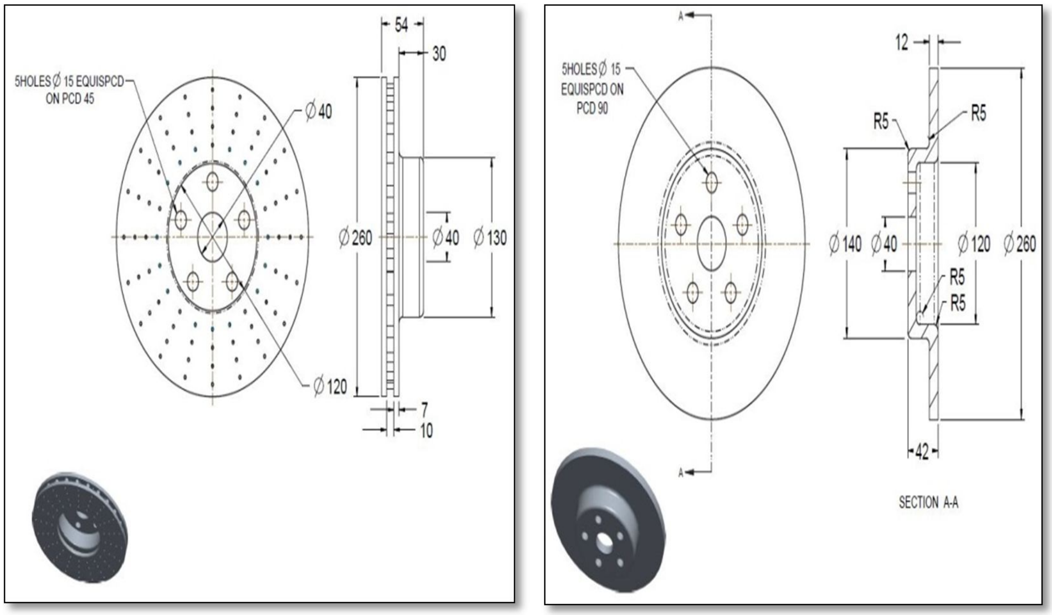


Figure 3: Dimensions of solid and ventilated brake discs

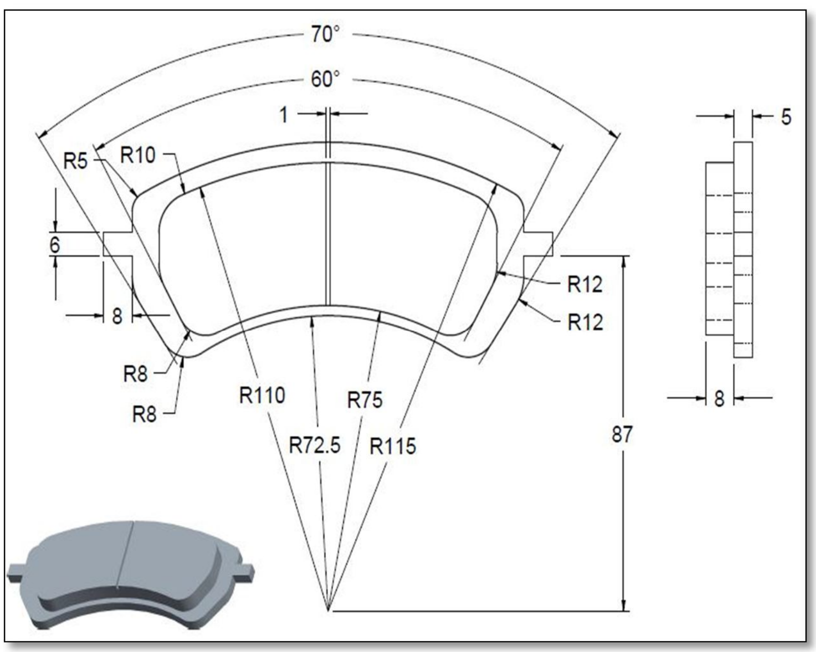


Figure 4: Dimensions of brake pad

IV. METHODOLOGY

For analyzing this designed model in Creo Parametric 2.0 software that model is tested in Ansys workbench 16.2 version software. In workbench there are different types of analysis platforms are available to work on any model. But the current work has to analyze the static structural and transient analysis on model of a disc brake. The process of simulation as follows.

A. Modeling Disc Brake with Pads

The 3D-modeling and assembly of a solid and ventilated brake discs with brake pads is done by using CREO 2.0 software, and the schematic diagrams are shown in below.

