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Fatigue and Structural Analysis of Disc Brake

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Abstract:
These day technologies go beyond us. For automotive field, the technology of engine develops very fast. Although the engineer gives priority for safety measure, but most consumers still have inadequate knowledge in safety system. Instead of having air bags, good suspension systems, good handling and safe cornering, there is one most critical system in the vehicle which is brake systems. 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, we have conducted a study on solid, drilled and ventilated type disc brake rotor of normal passenger vehicle. The project is aimed at evaluating the performance of disc brake rotor under braking conditions and there by assist in disc rotor design and fatigue analysis.

Keywords: CATIA, ANSYS, VONMISSES STRESS, FATIGUE ANALYSIS.

PRINCIPLE

1. *INTRODUCTION*

Brakes are most important safety parts in the vehicles. Generally all of the vehicles have their own safety devices to stop their car. 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 all of the modern vehicles and the safe operation of vehicles. In short, brakes transform the kinetic energy of the car into heat energy, thus slowing its speed.

BRAKING REQUIREMENTS

1) The brakes must be strong enough to stop the vehicle within a minimum distance in an emergency. But this should also be consistent with safety. The driver must have proper control over the vehicle during emergency braking and the vehicle must not skid.

2) The brakes must have good anti-fade characteristics i.e. their effectiveness should not decrease with constant prolonged application e.g., while descending hills. This requirement demands that the cooling of the brakes should be very efficient.

BRAKE EFFICIENCY AND STOPPING DISTANCE

The maximum retarding force applied by the brake at the wheels, F, depends upon the coefficient of friction between the road and the tyre surface μ, and the component of the weight of the vehicle on the wheel, W, i.e.,
$F = \mu W$

CLASSIFICATION OF BRAKES

1) Purpose:

- Primary brakes
- Secondary brakes

2) Construction:

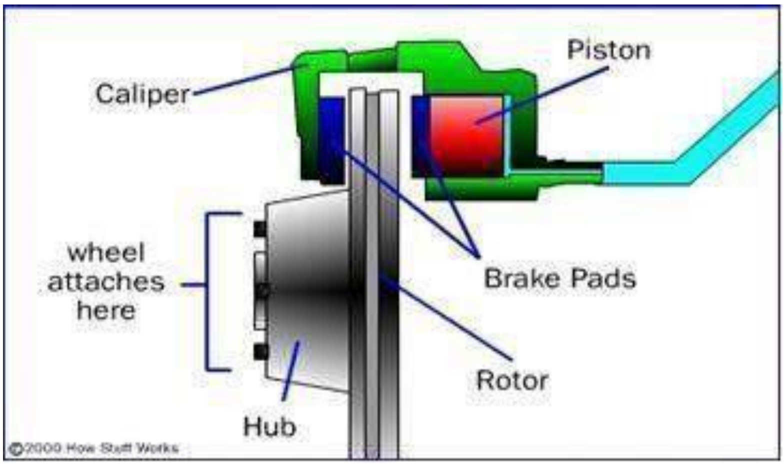
- Drum brakes
- Disc brakes

3) Method of Actuation:

- Mechanical brakes
- Hydraulic brakes
- Electric brakes
- Vacuum brakes
- Air brakes
- By-wire brakes

4) Extra braking effort:

- Power assisted brakes
- Power operated brakes



Parts of a disc bra

Table 1.2 Material properties

PROPERTIES	Aluminium Metal Matrix	Titanium Alloy	Structural Steel	Gray Cast Iron	Carbon Ceramic
Density , Kg/m³	2712	4620	7850	7200	1750
Thermal conductivity , w/m-K	250	20	60	54	1.45
Young's Modulus , N/m²	69×10^{9}	9.6×10^{10}	2×10^{11}	1×10^{11}	1.95×10^{11}
Poisson's Ratio	0.33	0.36	0.3	0.28	0.31
Specific Heat , J/Kg-K	910	520	490	586	850
Coefficient of Linear Expansion , /K	23×10^{-6}	9.6×10^{-6}	11.7×10^{-6}	9.9×10^{-6}	2×10^{-6}

ke

LITERATURE REVIEW

Blot [2] defined several numerical procedures for the fatigue 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. As well as specifying the energy input and output accurately, the material properties (e.g. thermal conductivity, specific heat, etc.) had a great influence on the temperature response.

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.

ketching of solid,ventilated and drilled:

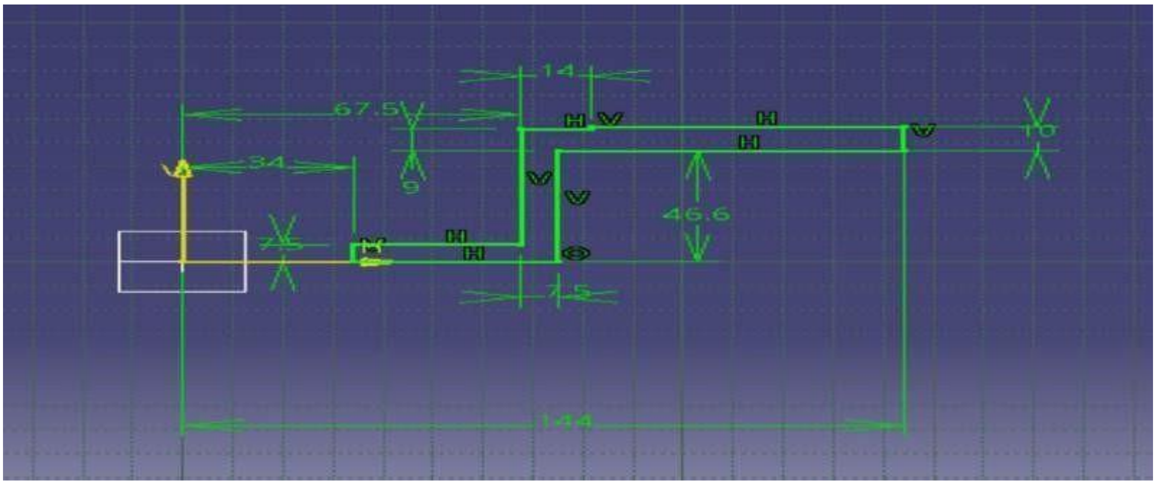


Fig. 3.1 Sketch of Solid type disc brake

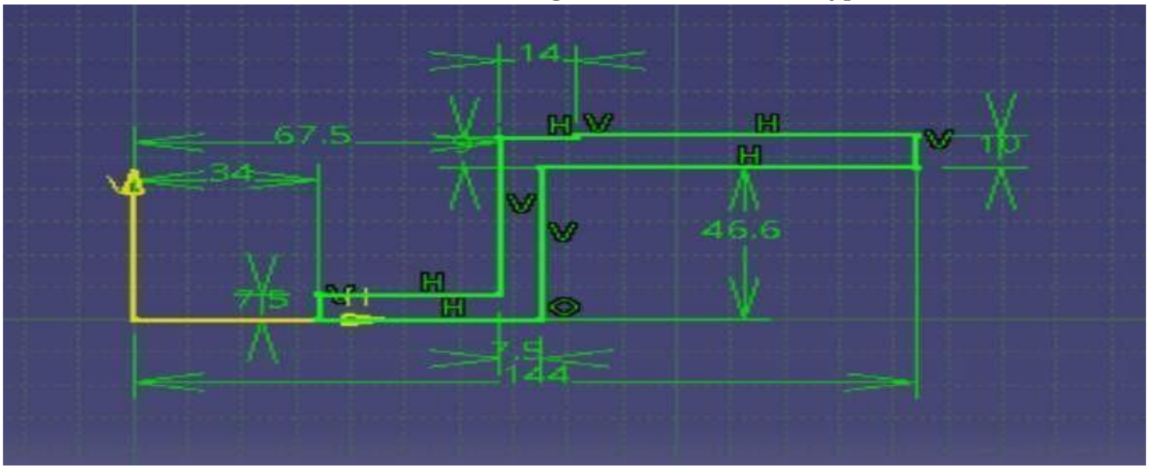


Fig. 3.2 Sketch of Ventilated type disc brake

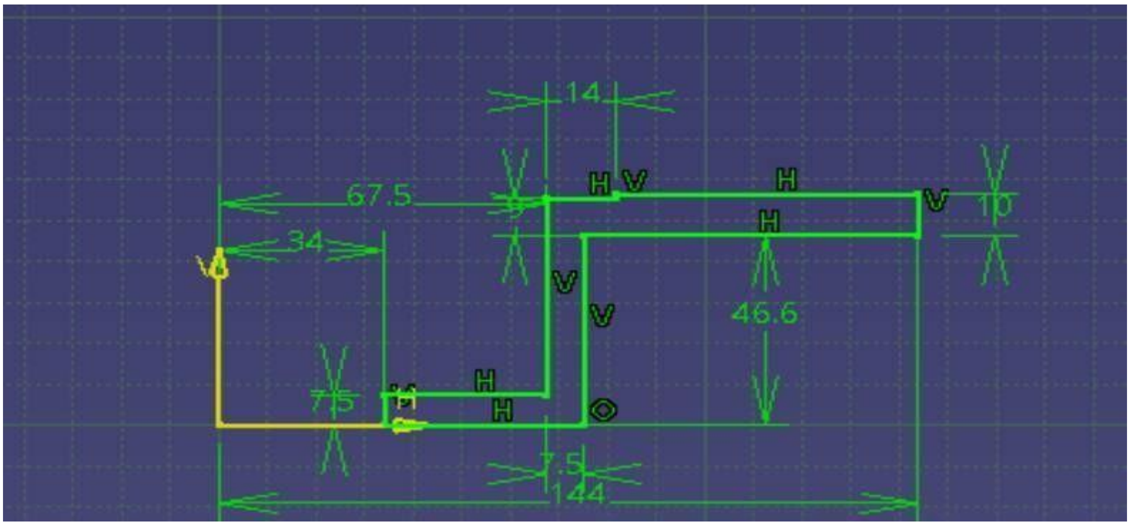


Fig. 3.3 Sketch of Drilled type disc brake

Modelling and Meshing of Solid,Ventilated and Drilled disc brake:

