DIGITAL INVESTIGATION OF FRICTION COMPOSITES FOR AUTOMOTIVE BRAKE PADS

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This work attempts to explore the coupled behavior of automotive disk brake while braking considering the Structural loading and steady state thermal loading approach using finite elemental analysis method. An automobile braking system is generally used to carry out the basic functions like to reduce and maintain speed of a vehicle at various operating conditions and to hold the vehicle at rest position. During braking operation, the brake system suffers from structural and wears issues under combined loading generated due to braking action. Hence, this work aims to determine temp distribution, to critically examine stress concentration over brake pad and rotor, contact pressure and structural deformation of brake discs-pads during single braking action using ANSYS simulation tool. It is found that the proposed NAO material performed well in comparison with conventional materials in terms of stress generation, temperature distribution, contact stresses. Furthermore, the investigation carried out to check the competency of friction composites.

Keywords: FEA, brake pad, friction material

1. Introduction

The disc brake used in the vehicles is safety-critical components. The transportation sector vehicles are under development to become capable of transporting passengers, goods at high speed as well as high capacities to achieve a performance requirement. This can be achieved by absorbing more kinetic energy during braking action of vehicles. The braking system performance strongly depends on the interface contact condition between pads and rotor. While braking action, brake pedal is pressed which results in piston movement inside the master cylinder using hydraulic fluid. It pushes the braking pads to contact the brake rotor. The frictional forces generated at the sliding point of contact amongst the brake disc-pads oppose the rotor movement which in turn reduces speed of vehicle. Braking frequency is dependent on the road condition and traffic hours. The nature of braking is different as per requirement like parking brakes are used to hold the vehicle at rest position and service brakes are used to reduce the speed of the moving vehicles. A huge frictional heat energy (400- 500 °C) is generated as result of kinetic energy transformation. Studies were conducted to determine the thermal conductivity influence on tribological performance of NAO brake-pads and

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reported that there is considerable Effect of contact temperature on the braking performance, thermo-physical properties, and durability of the material. The released friction heat is absorbed by the brake disc assembly in turn increases temperature. This temperature may go beyond the critical temp for corresponding friction material and leads to detrimental Effects such as thermal cracks and vibration, judder, thermal distortion due to uneven temp distribution, brake fade, thermo-elastic Instability, premature wear, local scoring. Hence it becomes essential to dissipate the generated heat energy through brake system. Karan Dhir studied Thermo-mechanical evaluation of Disc Brakes and concluded that heat dissipation can be achieved with improvement in the properties like thermal conductivity, surface volume ratio which plays role in convection, resistance to mechanical wear. These parameters are controlled by material composition and brake structure [13,14].

In general, frictional brakes are classified in two types the drum brake & the disc brake. The tendency of the disc brake is that it cools sooner compared with drum brake. This happens due to higher empty range, relatively high contact of air flow. It confirms a self-cleaning nature because of centrifugal force. Disc brake is subjected to several types of mechanical stresses. The first one is centrifugal effect driven traction force because of the disc rotation at no braking condition. Few more supplementary forces experienced by the disc brake during braking operation are compression force created by pressing the brake pad against disc, perpendicular to the disc surface to slow down the movement. During this, the rubbing between brake pad and disc surface generates braking action. This braking action is converted into traction force in the opposite track to that of the disc revolution on the disc surface. The last type of mechanical stress is due to uneven pressure distribution. This causes uneven wear, undue mechanical stress & reduced life of pads. Yevtushenko concluded this temperature influence on performance of pad/disc during braking [3].

A review of numerical and experimental study on disc brake performance is carried out by Afzal et.al. He proposed that numerical tools and techniques made analysis easier and effective. Finite element analysis (FEA) is simulations tool used to solve actual life complex boundary value problems, optimal design problems by simulating all the relevant practical situations. Considering the high manufacturing and experimentation cost for variety of structural designs, researchers have targeted the use of FEA [1,10]. The Balhocine et al used FEA tool to recognize the various design aspects and frictional contact for the brake disc [2,3]. The H.B.Yan studied ventilated brake disc using FEA to predict the cooling factors [11,12]. The Shahzamanian et al studied FEA tool to analyse the thermal-elastic behaviour using axi-symmetric brake disks [4]. Yash Vardhan et al. performed structural and thermal analysis of the solid and ventilated disc for various configurations and found ventilated disc as a better alternative as thermos-structural point of view [5].