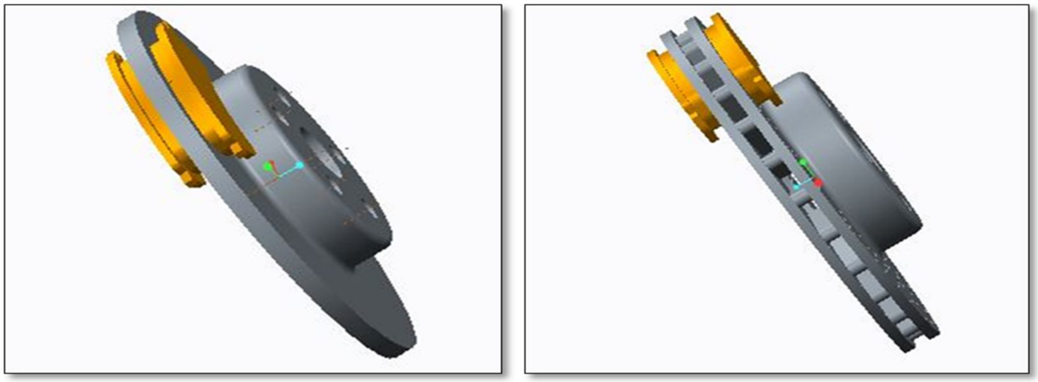


Fig 2: 3D- models of solid and ventilated disc brakes

B. Meshing on Model of a Disc Brake

After importing the CAD model to the design modular of ANSYS workbench, meshing is generated on the brake disc. The meshed models of solid and ventilated brake disc for carrying out both static structural and thermal analysis is as shown in Figure 5. The model is meshed with triangular surface mesher for doing analysis. The meshed CAD model of solid disc has 82518 nodes and 45341 elements and that of ventilated disc has 261547 nodes and 152026 elements and further analysis is done after meshing.

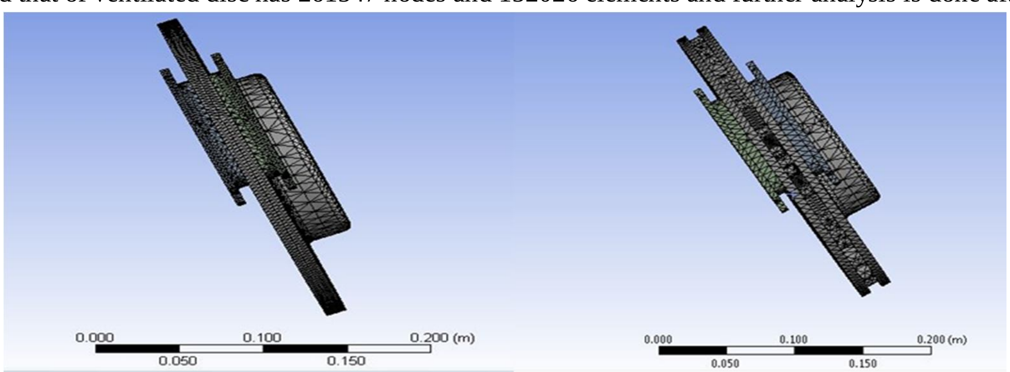
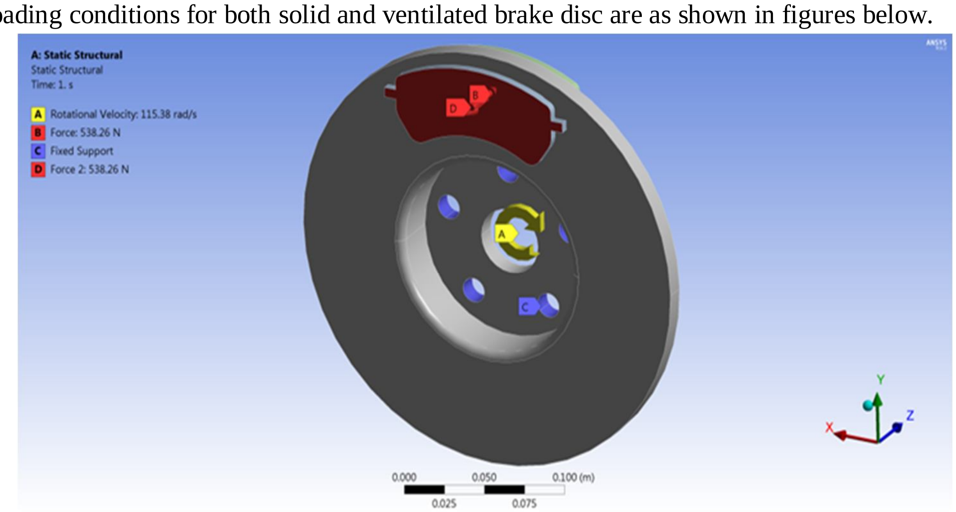


Figure 5: Meshing of both solid and ventilated disc

C. Boundary Conditions

For static structural analysis, the deformation and stresses developed are based on rotational velocity and force or pressure applied on brake disc. The loading conditions for both solid and ventilated brake disc are as shown in figures below.