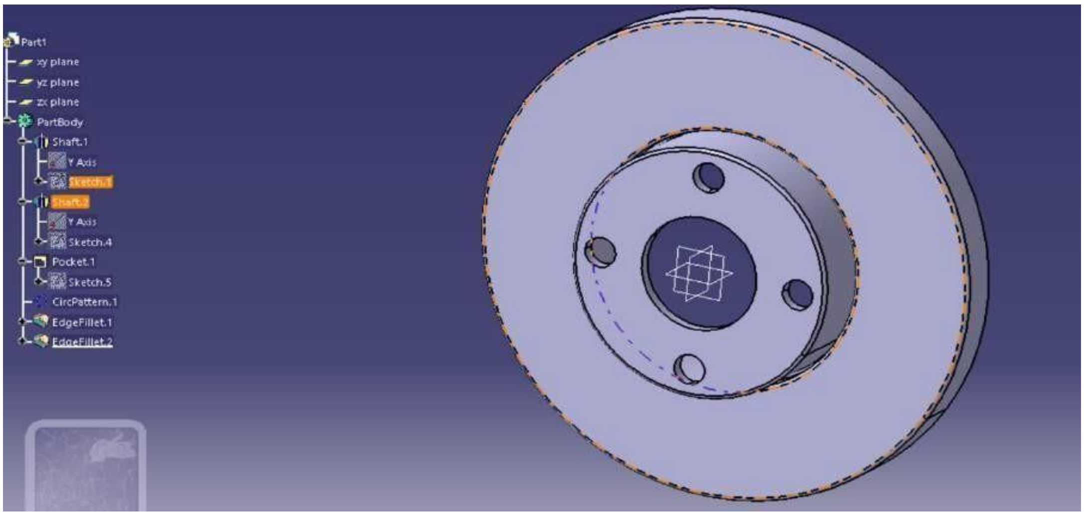


Fig. 3.4 Solid model of Solid disc brake

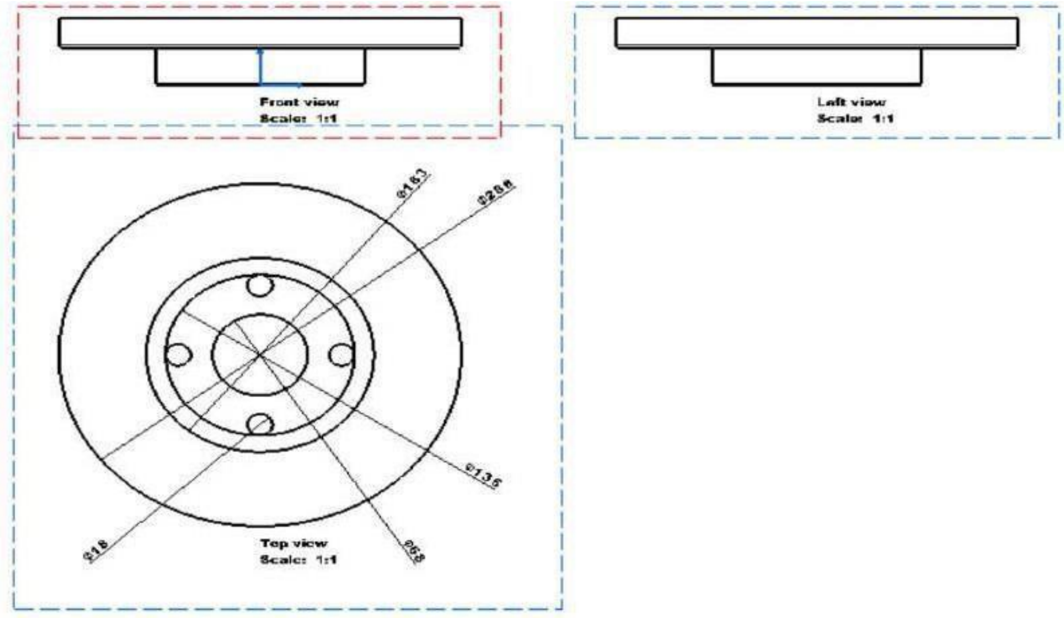


Fig. 3.5 Drafting of Solid disc brake

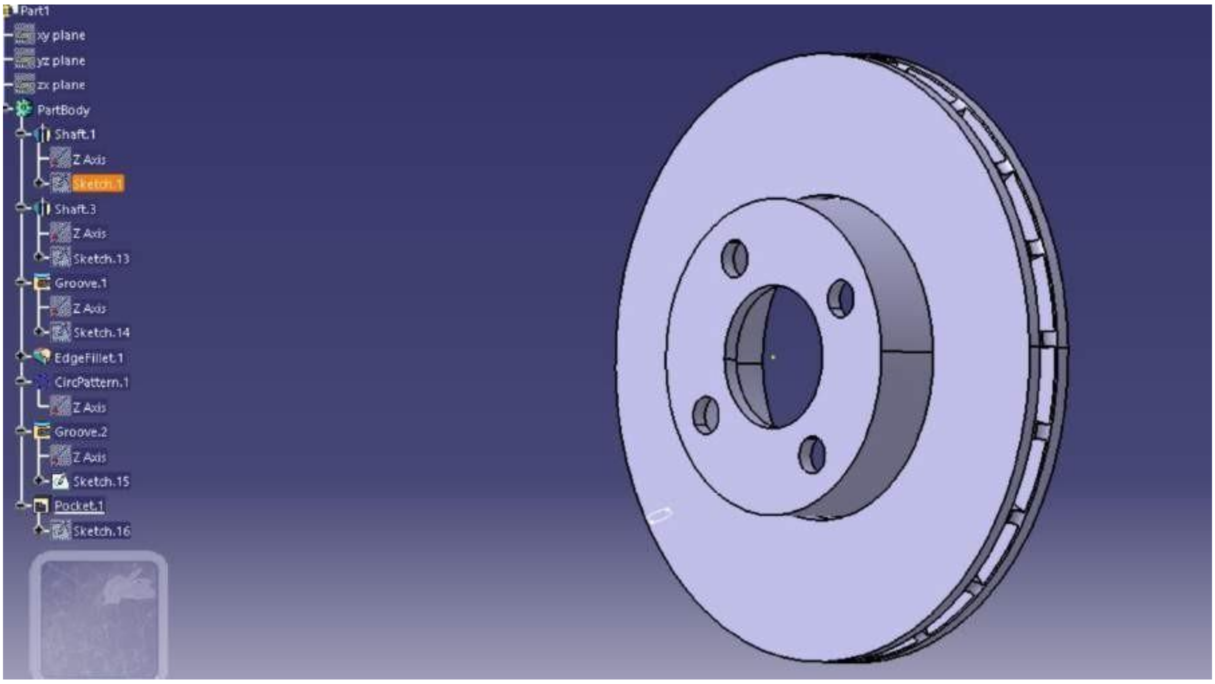


Fig. 3.6 Solid model of Ventilated disc brake

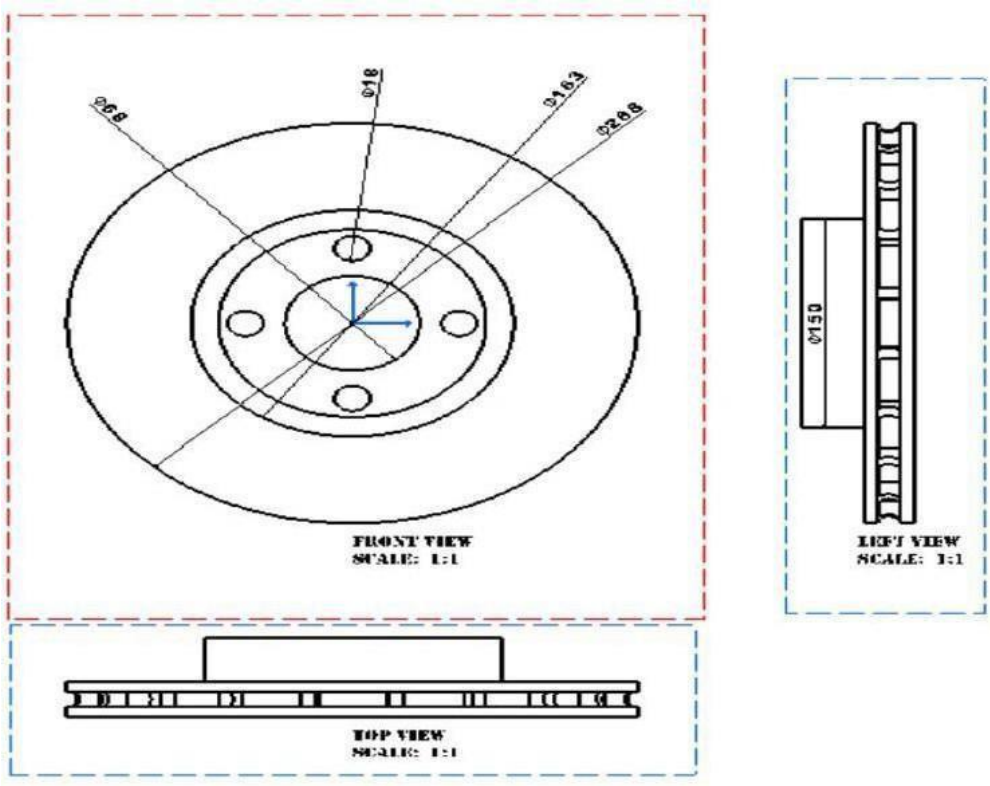


Fig. 3.7 Drafting of Ventilated disc brake

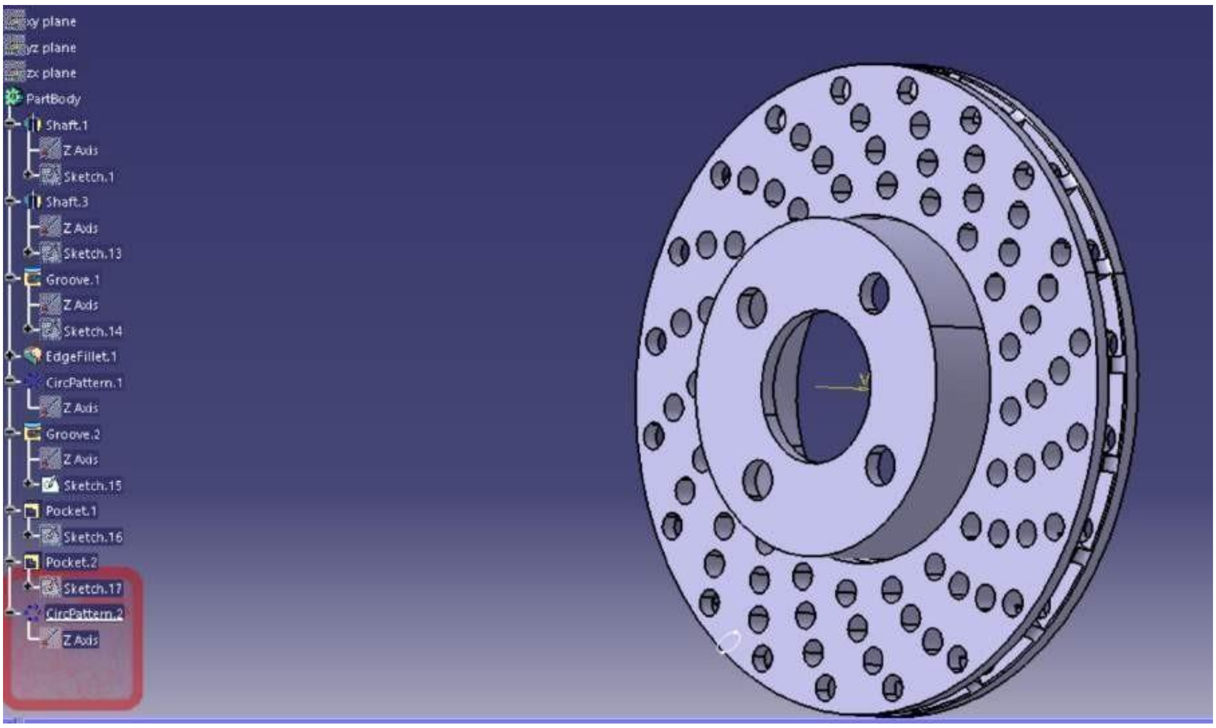


Fig. 3.8 Solid model of Drilled disc brake

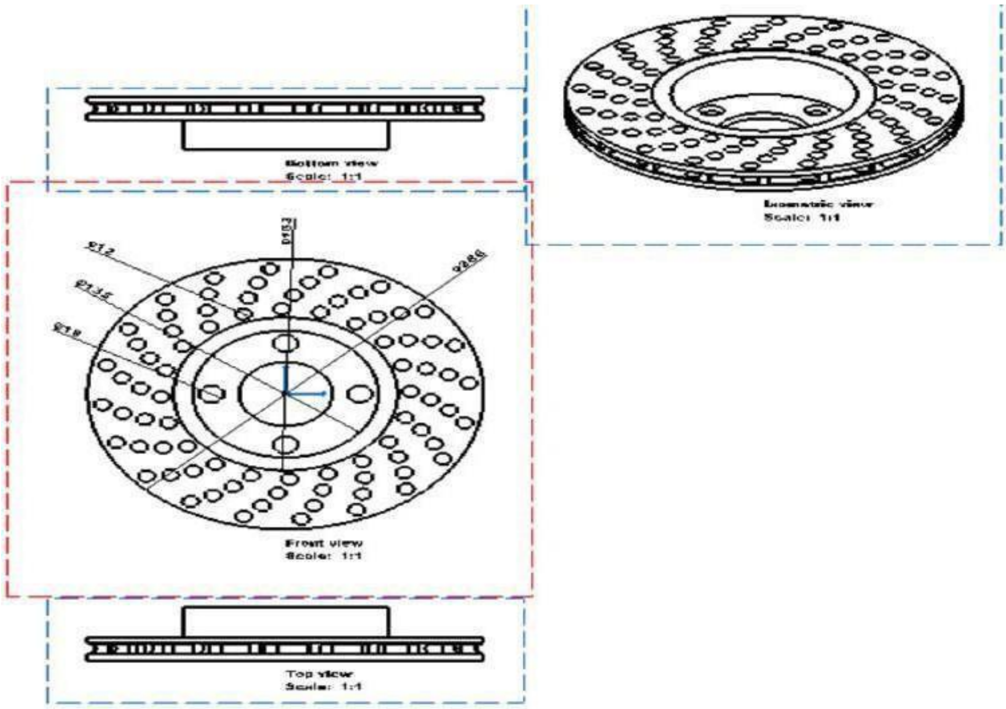


Fig. 3.9 Drafting of Drilled disc brake

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.
3. Review the results.

(1) Building a Model

Building a finite element model requires more of an ANSYS user's time than any other part of the analysis. First, you specify a job name and analysis title. Then, you use the PREP7 pre- processor to define the element types, element real constants, material properties, and the model geometry.

(2) Apply loads and obtain the solution

In this step, you use the SOLUTION processor to define the analysis type and analysis options, apply loads, specify load step options, and initiate the finite element solution. You also can apply loads using the PREP7 pre-processor.

(3) Review the results

Once the solution has been calculated, you can use the ANSYS postprocessors to review the results. Two postprocessors are available: POST1 and POST26.

LOADING OVERVIEW

The main goal of a finite element analysis is to examine how a structure or component responds to certain loading conditions. Specifying the proper loading conditions is, therefore, a key step in the analysis. The loads can be applied on the model in a variety of ways in the ANSYS program. Also, with the help of load step options, one can control how the loads are actually used during solution.

SOLUTION

In the solution phase of the analysis, the computer takes over and solves the simultaneous equations that the finite element method generates. The results of the solution are:

- nodal degree-of-freedom values, which form the primary solution
- derived values, which form the element solution

STRUCTURAL ANALYSIS

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.

TYPES:

The seven types of structural analyses available in the ANSYS family of products are explained below. The primary unknowns (nodal degrees of freedom) calculated in a structural analysis are *displacements*. Other quantities, such as strains, stresses, and reaction forces, are then derived from the nodal displacements.

Structural analyses are available in the ANSYS/Multi physics, ANSYS/Mechanical, ANSYS/Structural, and ANSYS/Linear Plus programs only.
One can perform the following types of structural analyses:

Static Analysis - Used to determine displacements, stresses, etc. under static loading conditions. It comprises of both linear and non linear static analysis. Non-linearities can include plasticity, stress stiffening, large deflection, large strain, hyper elasticity, contact surfaces, and creep.

Modal Analysis - Used to calculate the natural frequencies and mode shapes of a structure. Different mode extraction methods are available.

Harmonic Analysis - Used to determine the response of a structure to harmonically time-varying loads.

Transient Dynamic Analysis - Used to determine the response of a structure to arbitrarily time- varying loads. All non linearities mentioned under Static Analysis above are allowed.
Spectrum Analysis - An extension of the modal analysis, used to calculate stresses and strains due to a response spectrum or a PSD input (random vibrations).

Buckling Analysis - Used to calculate the buckling loads and determine the buckling mode shape. Both linear (eigen value) buckling and nonlinear buckling analyses are possible.

Explicit Dynamics Analysis - ANSYS provides an interface to the LS-DYNA explicit finite element program and is used to calculate fast solutions for large deformation dynamics and complex contact problems.

In addition to the above analysis types, several special-purpose features are available:

- Fracture mechanics
- Composites
- Fatigue
- p-Method

FATIGUE ANALYSIS

While many parts may work well initially, they often fail in service due to fatigue failure caused by repeated cyclic loading. Characterizing the capability of a material to survive the many cycles a component may experience during its lifetime is the aim of fatigue analysis. In a general sense, Fatigue Analysis has three main methods, Strain Life, Stress Life, and Fracture Mechanics; the first two being available within the ANSYS Fatigue Module. The Stain Life approach is widely used at present. Strain can be directly measured and has been shown to be an excellent quantity for characterizing low-cycle fatigue. Strain Life is typically concerned with crack initiation, whereas Stress Life is concerned with total life and does not distinguish between initiation and propagation. In terms of cycles, Strain Life typically deals with a relatively low number of cycles and therefore addresses Low Cycle Fatigue (LCF), but works with high numbers of cycles as well. Low Cycle Fatigue usually refers to fewer than 105 cycles. Stress Life is based on S-N curves (Stress – Cycle curves) and has traditionally dealt with relatively high numbers of cycles and therefore addresses High Cycle Fatigue (HCF), greater than 105 cycles inclusive of infinite life. Fracture Mechanics starts with an assumed flaw of known size and determines the crack's growth as is therefore sometimes referred to as "Crack Life". Facture Mechanics is widely used to determine inspection intervals.

inspection technique, the smallest detectable flaw size is know. From this detectable flaw size we can calculate the time required for the crack to grow to a critical size. We can then determine our inspection interval to be less than the crack growth time. Sometimes, Strain Life methods are used to determine crack initiation with Fracture Mechanics used to determine the crack life. In this situation, crack initiation plus crack life equals the total life of the part.

Analysis Decisions Common Decisions for Fatigue Analysis
There are 5 common input decision topics upon which your fatigue results are dependent upon. These fatigue decisions are grouped into the types listed below:

- Fatigue Analysis Type
- Loading Type
- Mean Stress Effects
- Multiaxial Stress Correction
- Fatigue Modification Factor

Types of Cyclic Loading

Unlike static stress, which is analysed with calculations for a single stress state, fatigue damage occurs when stress at a point change over time. There are essentially four classes of fatigue loading, with the ANSYS Fatigue Module currently supporting the first three:

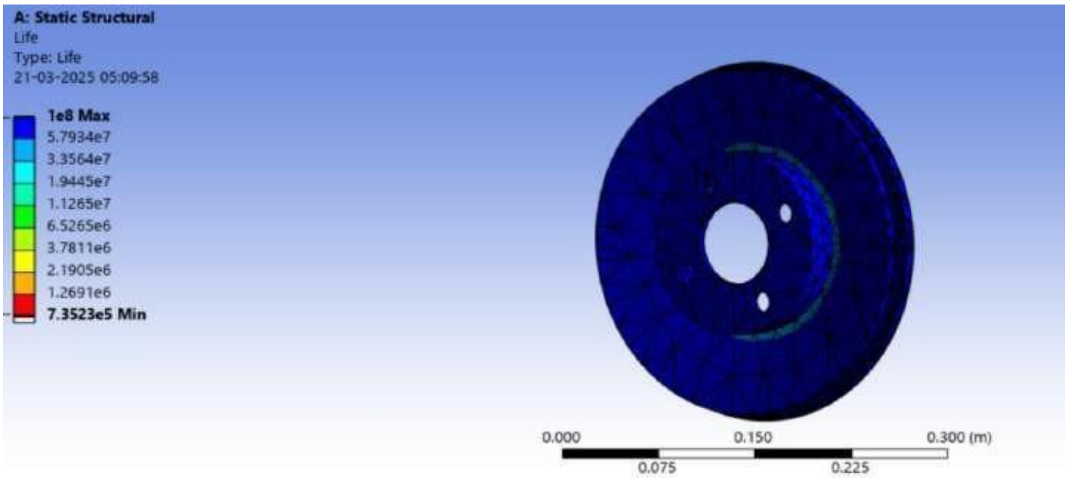
- Constant amplitude, proportional loading
- Constant amplitude, non-proportional loading
- Non-constant amplitude, proportional loading
- Non-constant amplitude, non-proportional loading