Rashid presented review on various possible geometries, materials for brake system and raised that despite of a variety of improvement, still working issues associated with the brake system [17]. Naveen Kumar performed analysis with two unique materials with carbon and glass fibre base, variety of disc designs and found that thermos-structural property improved with proper ventilation and material properties [6]. Thermal related properties can be improved by adding copper inserts in the composite. Zhang et al. studied a combined effect of thermal and mechanical properties for ventilated disc brake using FEA tool [15]. The Riva proposed tool considering airborne articles to simulate the disc brake assembly [8].

In present work, the comparative structural and steady state thermo-structural analysis of passenger car's disc brake assembly is done. Various friction materials are used to understand the temperature distribution, deformation, the contact pressure and induced stresses (Von Mises stress) distribution over the disc and pad surfaces using the ANSYS FE software. The results of all the proposed friction materials are compared with the existing brake pad material.

2. Analytical Investigation

Regarding the thermal modelling of automotive brake pads, generally two methods are used for brake analysis and calculating heat generation rate named the uniform pressure and the uniform wear condition at the contacting surfaces. In contact region, Uniform pressure distribution concept is valid when the friction pad is newly used. However, a concept of uniform wear becomes realistic after braking for several times.[9]

In real life scenario, the brakes are applied may times. Here uniform wear is stabilized between brake disc and pad, hence the heat flux generated is only a function of time. While doing analytical investigation, we must consider assumptions to compensate the system errors [2].

i. *Kinetic Energy (K.E.) of the Vehicle,*

Kinetic Energy = $Mv^2/2 = (762*16.67^2)/2 = 105875.67$ J (1)

Where, M= vehicle Mass, Kg

V = vehicle velocity, m/s

ii. *Vehicle Stopping distance*

Maximum frictional force, $F=\mu Mg = 0.7*762*9.81 = 5232.65$ N (2)

Where, μ= frictional coefficient between tire and road in dry condition.

Now, deceleration is given by, $\alpha = F/M = 5232.65/762 = 6.86$ m/s^2 (3)

The time required to stop the vehicle is given by $t = (v-u)/\alpha$ (4)

$= 16.67/6.86 = 2.43$ s

Vehicle Stopping distance, $S = v^2/2\mu g = 28.32$ m (5)

Where, μ= coefficient of friction between disc and brake pads

iii. Average braking power

Average braking power is given by [3,7],

$$Q_o = k(1\text{-}s)*u*a*w*3600 /(2*778) \quad (6)$$

Q_o= 40084.1 Watt

Considering all factors, $Q=Q_o*0.6*0.5*0.5*0.9$

Q= 5411.36 Watt

Where, 0.60 = front wheels weight distribution factor

0.50 = one brake rotor use factor

0.50 = one sided use of disc

0.90 = 10% of heat is lost to atmosphere

iv. Heat flux [15]

Disc Rotor Area = $\pi/4*(Do^2 - Di^2)$

= $\pi/4*(0.240^2–0.140^2)$

= 0.0298 m^2

Final braking power for each disc brake =1352.84 Watt

Heat flux, q = braking power / disc area

q = 1352.84/0.0298 = 45397.3 w/m^2

v. Heat transfer coefficient

The coefficient of convective heat transfer is given by [16],

$h = 0.04*(ka/D) (Re^{0.8})$

h = 106.18 w/m^2k

Where, ka = Thermal conductivity Coefficient for air, BTU/h°f ft

D = disc diameter, ft

vi. Braking pressure

Pressure applied on pads is given by, $P = 1/A_{mc} * [(Fp/2)*l_p*n_p]$ (7)

= 1/490.625 * [(250/2)*6*0.8]

= 2.445 MPa

Where, A_{mc} , Area of cylinder = 0.004906 $m^{2,}$

l_p , lever ratio (pedal) = 6:1

n_p , lever efficiency (Pedal) = 0.79

Fp, Force on brake pedal

vii. Braking Torque [3,17],

Tb = 2*Fc*μ*Rm

Tb = 2*600*0.5*0.194 = 116.4 Nm

Whereas, Fp, is for two parallel cylinders, so force on each cylinder = 1200/2= 600N,