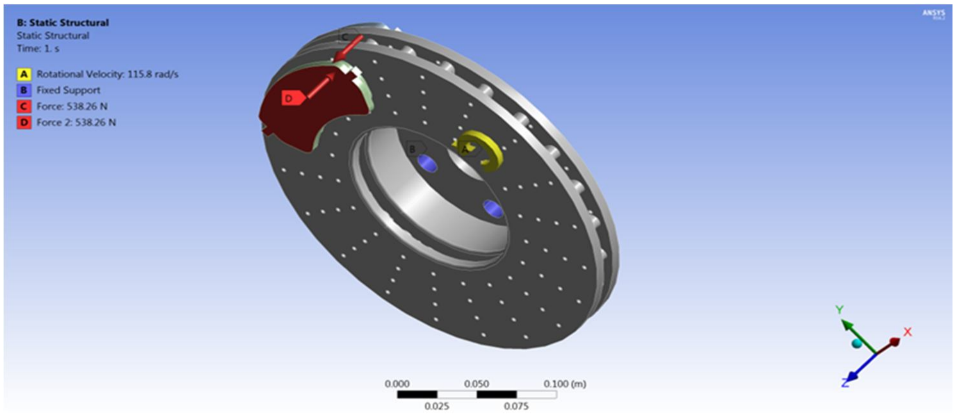


Figure 6: Boundary conditions for both solid and ventilated disc

For transient thermal analysis, the variation of temperature in the brake disc is depend on heat flux entering through both sides of the disc and convectional heat transfer coefficient. The initial and boundary conditions are as follows

1) Initial temperature of the disc = 60 ℃
2) Heat flux = 66.4 kW/m^2
3) Heat transfer coefficient = stagnant air condition
4) Number of time steps = 50
5) Initial time step = 0.25 [s]
6) Minimum time step = 0.125 [s]
7) Maximum time step = 0.5 [s]

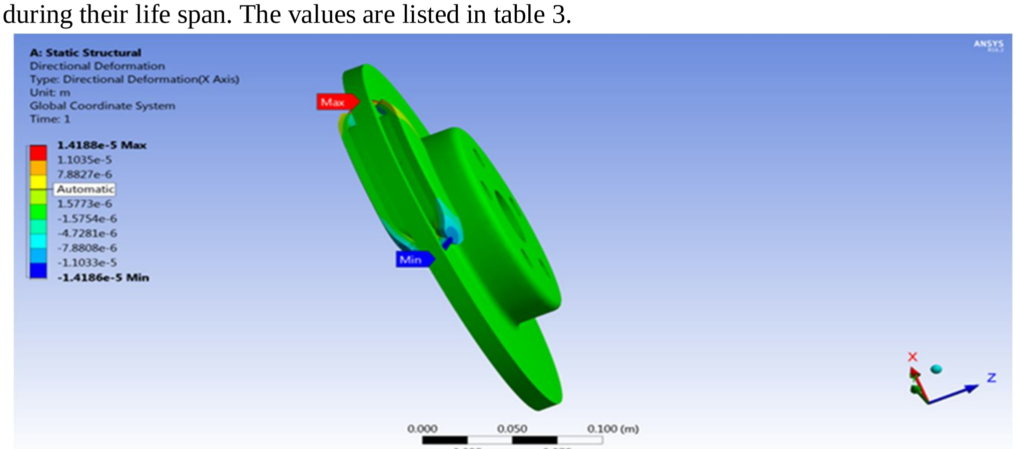
V. RESULTS AND DISCUSSION

A. Results of Static Structural Analysis

The analysis is carried out on both solid and ventilated brake disc under same loading conditions to obtain the values of deformation, equivalent strain, von-mises stresses, and maximum principle stresses. The results for static structural analysis for disc brake with brake pads using grey cast iron material was performed under given loading conditions of braking force F= 538.26 N on each brake pad and an angular velocity ω = 115.38 rad/sec.

Figure 7 shows the distribution of directional deformation (X-direction) for both solid and ventilated disc brake using grey cast iron. The values deformation varies from ± 0.00142 mm for solid disc and that of ventilated disc is ± 0.00131 mm. The square root of sum of the squares of directional deformation in all the directions gives total deformation which is as shown in Figure 8. The total deformation values vary from 0 to 0.00648 mm for solid disc and 0 to 0.00583 mm for ventilated disc brake. Figure 9 shows the changes in shape and size of brake disc before and after the braking.

The distribution of von-mises stresses and maximum principal stresses for solid and ventilated disc brake is shown in Figure 10 and Figure 11. The maximum Von-Mises and principal stress values are 17.3 MPa, 22.07 MPa for solid disc and 16.23 MPa, 15.7 MPa for ventilated disc brake respectively. The lesser values of deformation and stresses in a disc brake indicate that it can with stand more no of cycles during their life span. The values are listed in table 3.