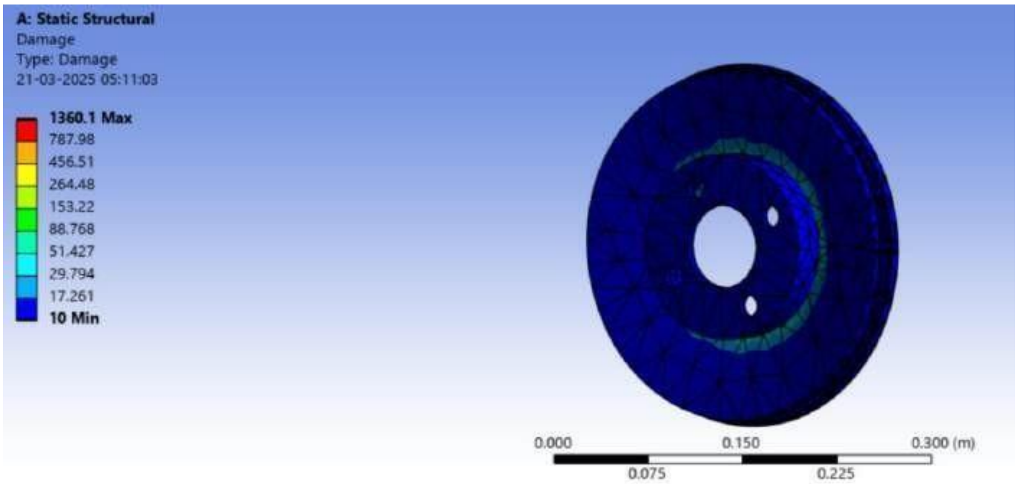
RESULTS:

2.1 *FATIGUE ANALYSIS*

(1) Ventilated disc brake

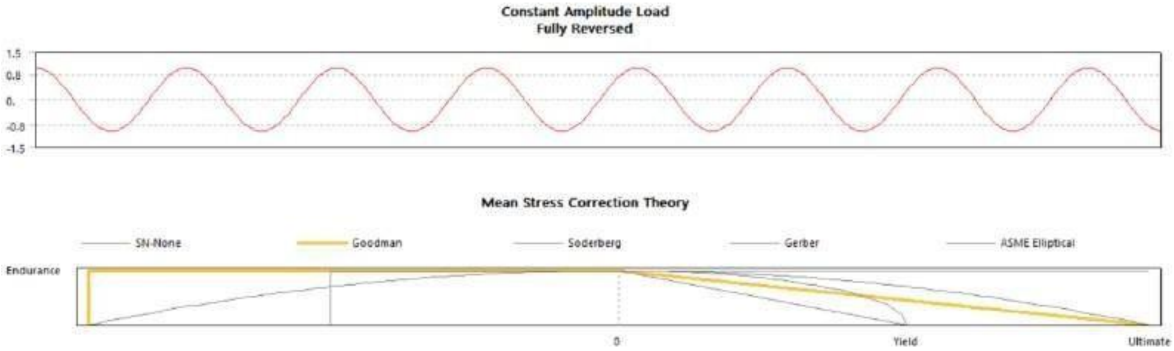
(a) Aluminium :



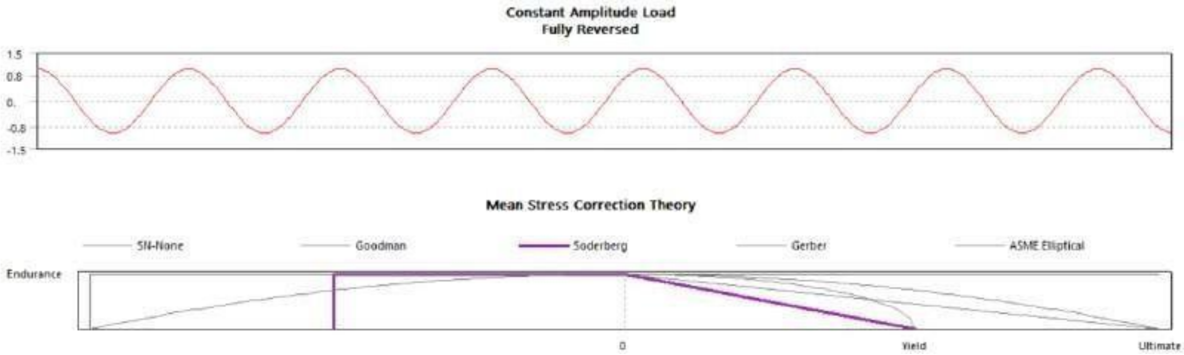


The above figures display the Life and damage of Ventilated disc brake made of Aluminium .

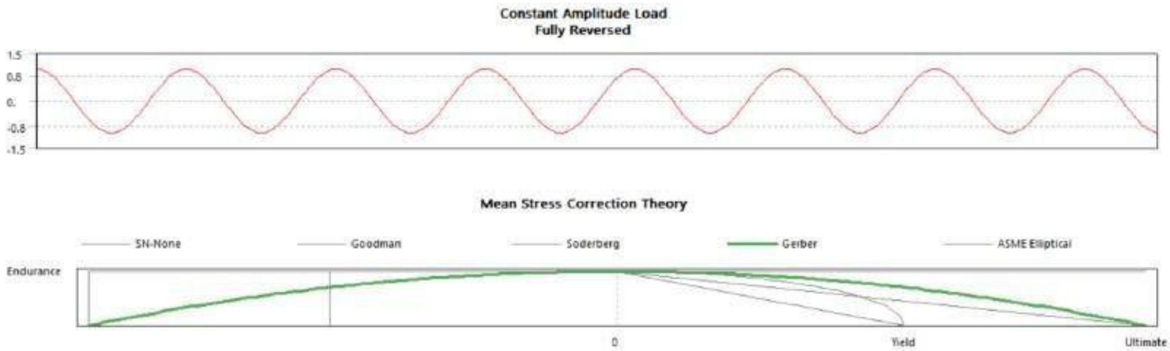
FATIGUE TOOL PLOTS FOR ALLUMINIUM VENTILATED DISC: GOODMAN FATIGUE PLOT:



SODERBERG FATIGUE PLOT:



GERBER FATIGUE PLOT:



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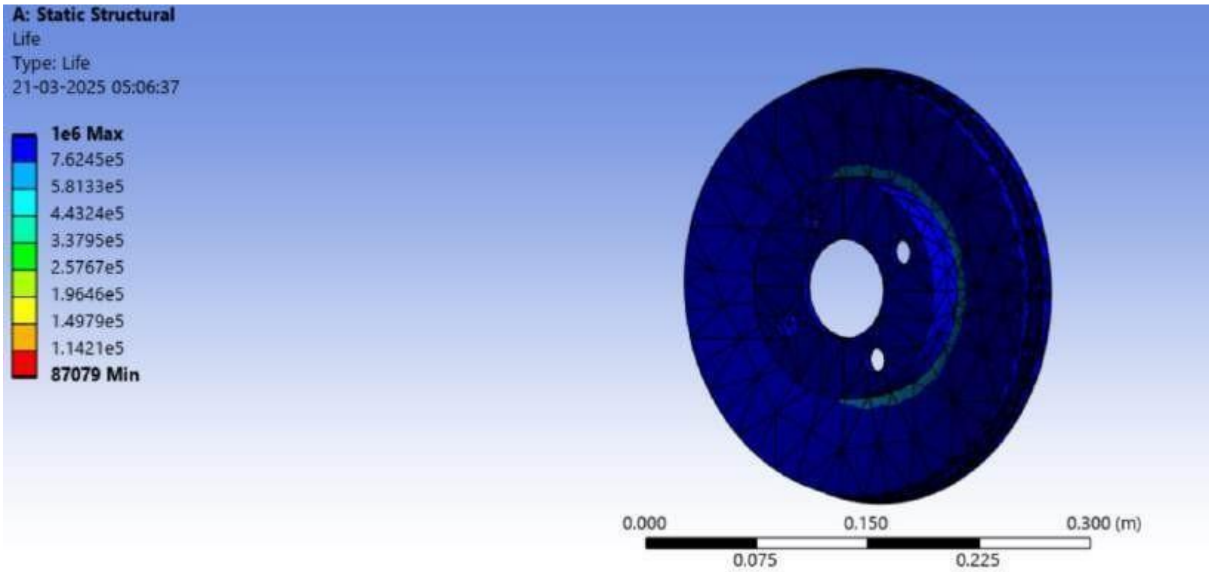
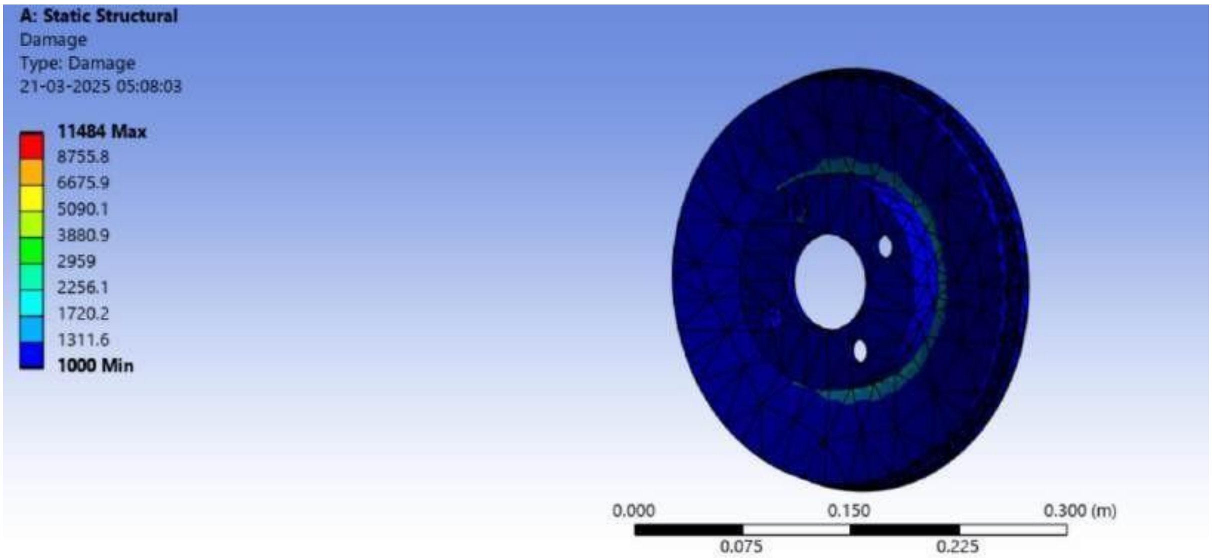
(b) Stuctural Steel





The above figures display the Life and damage of Ventilated disc brake made of structural steel FATIGUE TOOL PLOTS FOR STRUCTURAL VENTILATED DISC:

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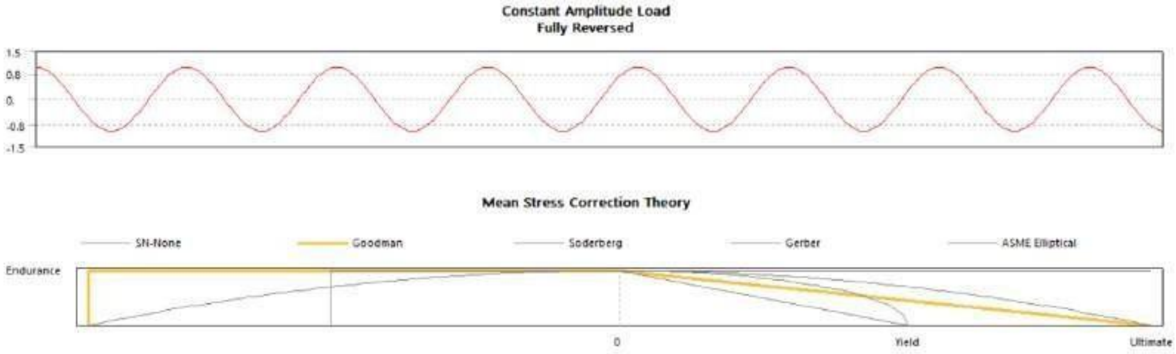
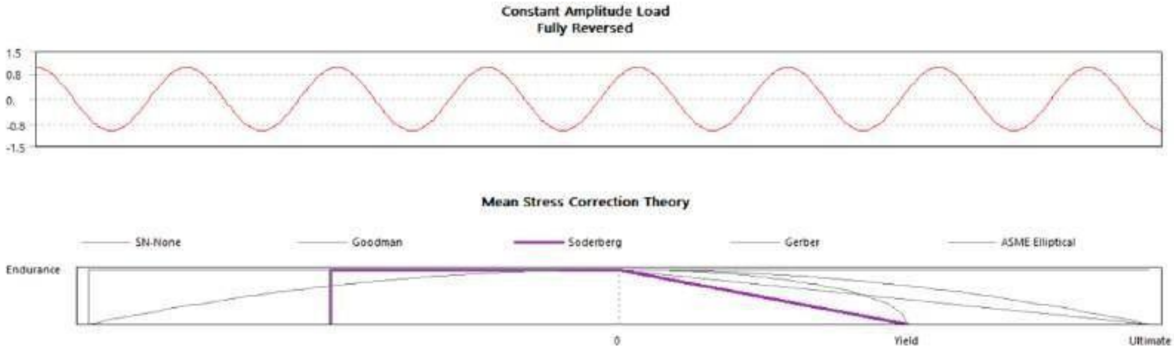
GOODMAN FATIGUE PLOT:



SODERBERG FATIGUE PLOT:



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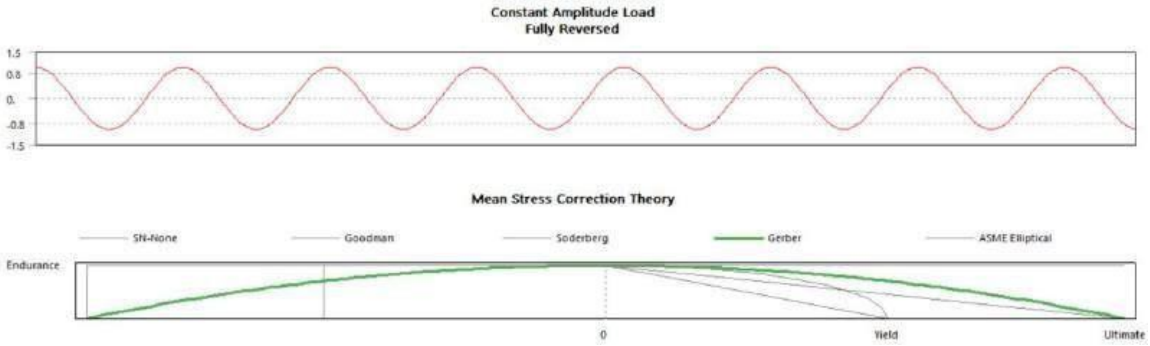