μ= coefficient of friction between disc and brake pads = 0.5,

Rm = mean radius where Fc is applied

$Rm = 2/3(Do^3\text{-}Di^3)/(Do^2\text{-}Di^2) = 0.194$ m

3. Geometric Details

Brake pads for one of the passenger cars were considered as per practice shown in figure 1. CATIA is a solid modelling tool used for preparing the 3D cad model of the disc brake assembly. It is considered that brake assembly remains stress-free before applying the brake force. Actual brake system dimensions are mentioned below,

Outer Disc radius= 240 mm
Inner Disc radius= 140 mm
Radius of hub= 65 mm
Area of brake pads= 3691.5 mm^2

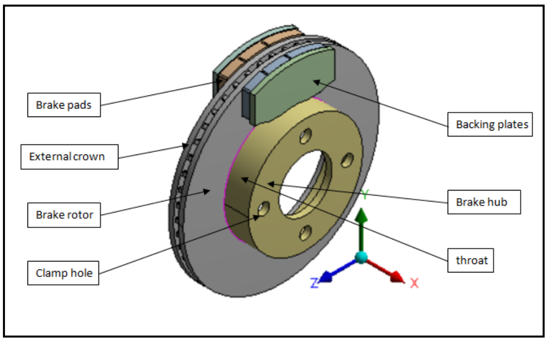


Fig. 1 Geometry details

4. Finite Element Modeling

A Finite element analysis is a technique of solving real life problem through various numerical method. ANSYS is analysis software package used for assessment of the brake assembly system in terms of deformation, temperature distribution, structural stresses, and pressure distribution

4.1 Material Selection

The friction material selection for the manufacturing of Disc Brake pad depends on the strength and operating conditions like wear, noise, load, squeal along with material execution cost. The design requirements for brake friction material are good thermo- structural stability and properties, noble frictional characteristics with low wear rates for long service. To check the competency of friction materials with respect to the design requirements, materials are selected for brake pads as mentioned in the table 1. The disc brake rotor is usually made of cast iron and same material selected for FEA analysis and experimentation as shown in figure 2.

- Disc = Gray caste iron
- Backing plate= stainless steel
- Hub= Structural steel

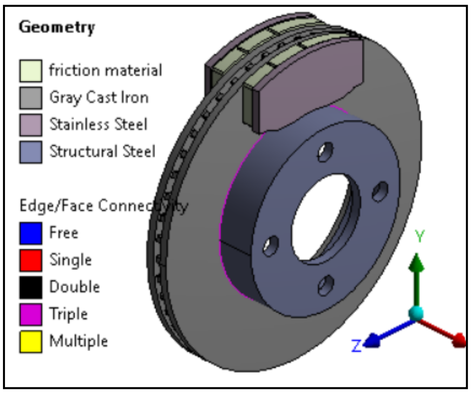
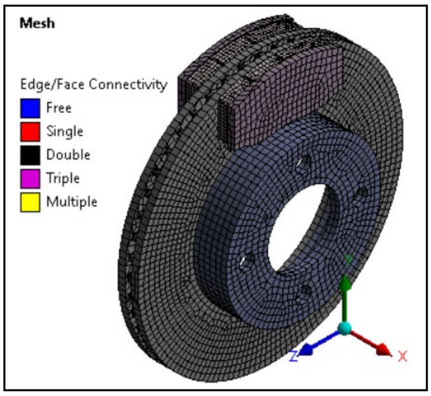


Fig.2 Material details

Table 1. Material details of Friction material

Material	Density Kg/m^3	Young's Modulus GPa	Poisons Ratio	Tensile strength MPa	Thermal Conductivity w/mK
Asbestos	2500	36	0.34	132	0.08
Al + Sic	2810	147	0.29	230	90
Structural steel	2500	36	0.34	132	0.08
Ceramic (Sic sintered)	3150	410	0.14	1600	125.6
Natural fiber based (NAO)	1790	4.36	0.3	21.5	0.4
Present Brake Pad	2310	2.3	0.25	18	2.41

4.2 Meshing



Statistics	
Nodes	95065
Elements	28729

Fig.3 meshing (quad elements)

Meshing is the process of discretization the complete model into small number of pieces called elements. The higher order hexahedral element type is preferred during meshing. A proper brick element selected for meshing to reduce error in the results. Meshed view of model along with element count is shown in figure 3.

4.3 Loading and Boundary conditions

Modal analysis:

Modal Analysis is executed to find out the natural frequencies of the model and to understand the pattern of vibration. The modal analysis plays important role in analyzing dynamic characteristics and checking structural integrity of the system. The modal analysis is executed by fixing the bolting locations of the disc hub as shown in Figure 4(a).