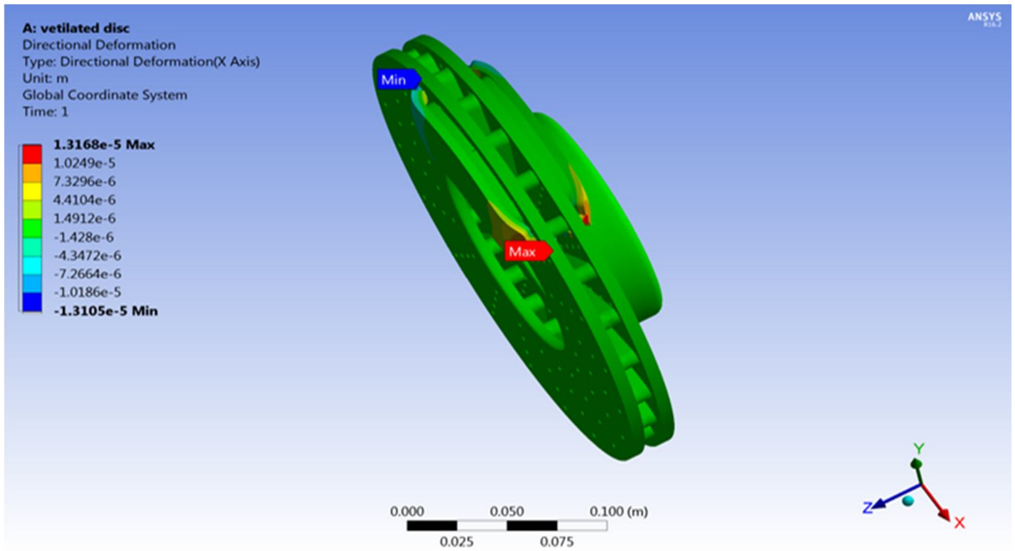


Figure 7: Distribution of directional deformation on brake disc

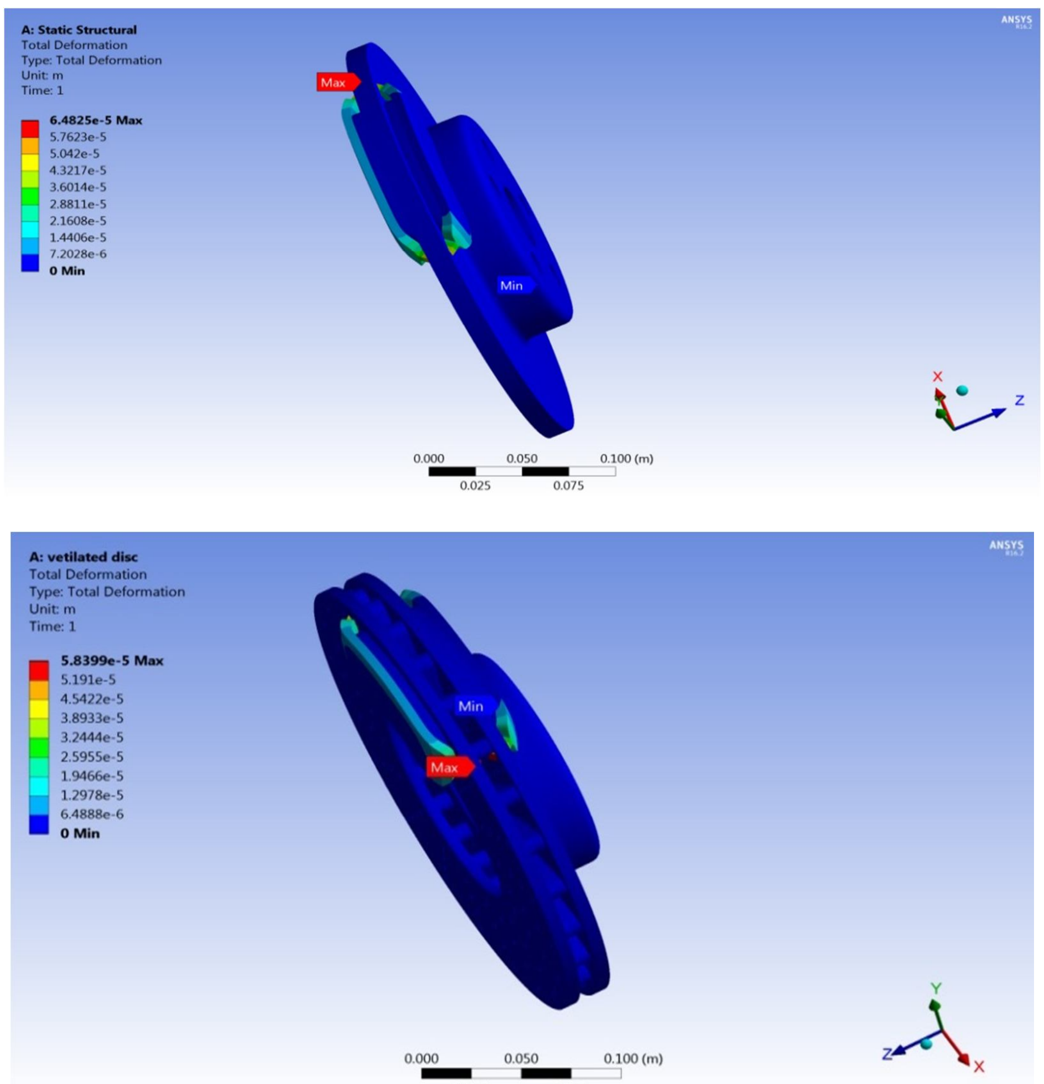
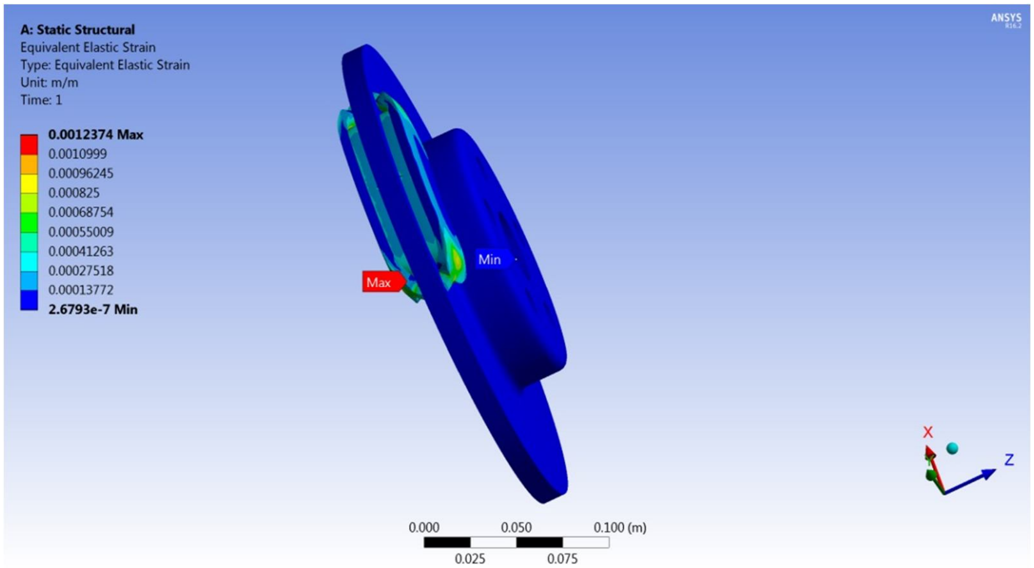