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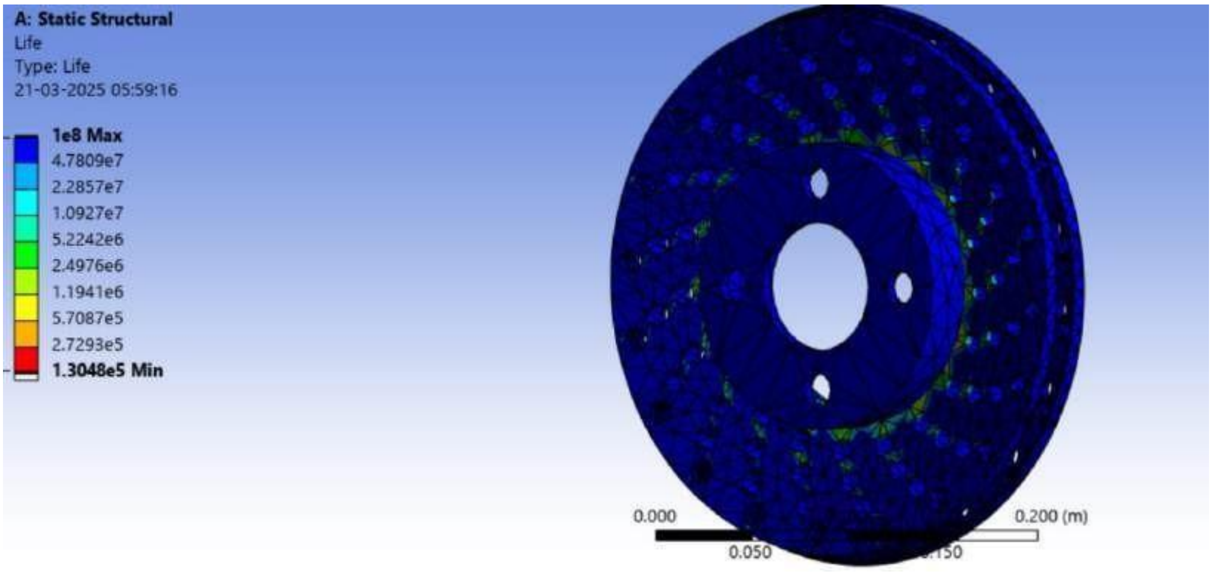
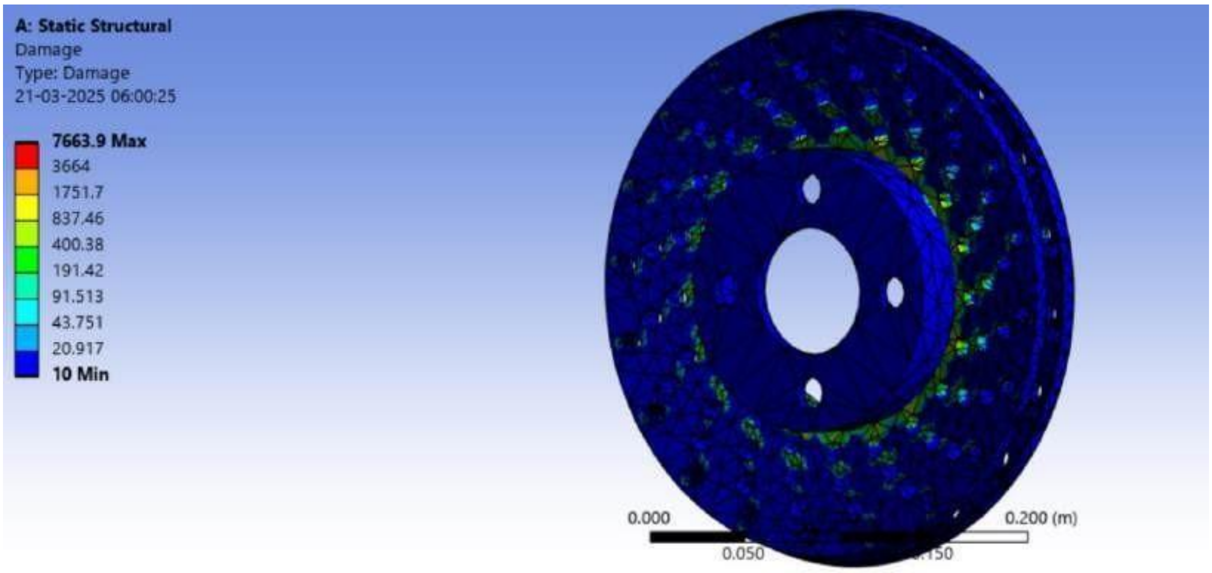
2) DRILLED DISC

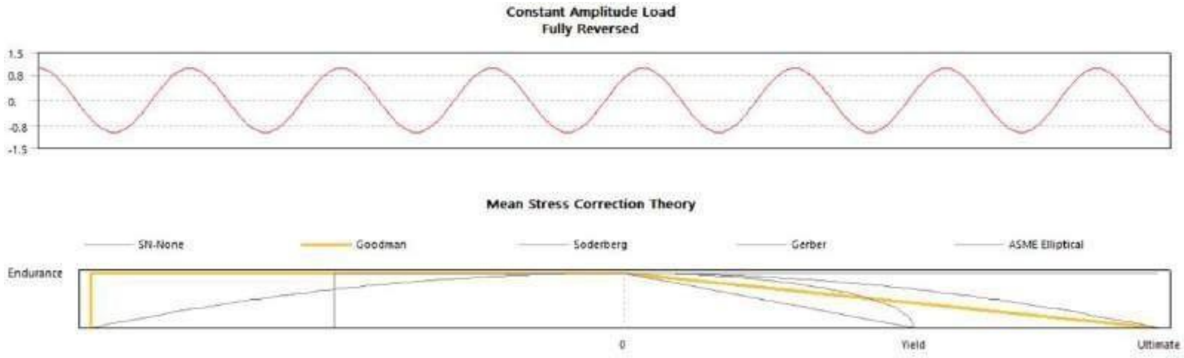
(a) Aluminium :



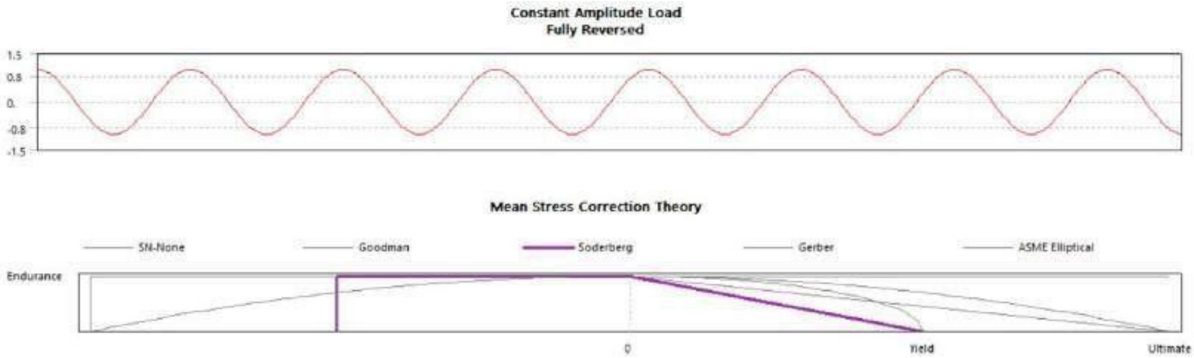


The above figures display the Life and damage of drilled disc brake made of Aluminium .

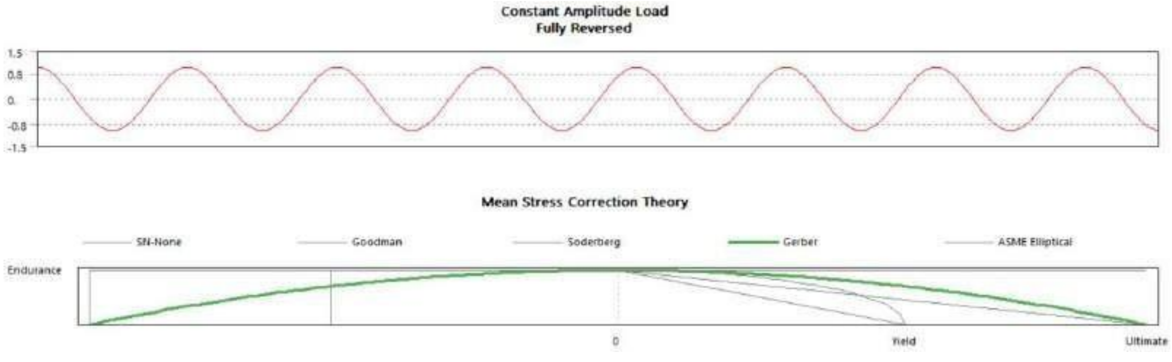
FATIGUE TOOL PLOTS FOR ALLUMINIUM VENTILATED DISC: GOODMAN FATIGUE PLOT:



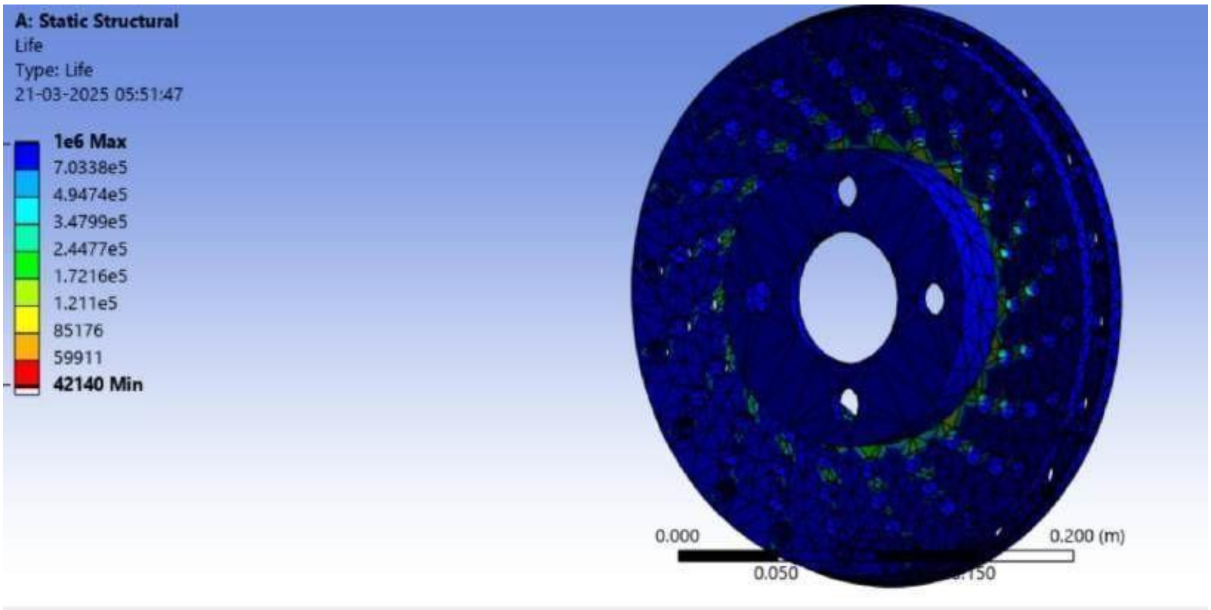
SODERBERG FATIGUE PLOT:

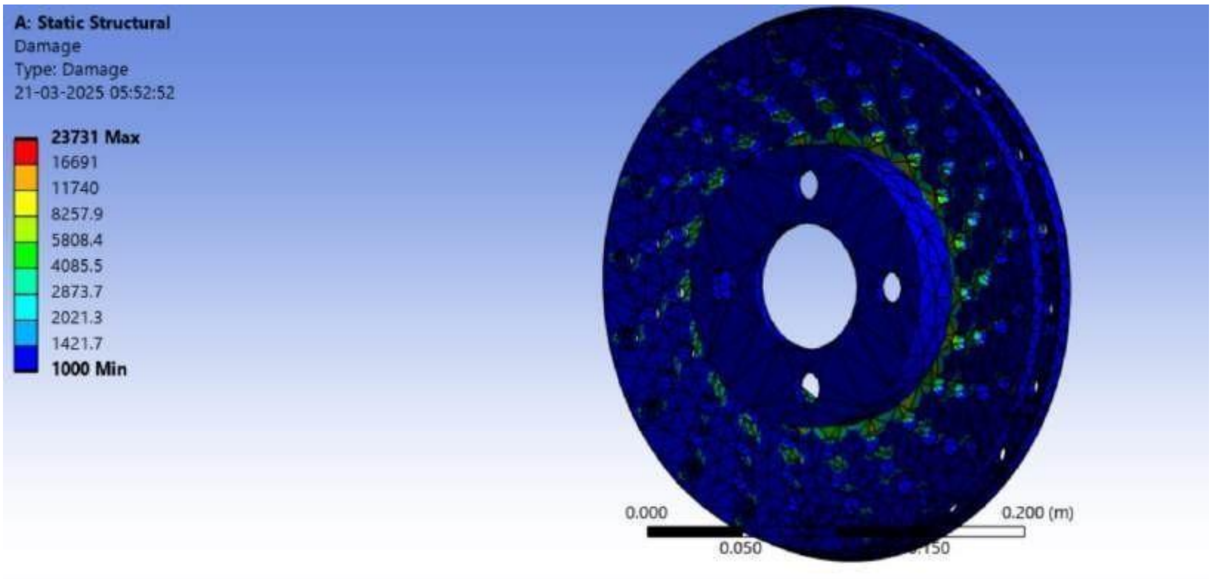


GERBER FATIGUE PLOT:



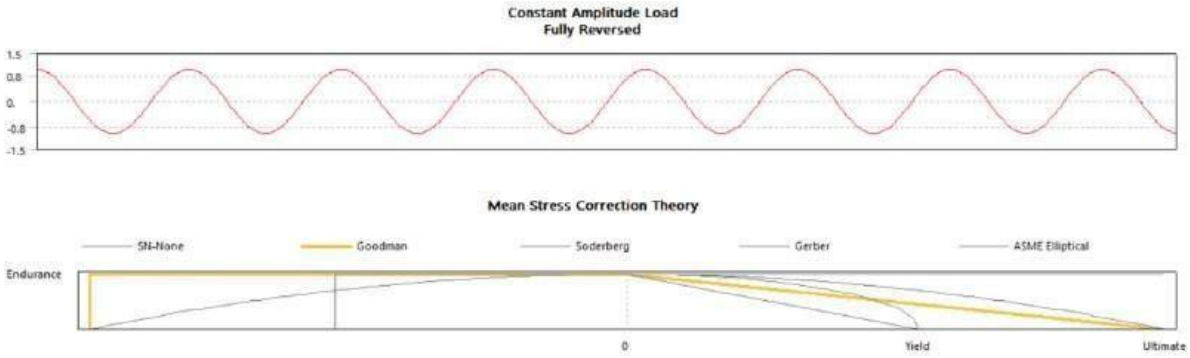
(b) Stuctural Steel





The above figures display the Life and damage of drilled disc brake made of Structural steel .