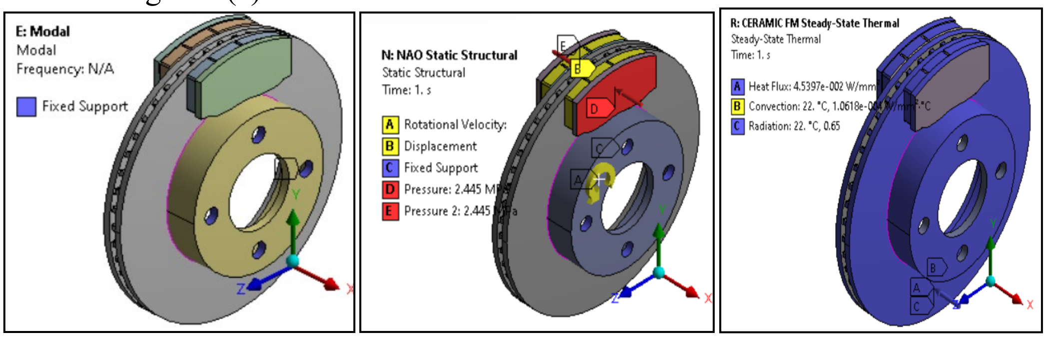


Fig. 4 Modal(a), Static Structural(b) and thermal(c) Boundary Conditions

Static Structural Analysis:

The static structural boundary conditions are shown in figure 4(b). The disk is constrained firmly altogether at the bolting location except in the direction of wheel rotation. The brake pads can move in normal direction to the brake surface. So that it can contact the disc surface. The amount of pressure applied on the brake pad is evaluated based on the force during braking. The pressure applied externally on the brake pads is 2.445 N/mm^2. The disc has rotational speed of 1327 rpm as average vehicle speed is considered for analysis (60 kmph).

Steady state thermal analysis:

The thermal analysis is performed on the model with all selected materials for boundary conditions shown n figure 4(c). The heat flux magnitude is evaluated from average braking power formula as mentioned earlier and the heat flux equal to 45397.3W/m^2 is applied on disc surface meeting the pads. Heat exchange is taking place through various modes like i.e. conduction within the parts; convection between parts and air and radiation were considered during cooling of the disc brakes shown in figure. The thermal conductivity values are considered as per material and the convective heat transfer coefficient evaluated as 106.18 W/m^{2}K. The surrounding temperature considered is 295K for both modes i.e. convection and radiation.

While simulating actual condition to find out temperature distribution over the parts, heat exchanges at the following locations were considered: Convection between disc, disc caliper and surrounding air, conduction at hub and disc, radiation form disc faces.

4.4 Analysis Approach

The individual modules are selected for the analysis and boundary conditions are applied in the respective modules. In Modal analysis, supporting is done is done as per requirement and natural frequency along with pattern of vibration is observed. The modal and structural analysis is done in coupled condition. Thermo-structural coupled analysis is performed to understand the temp effect.

5. Result and Discussion

It is executed by fixing the bolting locations of the disc hub. The fundamental frequency of model is 934 Hz calculated after modal analysis.

5.1 Structural Analysis results:

During analysis brake pads and disc are considered for evaluation. The stress generated due to stress concentration factors and contact stresses (imaginary stresses generated due to additional contacts) are not considered in evaluation.

a. *Deformation:*

Following figures represents the brake pad and disc deformations during the time of braking. From the figures 5, it is found that the larger deformation is observed at the outer radius of disc which in contact with the brake pad. Present friction material, NAO and asbestos based brake pads are showing highest structural deformation due to less rigidity. The maximum deformation is of 35 microns at the brake pad whereas disc showing deformation up to 5 microns as mentioned in the table