Figure 8: Distribution of total deformation on both solid and ventilated disc



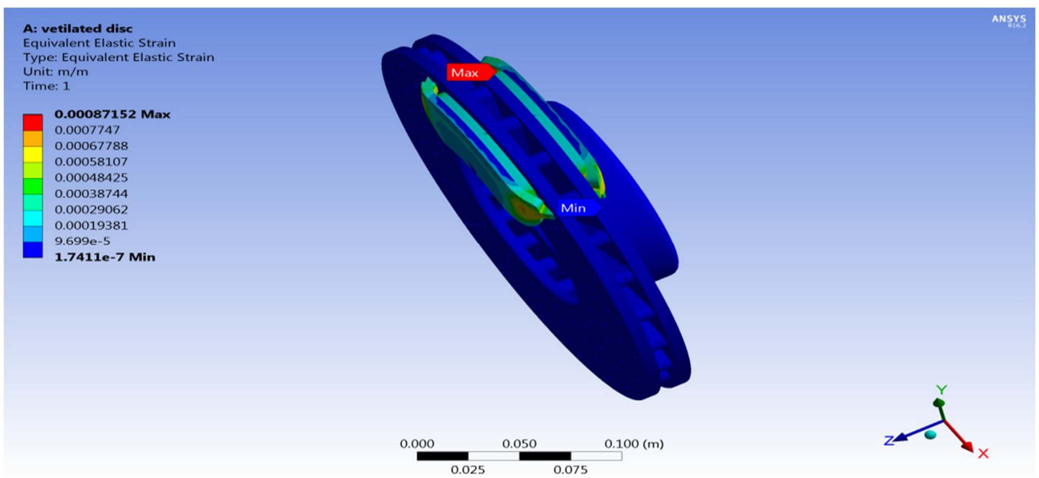
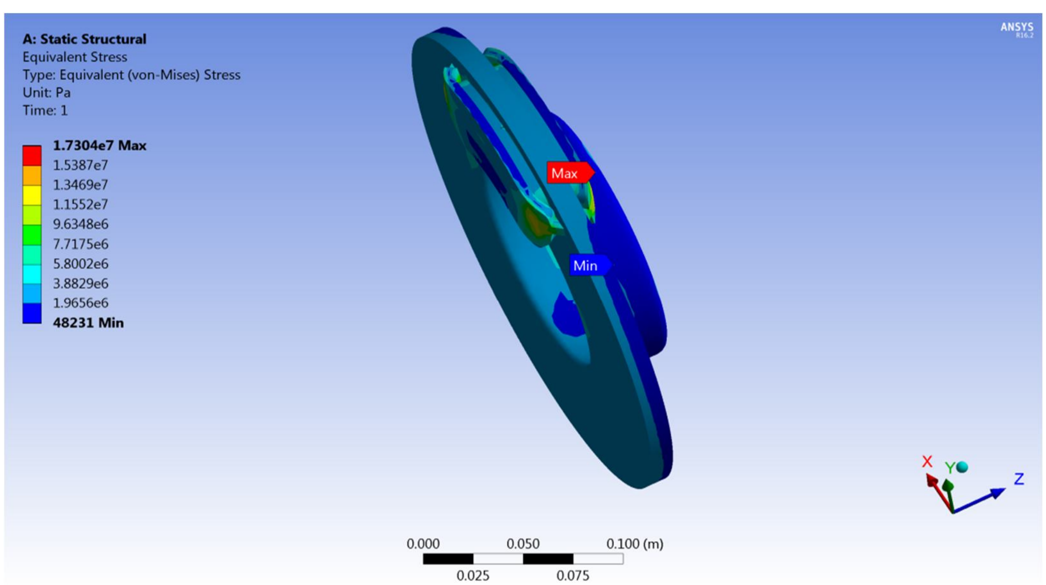