FATIGUE TOOL PLOTS FOR STRUCTURAL DRILLED DISC: GOODMAN FATIGUE PLOT:



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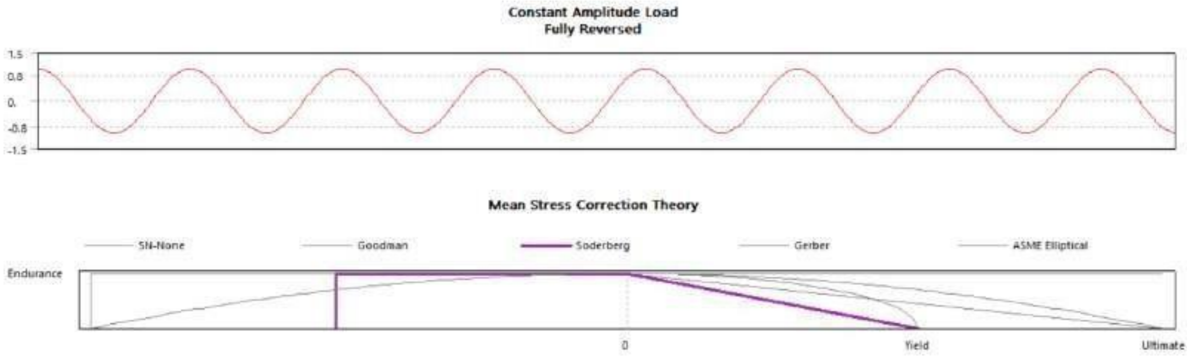

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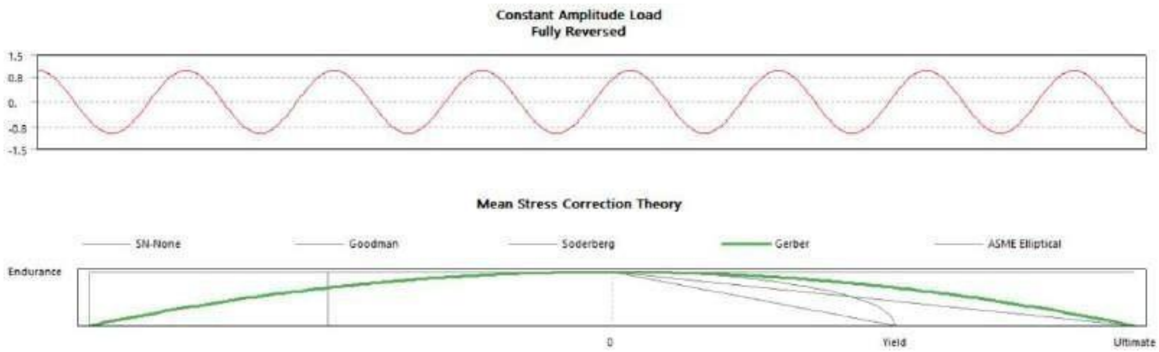
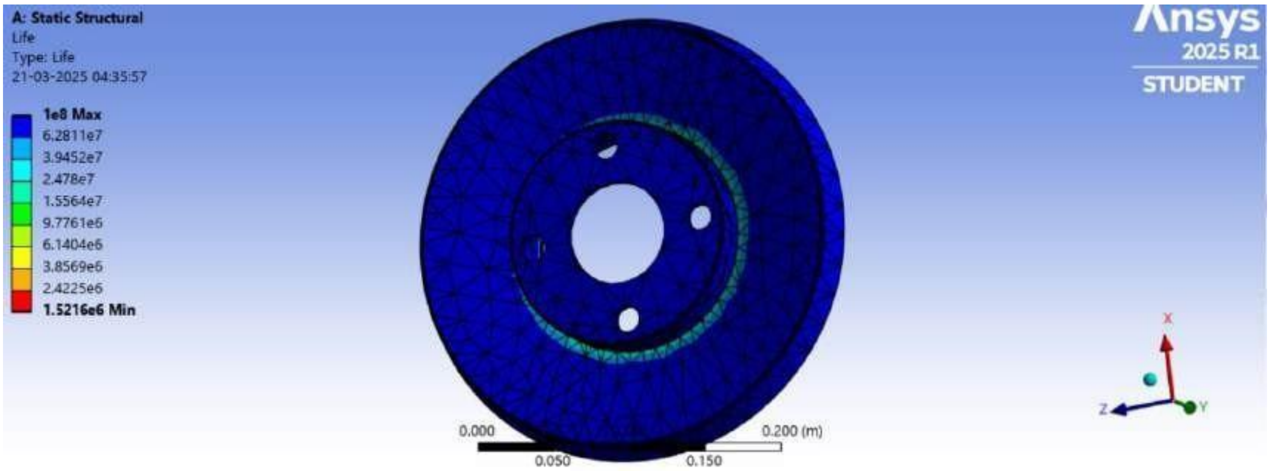
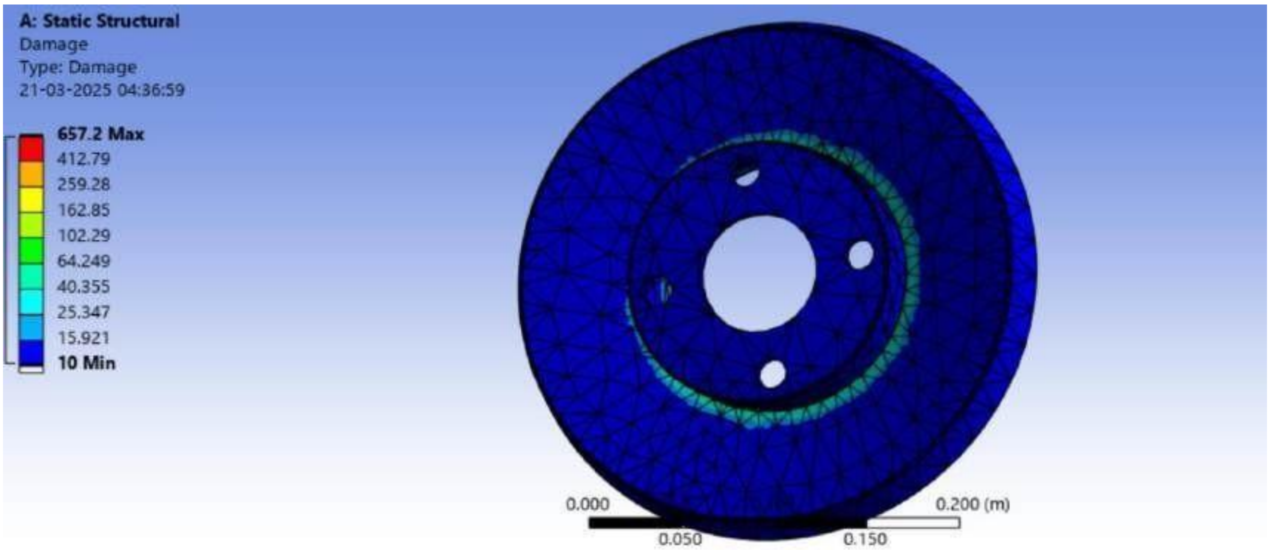


(1) Solid disc brake

a) Aluminium :

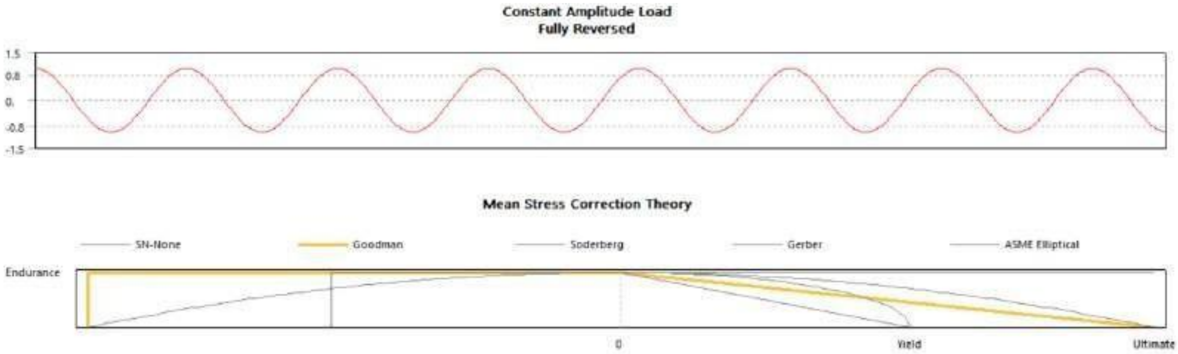




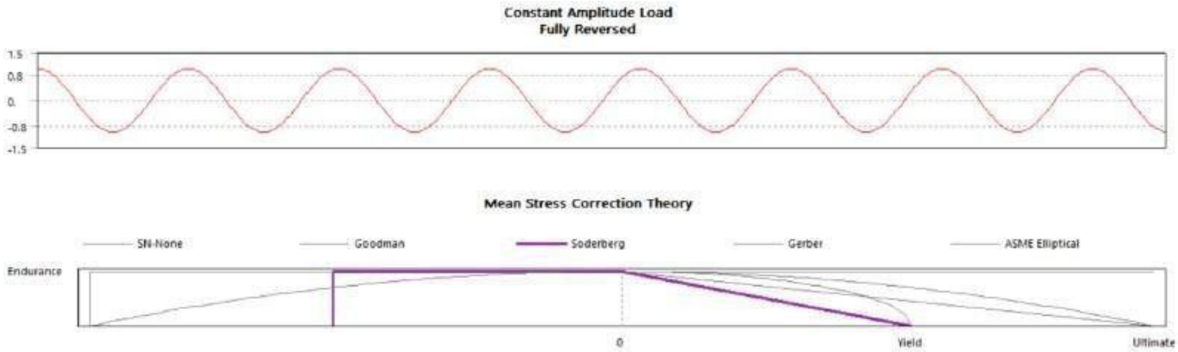
The above figures display the Life and damage of Solid disc brake made of Aluminium .

FATIGUE TOOL PLOTS FOR ALLUMINIUM SOLID DISC:

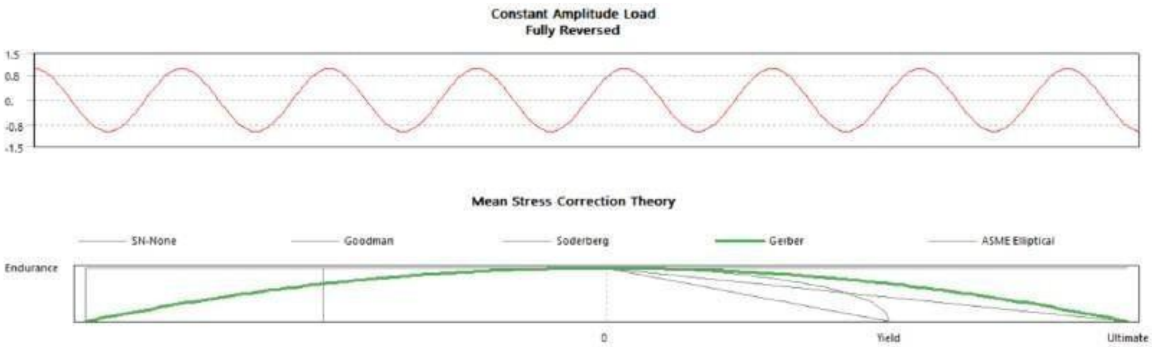
GOODMAN FATIGUE PLOT:



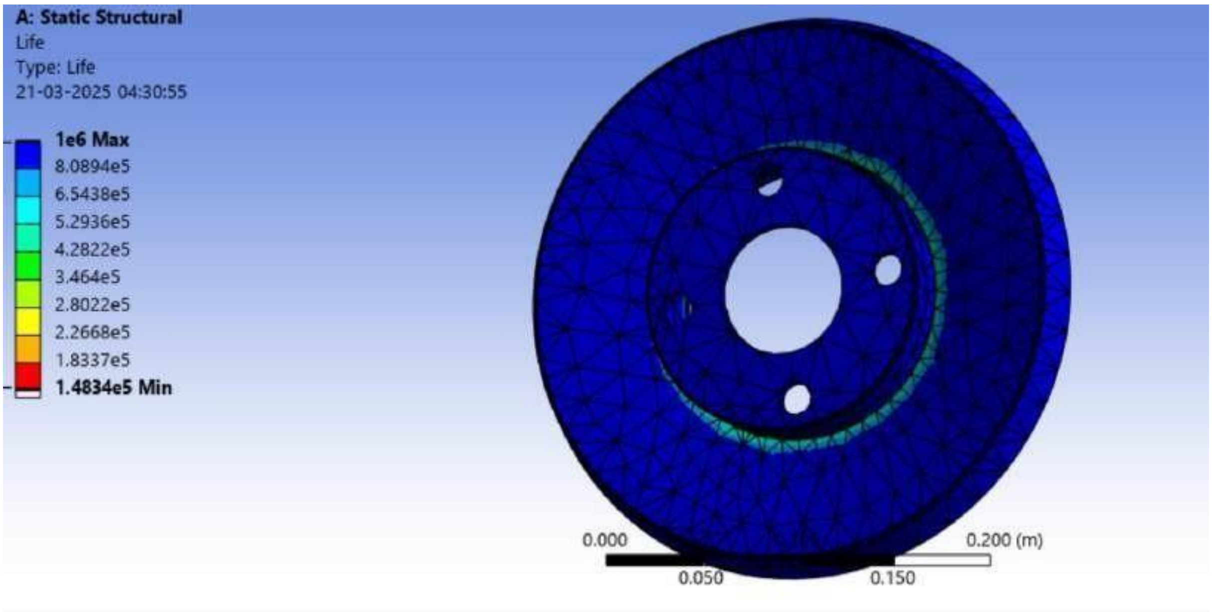
SODERBERG FATIGUE PLOT:

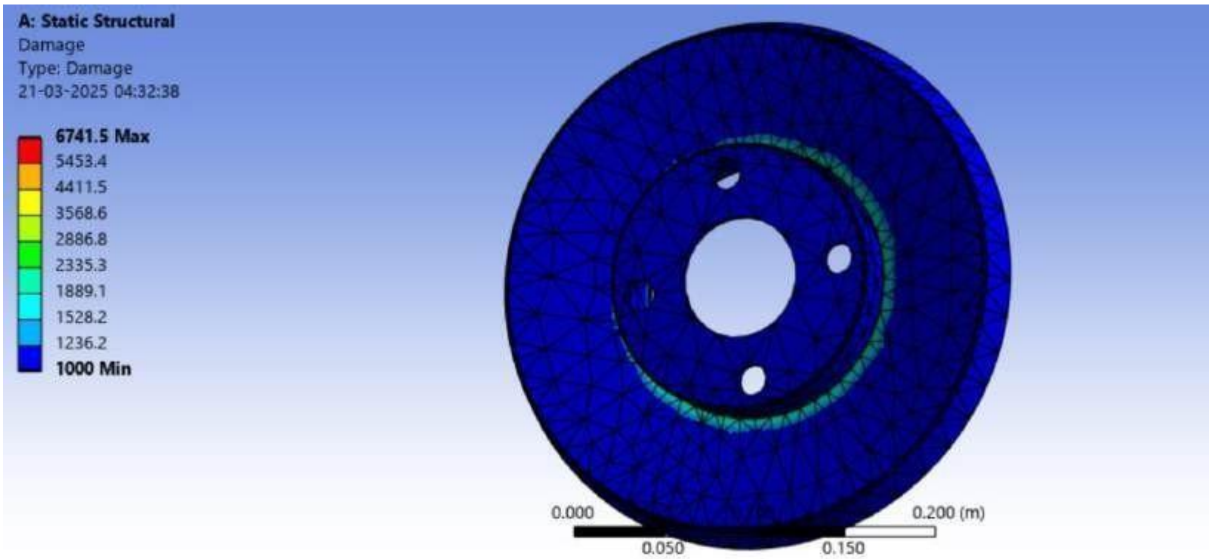


GERBER FATIGUE PLOT:



(b) Stuctural Steel

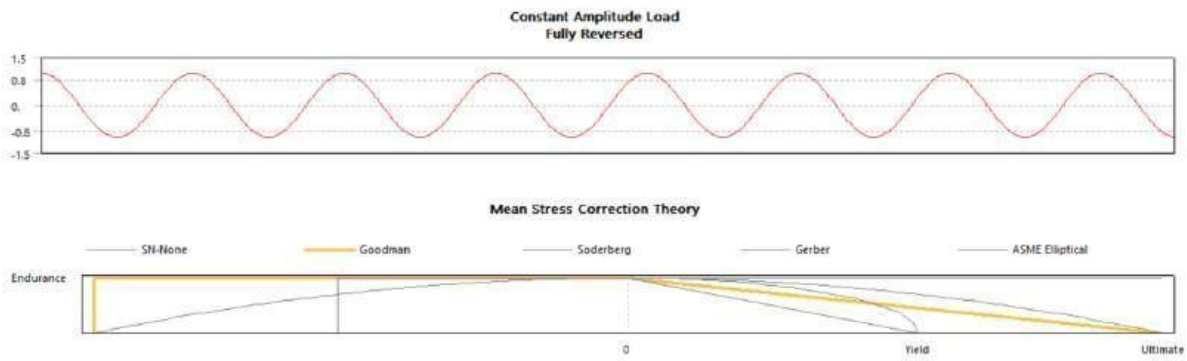




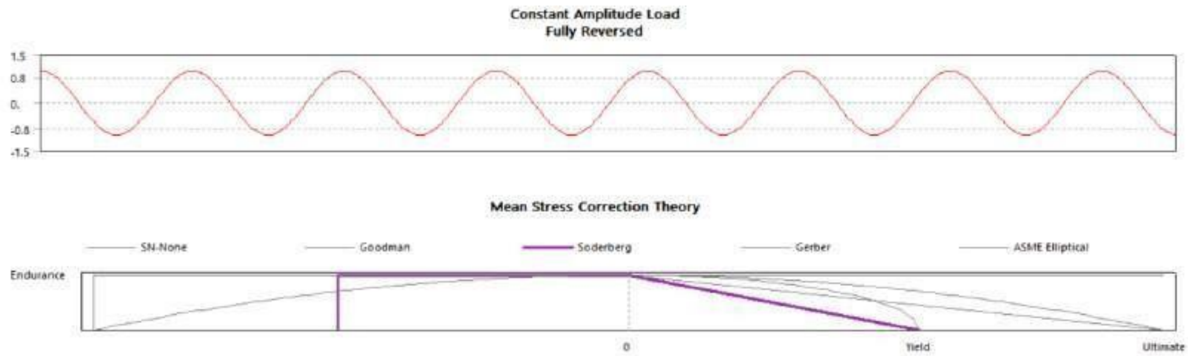
The above figures display the Life and damage of Solid disc brake made of structural steel .