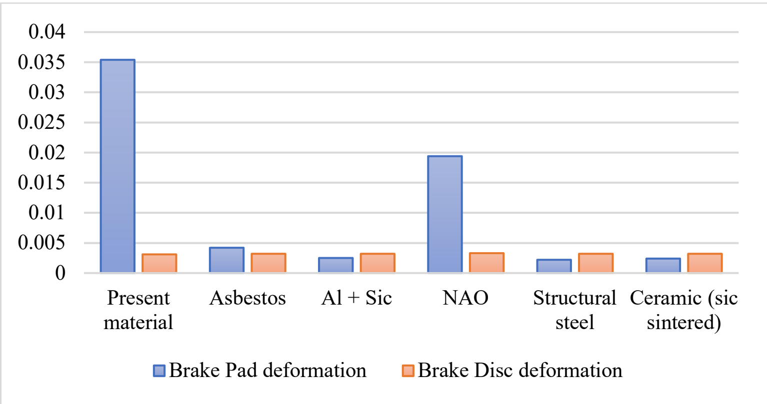


Fig. 5 Comparative Deformation without considering thermal effect

b. *Von Mises Stress*

The von-mises stress distribution shown in the following figure 6. The maximum stress on the disc brake surface is of order of 10-12 MPa. The maximum stresses are observed on metal-based friction pads. Nonmetallic brake pads are showing minimum surface stresses and best fits as a structural point of view.

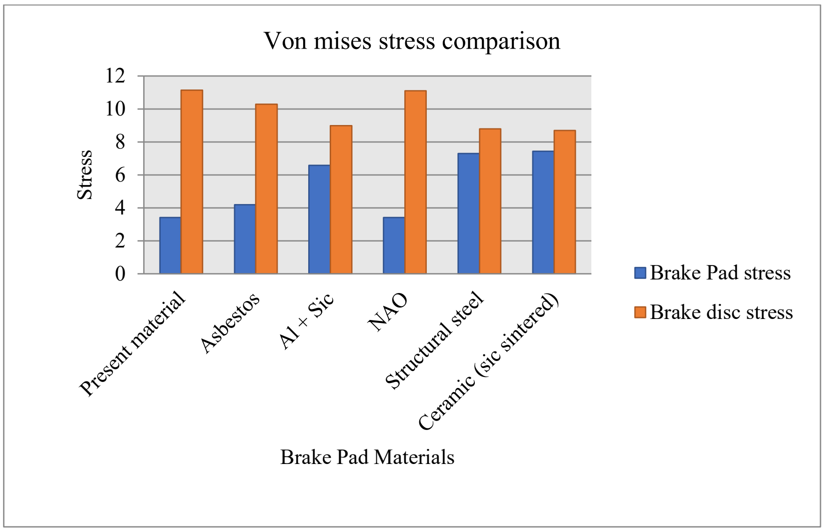


Fig. 6 Comparative Von Mises stress without considering thermal effect

c. Frictional stress and contact pressure

The Frictional stresses are the stresses induced in the system during transmitting the frictional forces. The contact pressure is pressure generated at sticking surfaces while transmitting motion.

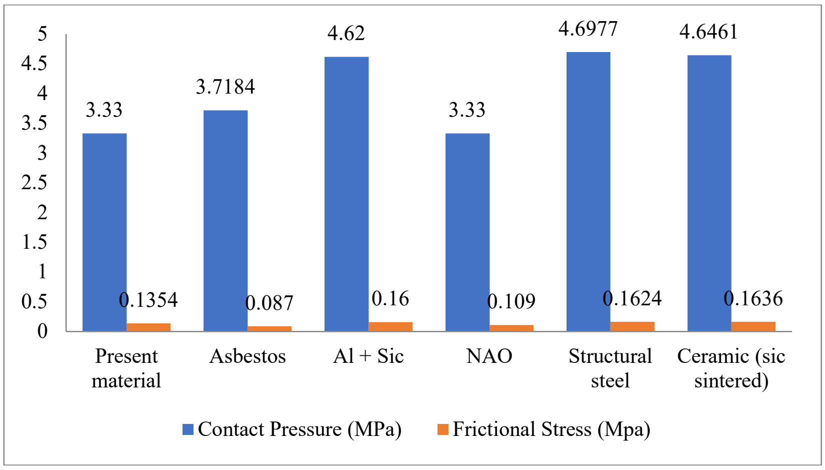
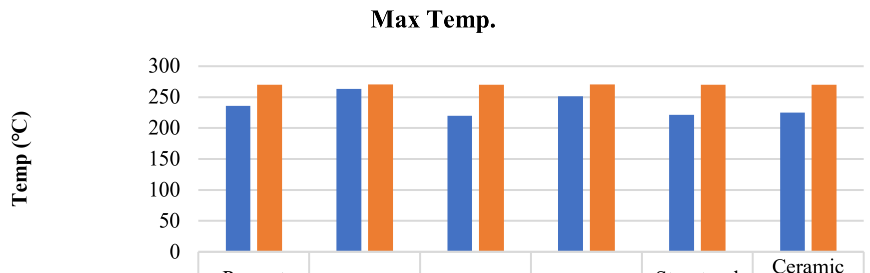