Figure 9: Distribution of equivalent strain on both solid and ventilated disc



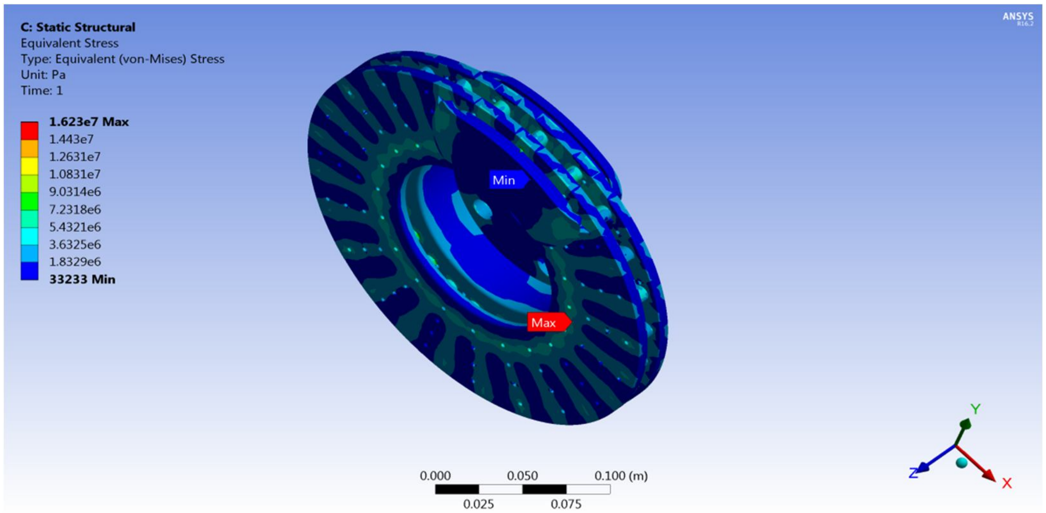


Figure 10: Distribution of equivalent stress on both solid and ventilated disc

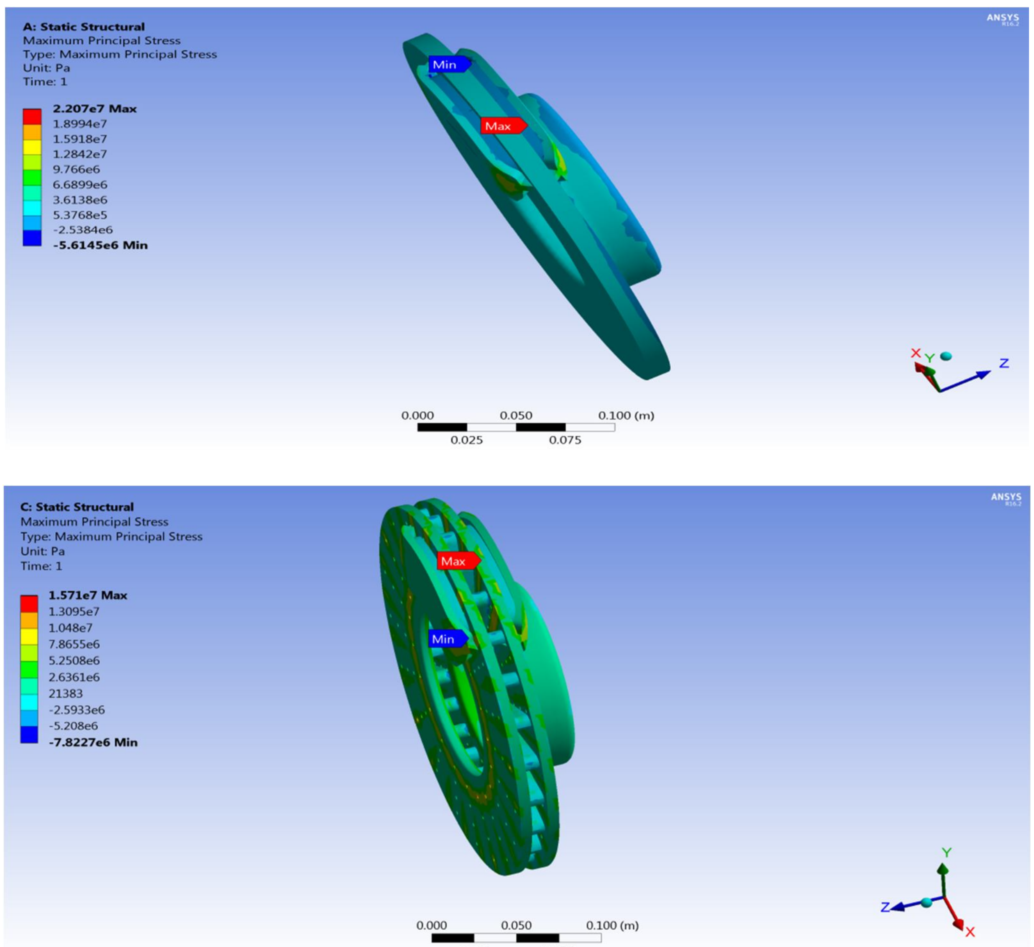
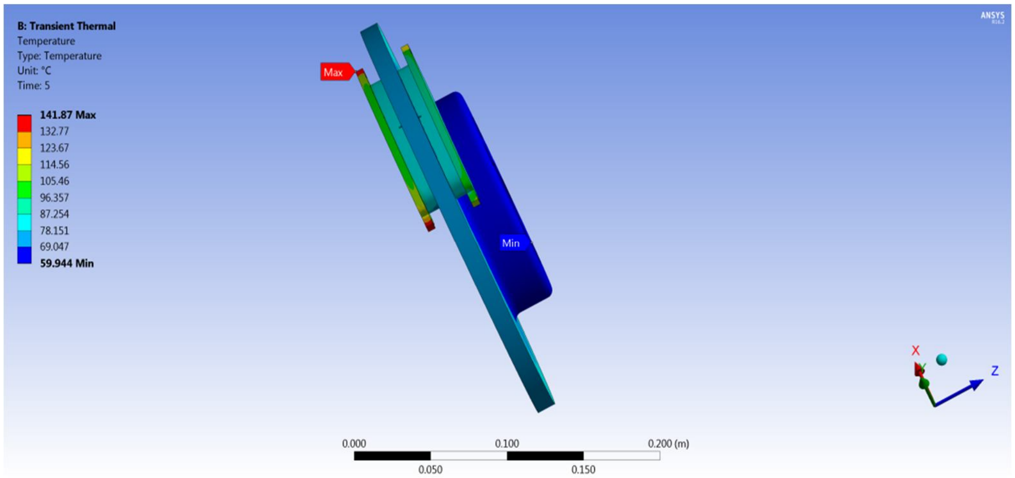