FATIGUE TOOL PLOTS FOR STRUCTURAL STEEL SOLID DISC:

GOODMAN FATIGUE PLOT:



SODERBERG FATIGUE PLOT:



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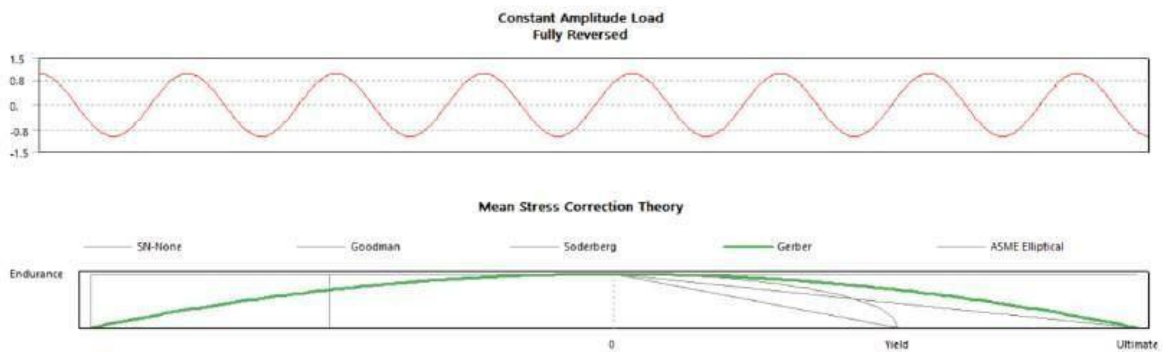
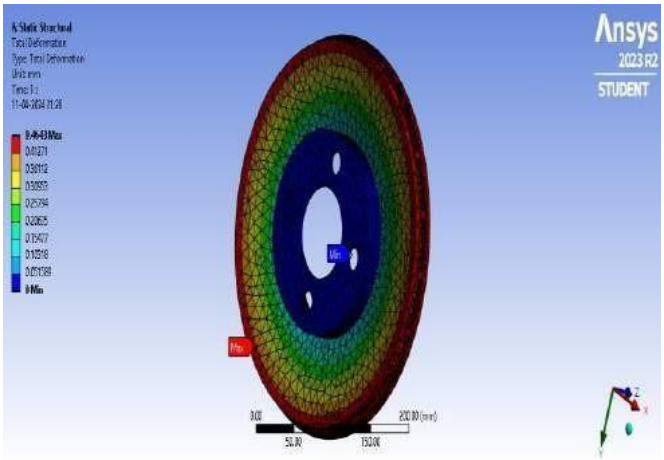
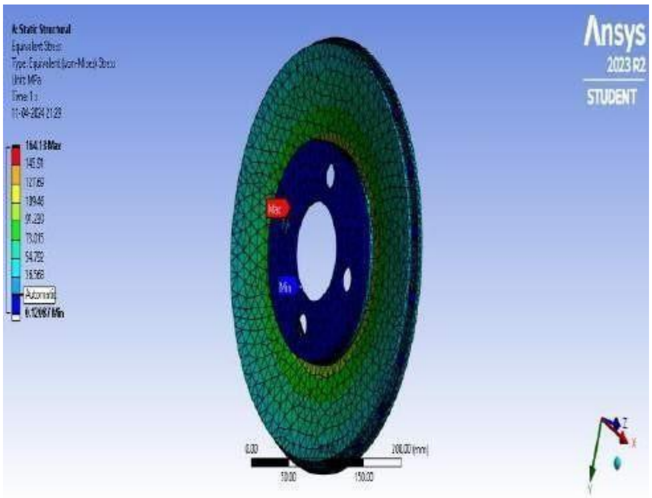


STRUCTURAL ANALYSIS

(1) <u>Ventilated disc brake</u>

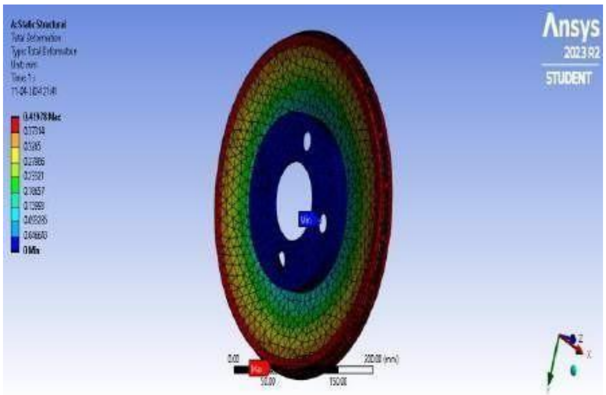
(a) Aluminium metal matrix

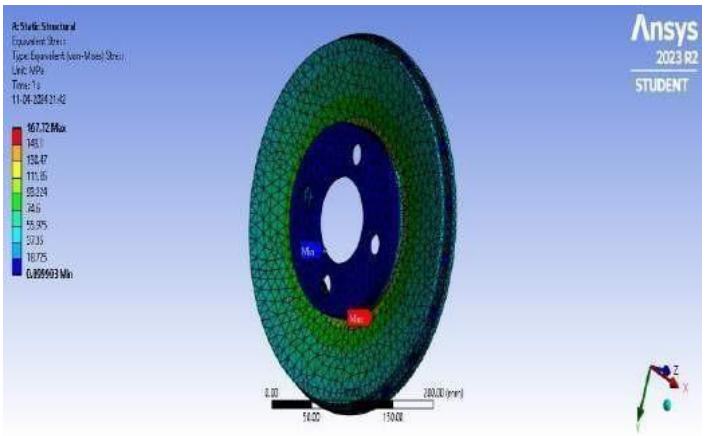




The above figures display the Total deformation and Equivalent (von-Mises) stress of Ventilated disc brake made of Aluminium. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.464 mm and 164.3 MPa respectively.

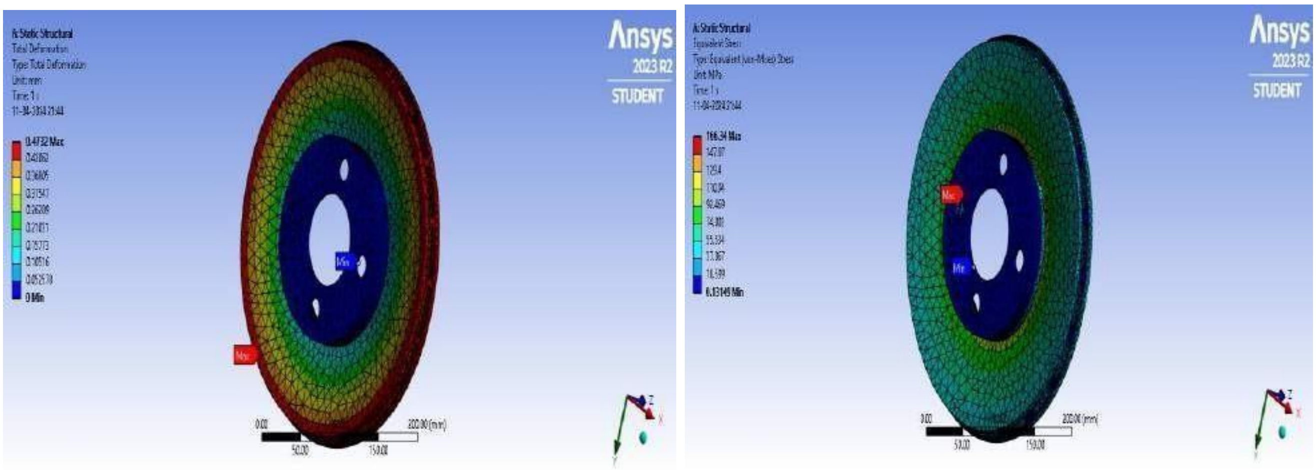
(b) Gray Cast Iron





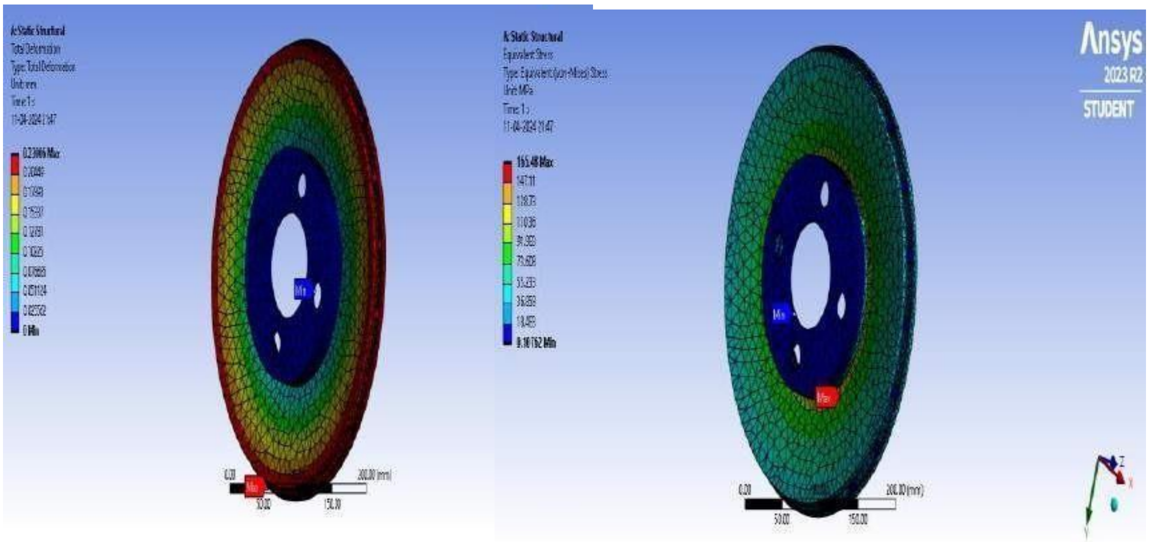
The above figures display the Total deformation and Equivalent (von-Mises) stress of Ventilated disc brake made of Gray Cast Iron. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.419 mm and 167.7 MPa respectively.

(c) Titanium Alloy



The above figures display the Total deformation and Equivalent (von-Mises) stress of Ventilated disc brake made of Titanium alloy. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.473m and 166.34MPa respectively.

(d) Structural steel



The above figures display the Total deformation and Equivalent (von-Mises) stress of Ventilated disc brake made of Structural alloy. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0,23mm and 165.48 MPa respectively.

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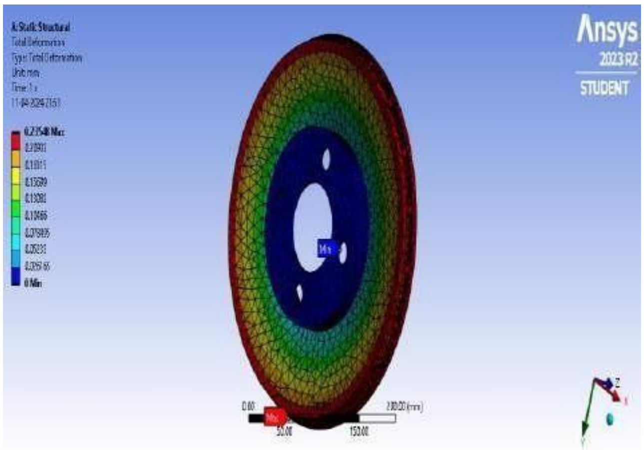
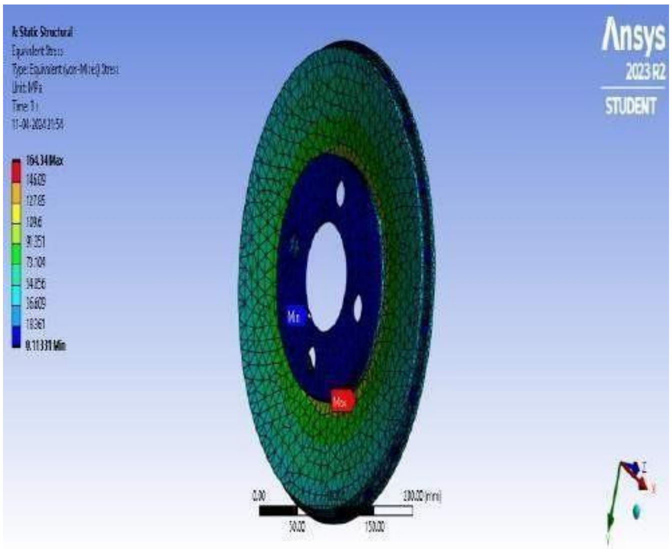
(e) Carbon ceramic

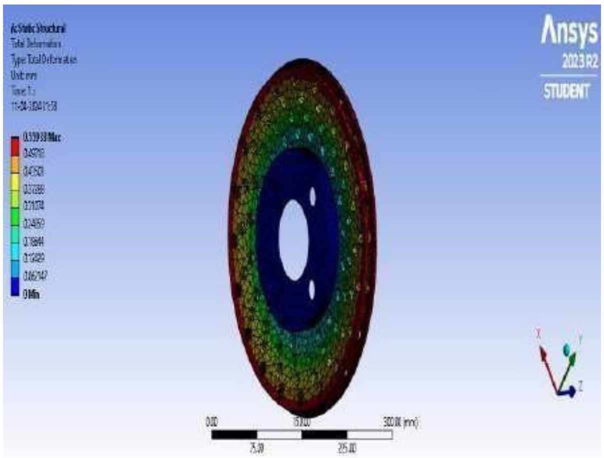


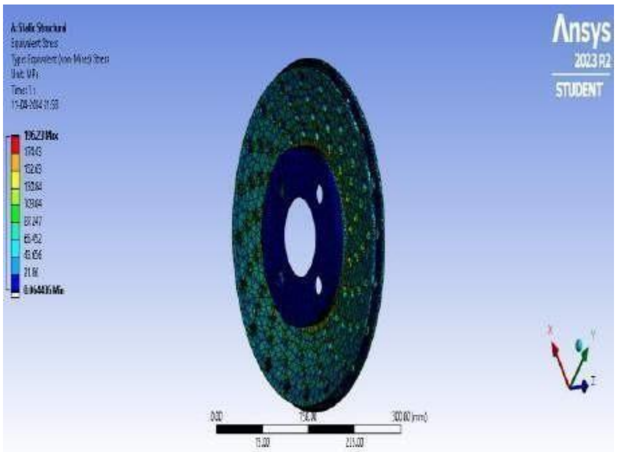


The above figures display the Total deformation and Equivalent (von-Mises) stress of Ventilated disc brake made of Carbon Ceramic. As it is evident from the figures, the maximum total deformation and equivalent (von-Mises) stress are represented by red colour and the values being,
0.235 mm and 164.34 MPa respectively.