Fig 7 Frictional Stress and Contact pressure without considering thermal effect

1.1. Thermo-structural Analysis:

a. Temperature



	Present material	Asbestos	Al + Sic	NAO	Structural steel	Ceramic (sic sintered)
Brake Pad temp	235.91	263.5	219.75	251.61	221.27	225.17
Brake Disc Temp	270.26	270.53	270.15	270.42	270.16	270.18

Fig 9 Maximum Temp for brake pads and disc

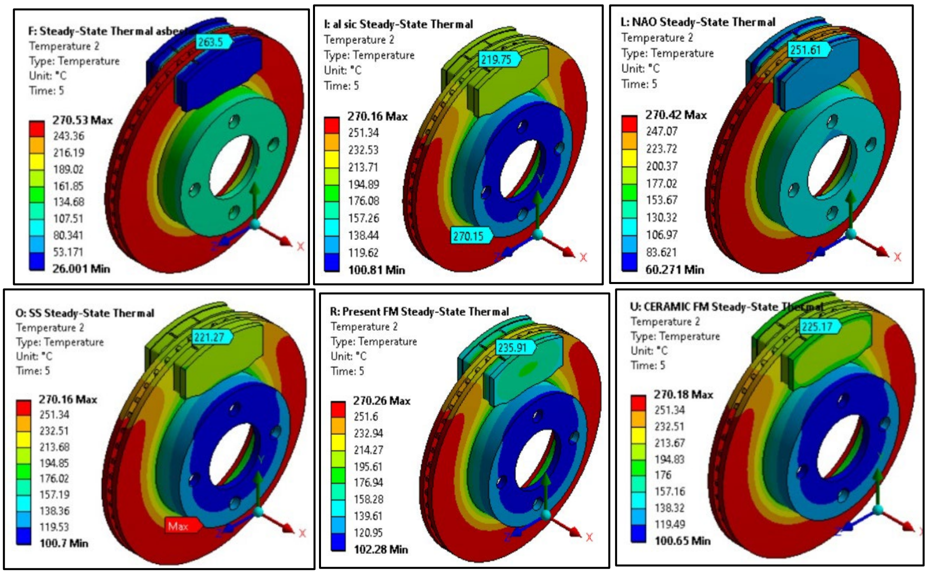


Fig 8 Temp distribution plot for brake pads and disc

Thermal boundary conditions are applied, and temperature values are evaluated over the friction brake pads and disc as shown in fig. 8,9. The maximum temp reached at disc is 270 °C.

b. Heat Flux

Heat flux is thermal flux or heat flux density (W/m^2). The highly conductive materials for system show more heat flux compared with non-metallic materials as shown in figure 10.

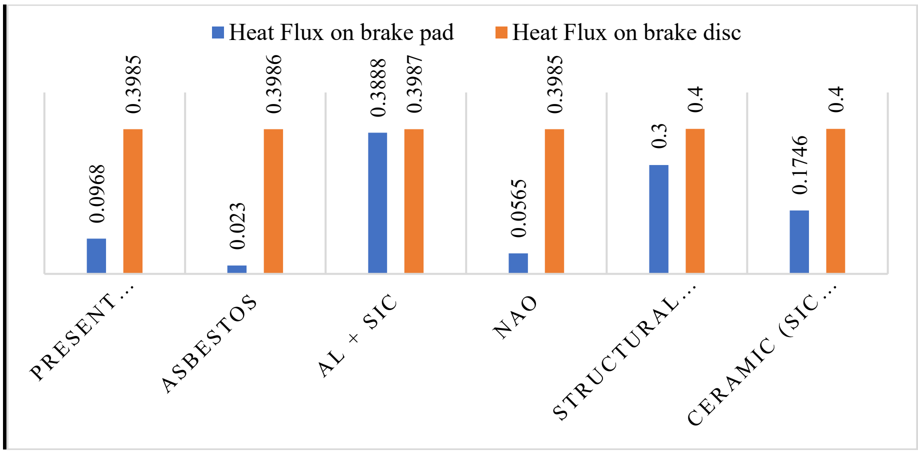


Fig 10 Comparative Heat Flux for brake pads and disc

c. *Deformation*

The thermo-structural analysis shows more stress and deformation compared to pure structural loading shown in Figure 11. It is also called as coupled analysis. The metal-based friction composites are having high coefficient of thermal expansion. Hence shows more deformation.