Figure 11: Distribution of Max. Principal stress on brake disc

B. Results of a Transient Thermal Analysis

The transient thermal analysis is carried out for both solid and ventilated brake disc under given boundary conditions to obtain the values of temperature distribution and total heat flux. During analysis the parameters such as braking time, cooling of disc and type of material are taken into consideration.

Figure 12 and fig.13 represents the variation of temperature distribution with respect to time during total simulation of braking for both solid and ventilated disc brake. The maximum values of temperature distribution at time intervals t = 5 sec, t = 10 sec are 141°C, 194 °C for solid disc and 88.46°C, 111.3 °Cfor ventilated brake disc. At given time interval the solid disc generates more temperature than ventilated disc it means ventilated brake disc withstand more temperatures and dissipates more heat to the outer side for easy cooling. The variation of temperature distribution with time is as shown in below.



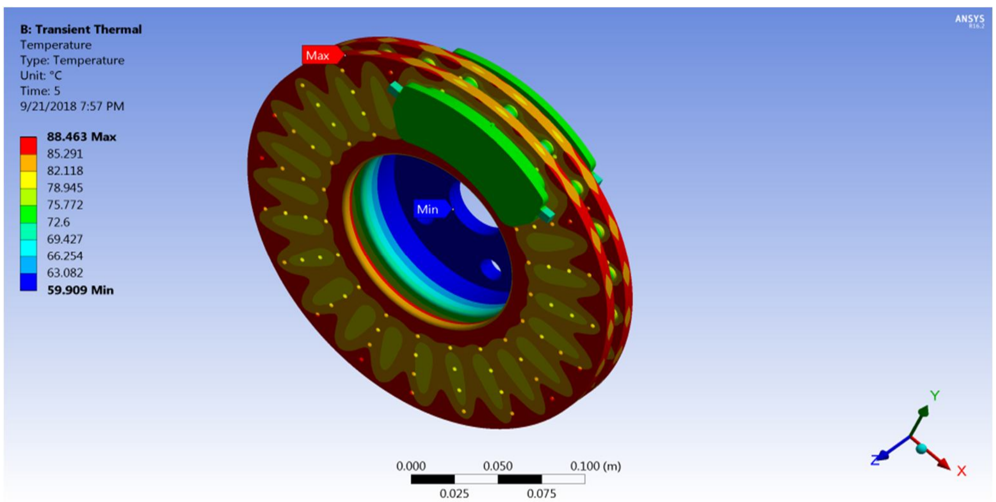
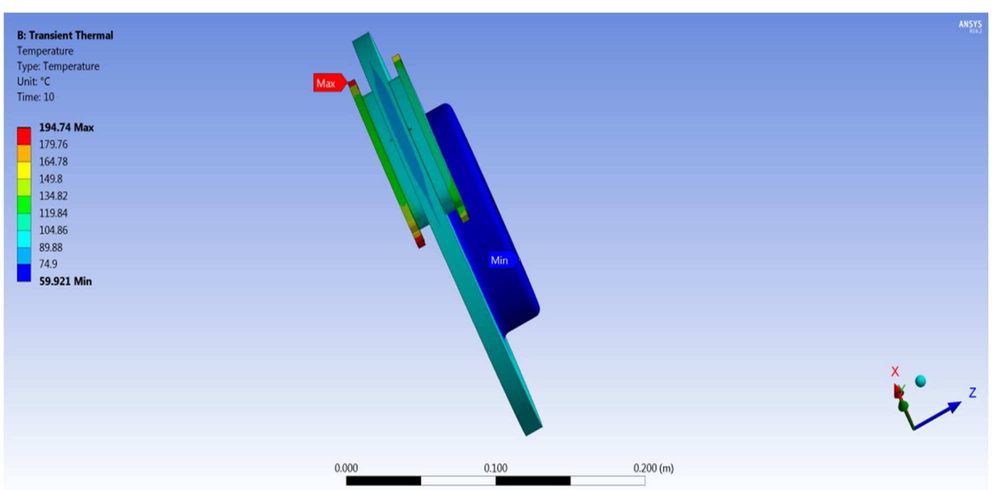