(2) <u>Drilled disc brake</u>

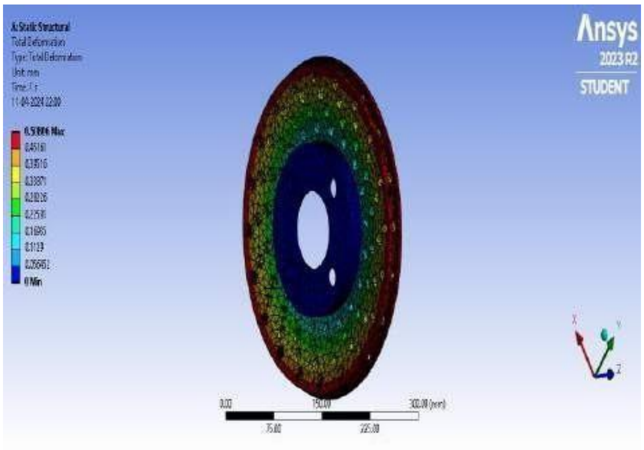
(a) Aluminium metal matrix

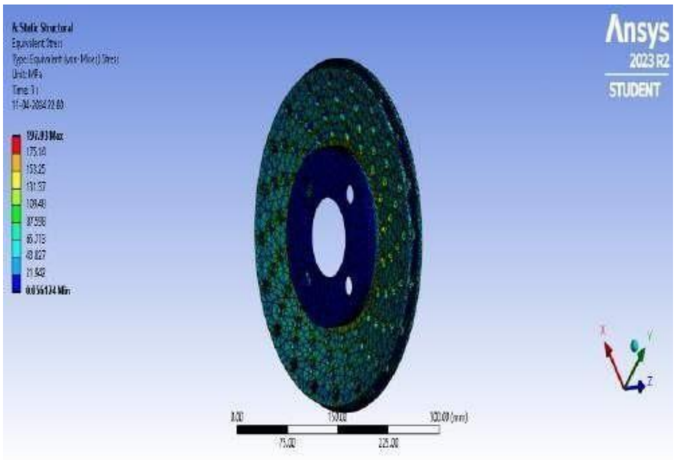




The above figures display the Total deformation and Equivalent (von-Mises) stress of Drilled disc brake made of Aluminium. As it is evident from the figures, the maximum total deformation and equivalent (von-Mises) stress are represented by red colour and the values being, 0.559 mm and
196.23 MPa respectively.

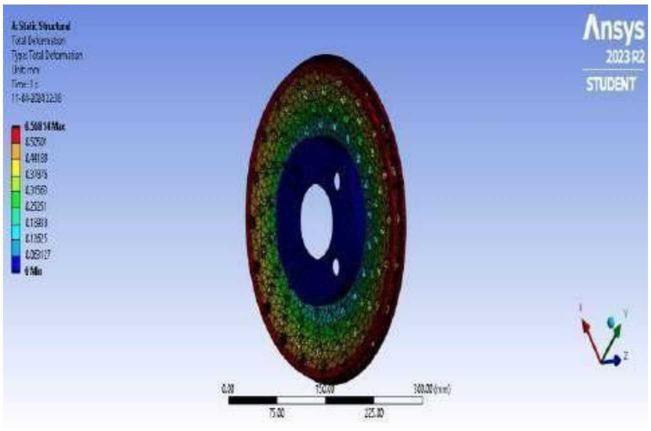
(b) Gray Cast Iron

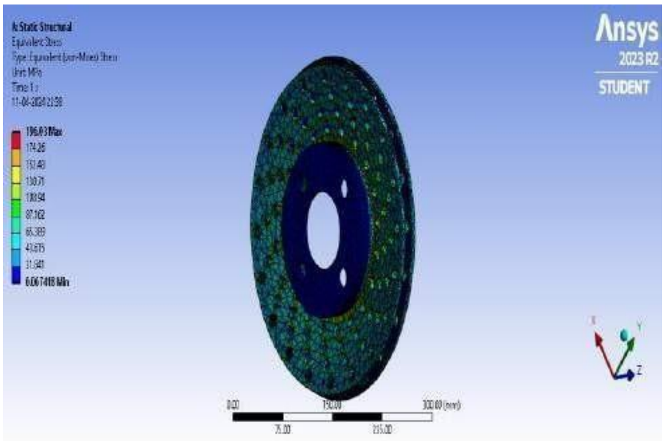




The above figures display the Total deformation and Equivalent (von-Mises) stress of Drilled disc brake made of Gray Cast Iron. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.508 mm and 197.03 MPa respectively.

(c) Titanium Alloy

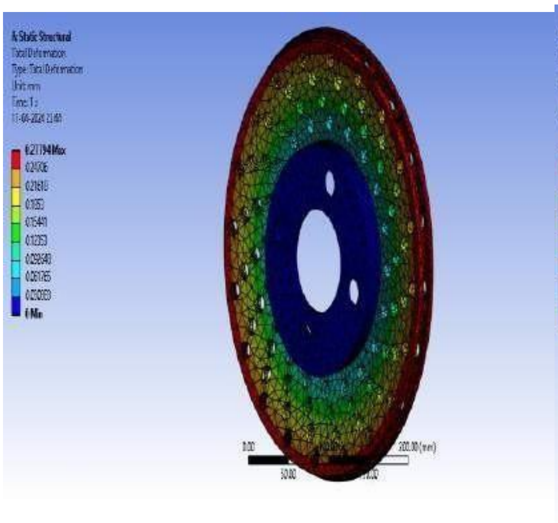


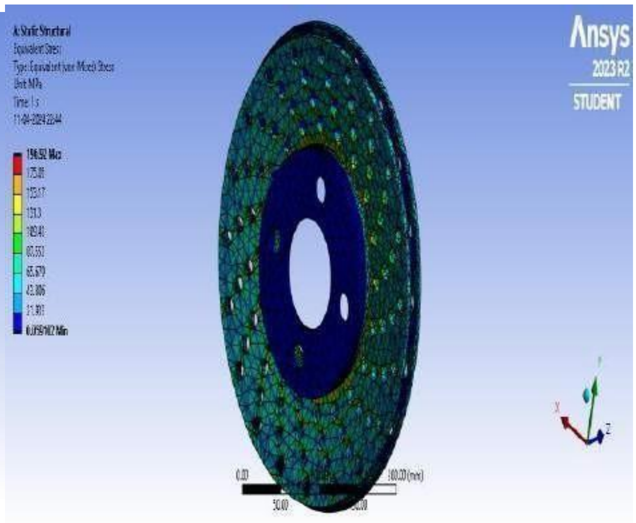


The above figures display the Total deformation and Equivalent (von-Mises) stress of Drilled disc brake made of Titanium alloy. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.568 mm and 196.03MPa respectively.

(d)
(e)
(f)
(g)
(h)
(i)

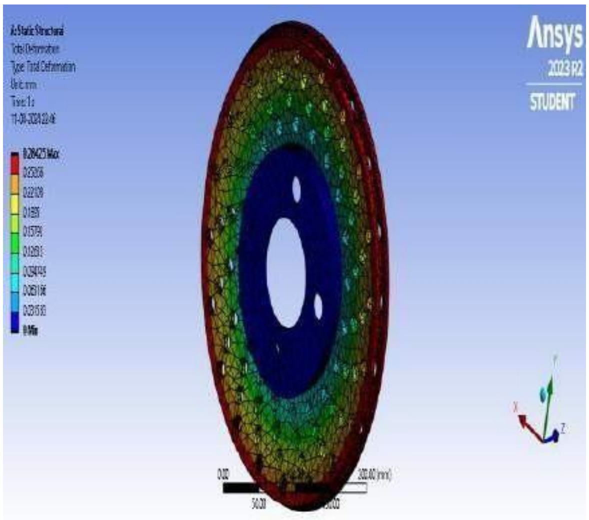
(j) Structural steel

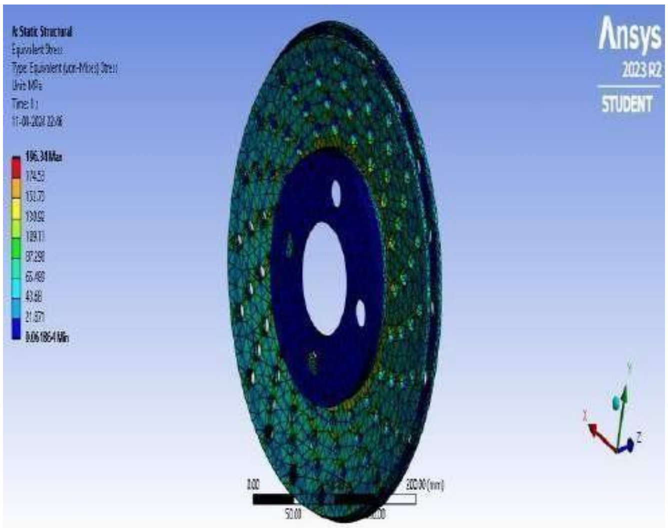




The above figures display the Total deformation and Equivalent (von-Mises) stress of Drilled disc brake made of Structural Steel. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.277 mm and 165.48 Mpa respectively.

(k) Carbon ceramic

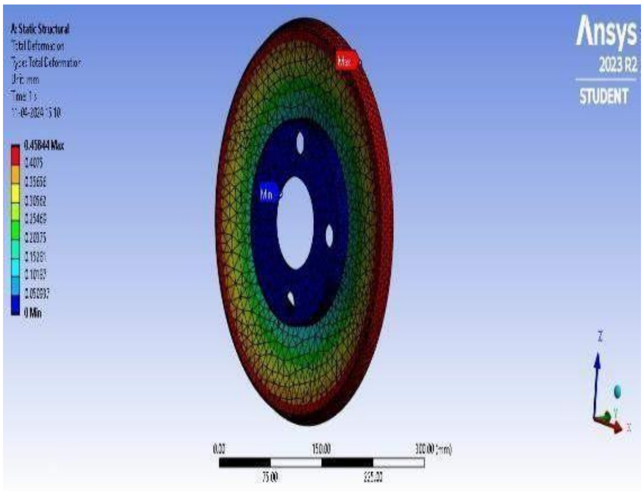


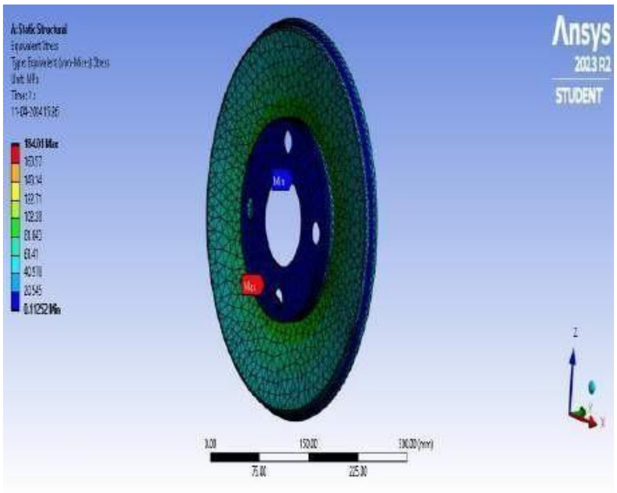


The above figures display the Total deformation and Equivalent (von-Mises) stress of Drilled disc brake made of Carbon Ceramic. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.284 mm and 196.34 MPa respectively.

(3) Solid disc brake

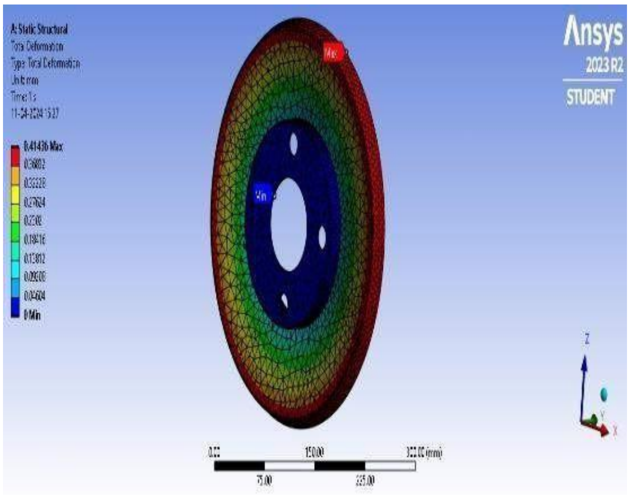
(a) Aluminium metal matrix

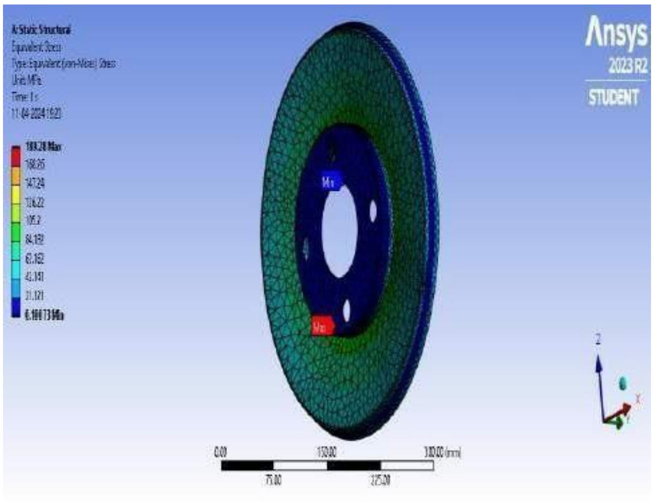




The above figures display the Total deformation and Equivalent (von-Mises) stress of Solid disc brake made of Aluminium. As it is evident from the figures, the maximum total deformation and equivalent (von-Mises) stress are represented by red colour and the values being, 0.458 mm and 184.01 MPa respectively.

(b) Gray Cast Iron





The above figures display the Total deformation and Equivalent (von-Mises) stress of Solid disc brake made of Gray Cast Iron. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.414 mm and 189.28 MPa respectively.