Figure 12: Distribution of temperature on brake disc at 5 sec



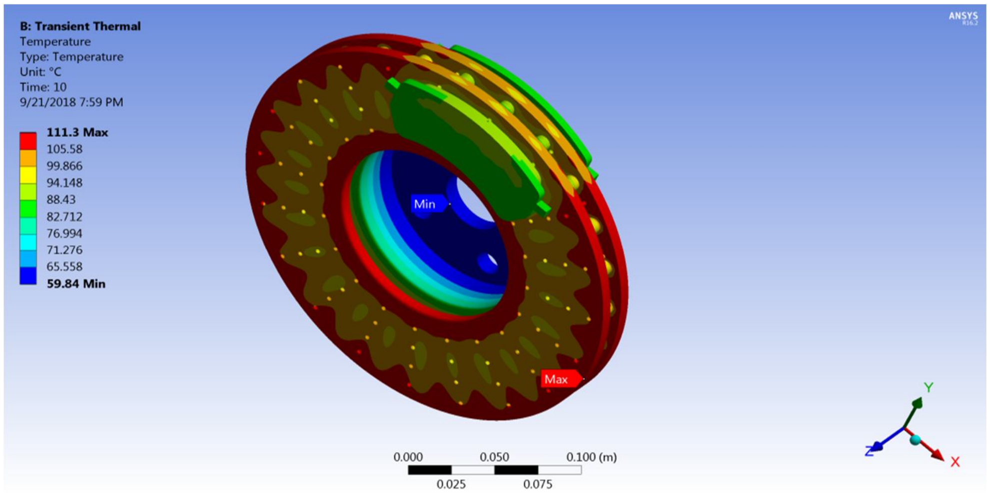


Figure 13: Distribution of temperature on brake disc at 10 sec

Table 2: Comparison of different results on disc brake models

S.No.	Parameter	Solid disc	Ventilated disc
1	Total Deformation	6.4825e-5 (m)	5.8399e-5 (m)
2	Directional Deformation	1.4188e-5 (m)	1.3168e-5 (m)
3	Equivalent (Von-Mises) Strain	0.001237	0.00087152
4	Equivalent (Von-Mises) Stress	1.7304e7 (Pa)	1.6230e7 (Pa)
5	Maximum Principle Stress	2.207e7 (Pa)	1.571e7 (Pa)
8	Temperature (t = 5 sec)	141 (°C)	88.46 (°C)
9	Temperature (t = 10 sec)	194 (°C)	111.3 (°C)

VI. CONCLUSION

By using ANSYS workbench 16.2, the analytical results of static structural analysis and transient thermal analysis with grey cast-iron as disc material the following conclusions can be drawn out.

A. The angular velocity, braking torque, braking force, temperature rise in each step, and heat flux are calculated with the help of brake disc specifications and wind turbine specifications.

B. Total deformation, Von-Mises stresses obtained from the static structural analysis of a ventilated brake disc and solid brake disc are 5.8399e-5 m, 6.4825e-5 and 16.23 MPa, 17.30 MPa respectively.

C. Temperature distribution obtained from the thermal analysis of a ventilated brake disc and solid disc at different time intervals are 88.46℃, 111.3 ℃ & 141℃, 194 ℃ respectively.

D. It shows that ventilated disc brake have relatively less values than solid disc brake. It can be concluded that ventilated disc plays a key role in cooling the brake discs, provides high temperature resistance and also have less weight. So, ventilated disc brake is best suitable for present application.

E. All the analytical values obtained from the analysis of a disc brake are less than the permissible values, so the design is safe based on strength and rigidity criterion.

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