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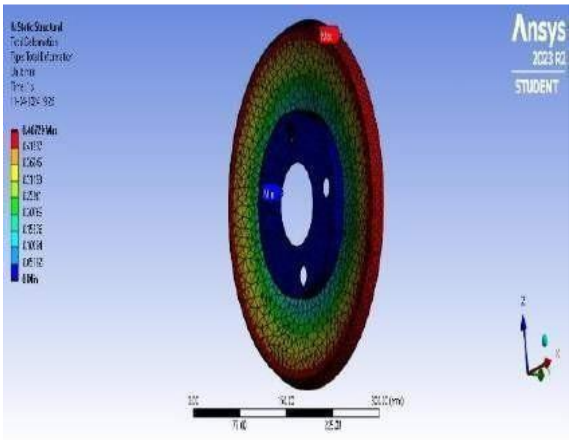
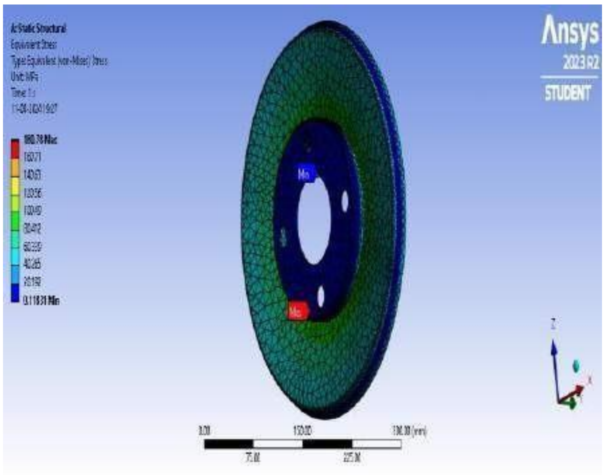
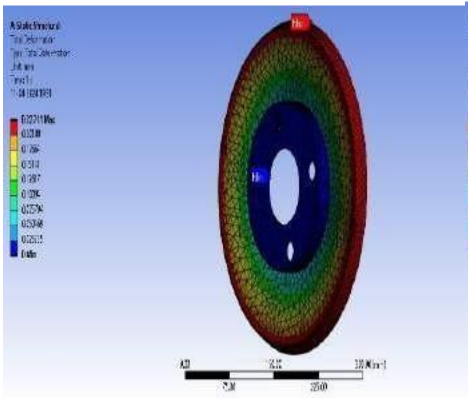
(c) Titanium Alloy

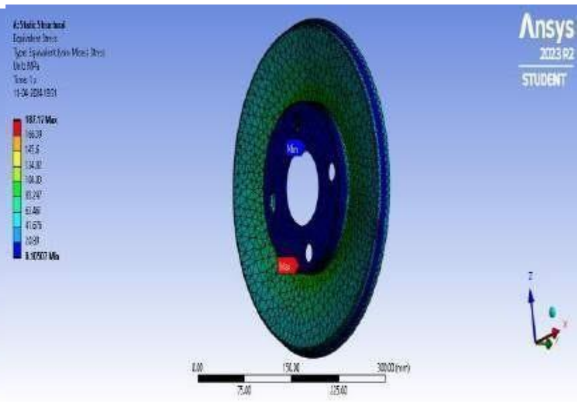




The above figures display the Total deformation and Equivalent (von-Mises) stress of Solid disc brake made of Titanium Alloy. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.467 mm and 180.78 MPa respectively.

(d) Structural steel





The above figures display the Total deformation and Equivalent (von-Mises) stress of Solid disc brake made of Structural steel. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.227mm and 187.17 MPa respectively.

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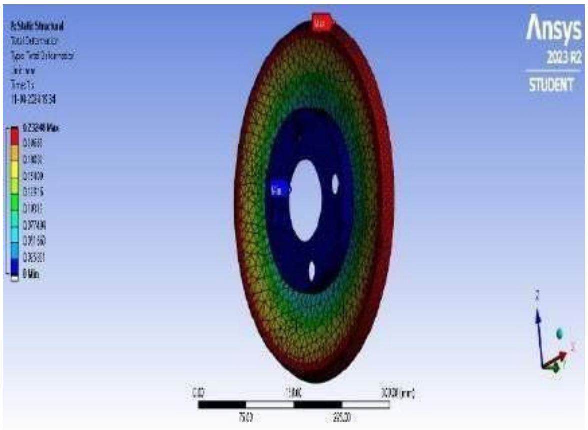
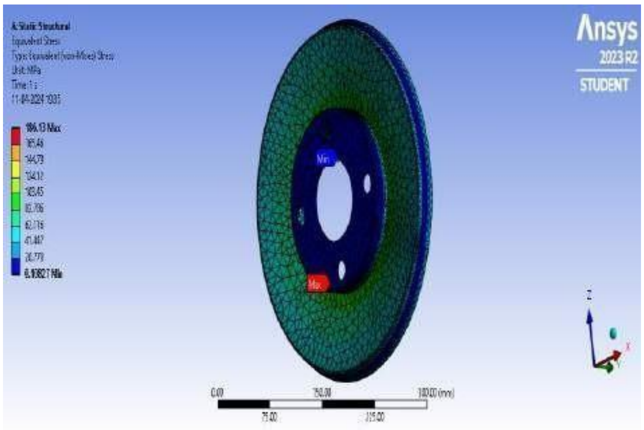
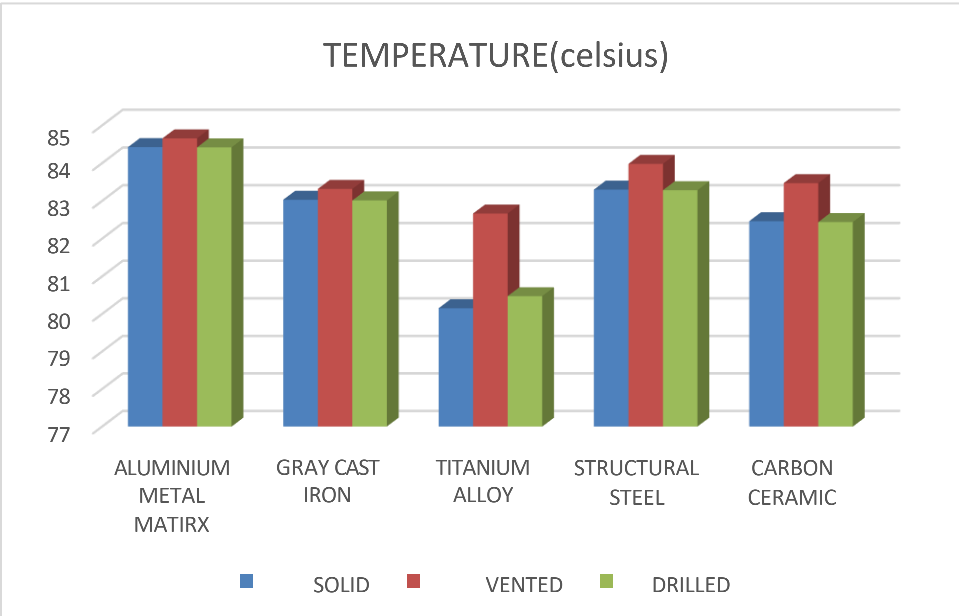
(e) Carbon ceramic



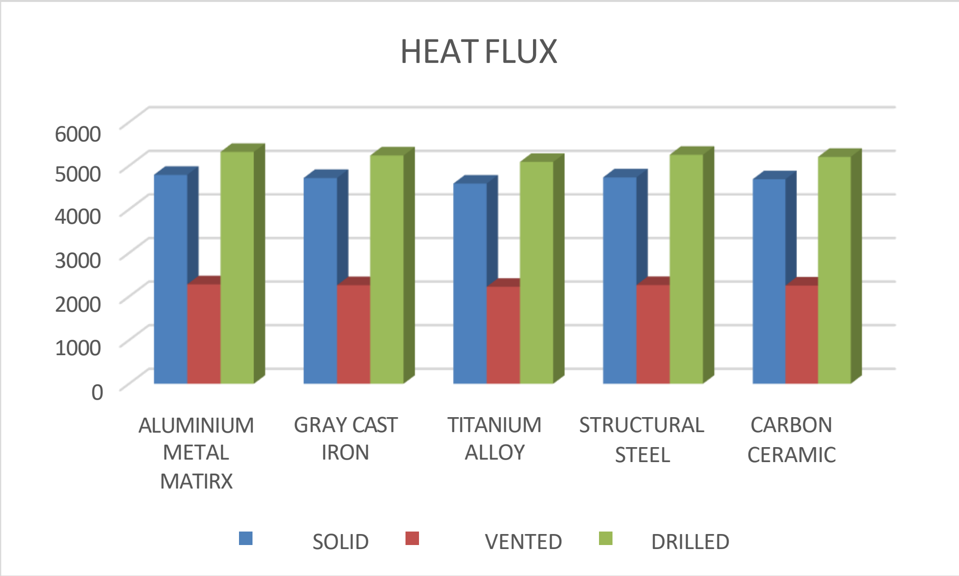


The above figures display the Total deformation and Equivalent (von-Mises) stress of Solid disc brake made of Carbon Ceramic. As it is evident from the figures, the maximum total deformation and equivalent (von- Mises) stress are represented by red colour and the values being, 0.232 mm and 186.13 MPa respectively.

GRAPHS

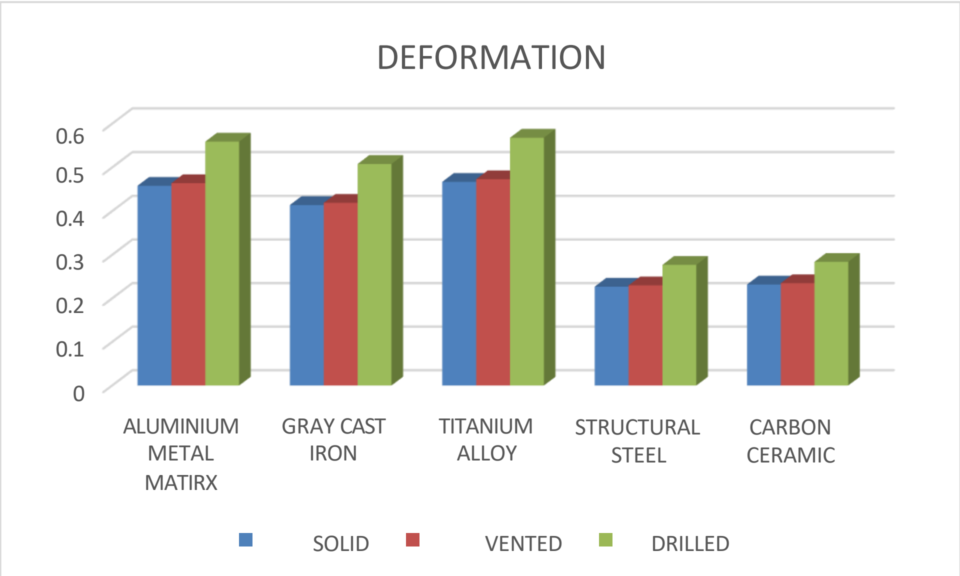


(a)

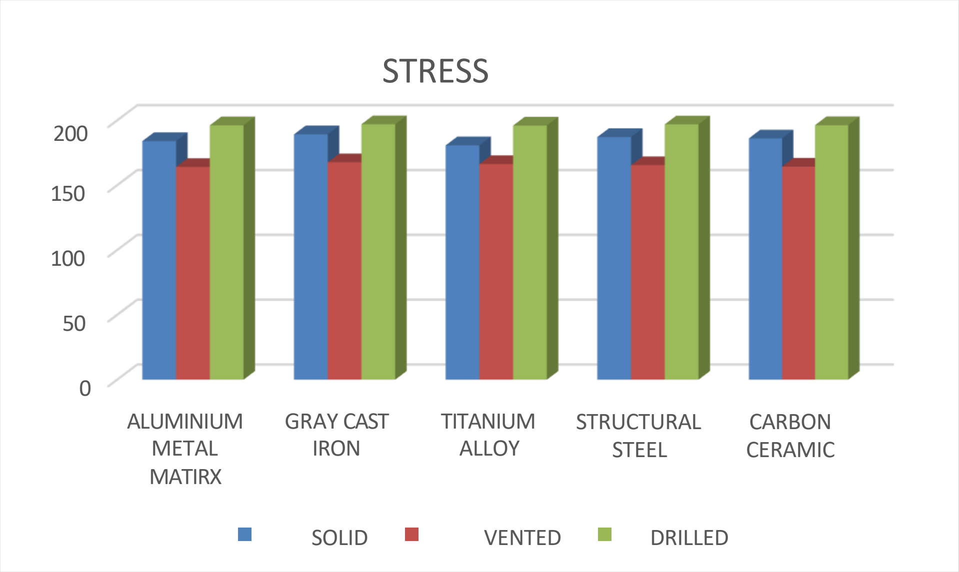


(b)

Thermal analysis of solid, vented and drilled disc brake for different materials { (a) & (b) }



(a)



(b)

Structural analysis of solid, vented and drilled disc brake for different materials { (a) & (b) }

6.4 COMPARISON OF RESULTS

THERMAL ANALYSIS

TEMPERATURE ANALYSIS:

MATERIAL	SOLID	VENTED	DRILLED
ALUMINIUM METAL MATIRX	84.424	84.656	84.418
GRAY CAST IRON	83.031	83.317	83.013
TITANIUM ALLOY	80.152	82.666	80.473
STRUCTURAL STEEL	83.3	83.98	83.285
CARBON CERAMIC	82.463	83.471	82.44

Heat Flux Analysis:

MATERIAL	SOLID	VENTED	DRILLED
ALUMINIUM METAL MATIRX	4791.9	2280.4	5318.6
GRAY CAST IRON	4720.5	2260.9	5236.9
TITANIUM ALLOY	4591.7	2225	5089.8
STRUCTURAL STEEL	4734.3	2264.7	5252.7

CARBON CERAMIC	4691.5	2252.9	5203.7

The results of the three materials: Aluminium metal matrix, Gray Cast Iron, Titanium alloy, Structural steel and Carbon ceramic shows that Solid type disc brake made of Titanium alloy gives less temperature value when the loads are applied. Therefore, Solid type disc brake made of Titanium alloy material is preferred.

Deformation Analysis:

STRUCTURAL ANALYSIS

MATERIAL	SOLID	VENTED	DRILLED
ALUMINIUM METAL MATIRX	0.458	0.464	0.559
GRAY CAST IRON	0.414	0.419	0.508
TITANIUM ALLOY	0.467	0.473	0.568
STRUCTURAL STEEL	0.227	0.23	0.277
CARBON CERAMIC	0.232	0.235	0.284

Stress Analysis:

MATERIAL	SOLID	VENTED	DRILLED
ALUMINIUM METAL MATIRX	184.01	164.13	196.23
GRAY CAST IRON	189.28	167.72	197.03
TITANIUM ALLOY	180.78	166.34	196.03
STRUCTURAL STEEL	187.17	165.48	196.92
CARBON CERAMIC	186.13	164.34	196.34

The results of the three materials: Aluminium metal matrix, Gray Cast Iron, Titanium alloy, Structural steel and Carbon ceramic shows that Vented type disc brake made of Carbon ceramic gives less deformation & Stress value when the loads are applied. Therefore, Vented type disc brake made of Carbon ceramic material is preferred.

7. *CONCLUSION*

1. Drilled type disc brake made of Aluminium material is preferred for Higher life.

2. Solid type disc brake made of Aluminium material is preferred for Lower damage.

3. Solid type disc brake made of Carbon ceramic material is preferred for lesser deformation.

4. Vented type disc brake made of Alluminium metal matrix material is preferred for lesser von-misses stresses.

In order to improve the braking efficiency and provide greater stability to the vehicle, an investigation is carried out into the usage of materials. In this project, we presented the fatigue and structural analysis of solid and ventilated type disk brake. We have shown that the ventilation system plays an important role in cooling the discs and provides a good high Fatigue resistance. The analysis results showed that, fatigue field and stress filed in the process of braking phase were fully coupled.

Static structural analysis is carried out by coupling the fatigue to the structural analysis. The present study can provide a useful design tool and improve the brake performance of disc brake system. From the above Tables, we can say that 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 present application While considering stresses and Drilled type disc brake is the best possible for present application while fatigue analysis observing analysis results, it is concluded that Carbon ceramic is the best material for Disc brake.

8. *FUTURE SCOPE OF THE PROJECT*

There is a significant scope for further work and this is summarised below:

- In the present investigation of Thermal analysis of disc brake, a simplified model of the disc brake without any vents with only ambient air cooling is analyzed by FEM package ANSYS. As a future work, a complicated model of Ventilated disc brake can be taken and there by forced convection is to be considered in the analysis. The analysis still becomes complicated by considering variable thermal conductivity, variable specific heat and non uniform deceleration of the vehicle. This can be considered for the future work.

- A full 3D analysis of the brake disc including the pads should be considered in order to investigate the effects of rotating heat source and the non-uniform heat flux over the rubbing surfaces due to non- uniform pressure distributions.

- A programme of experimental work needs to be undertaken using a full size dynamometer since it can subject the brake to the same sequence of high energy stops that has been modelled in the numerical situation. This will provide the necessary data to validate the model and provide an indication of the location of possible fracture sites.

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