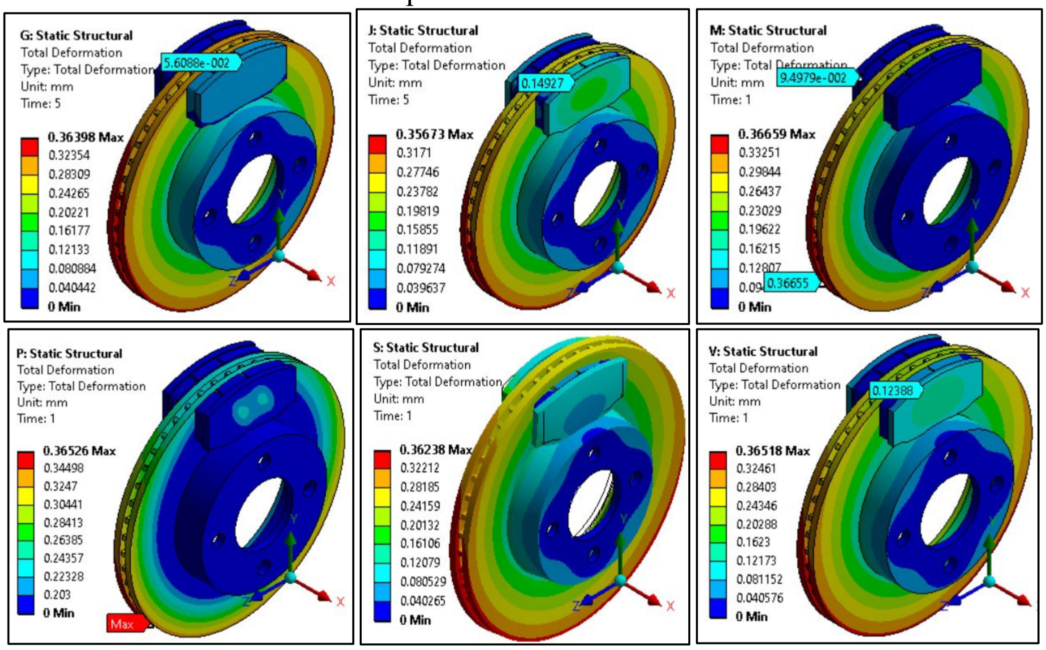


Fig.11 Deformation plots with thermal effect

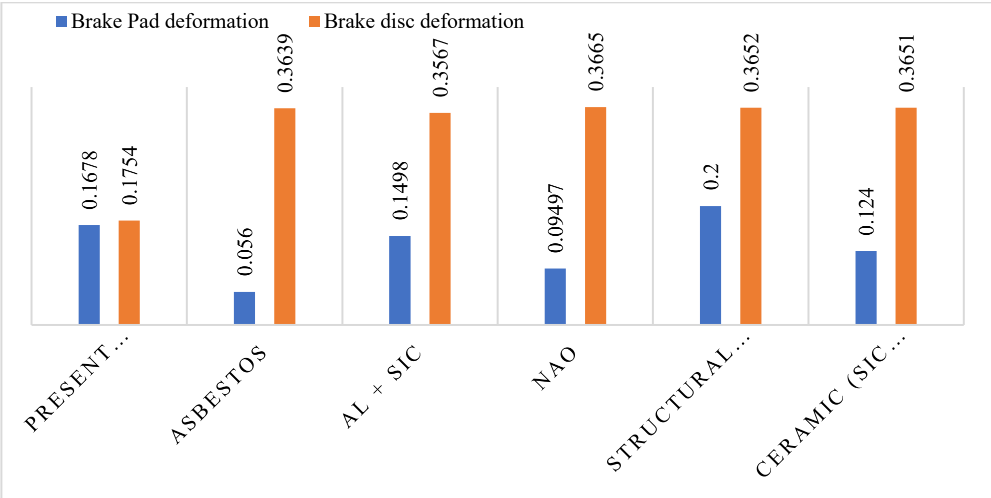


Fig 12 Comparative Deformation with thermal effect

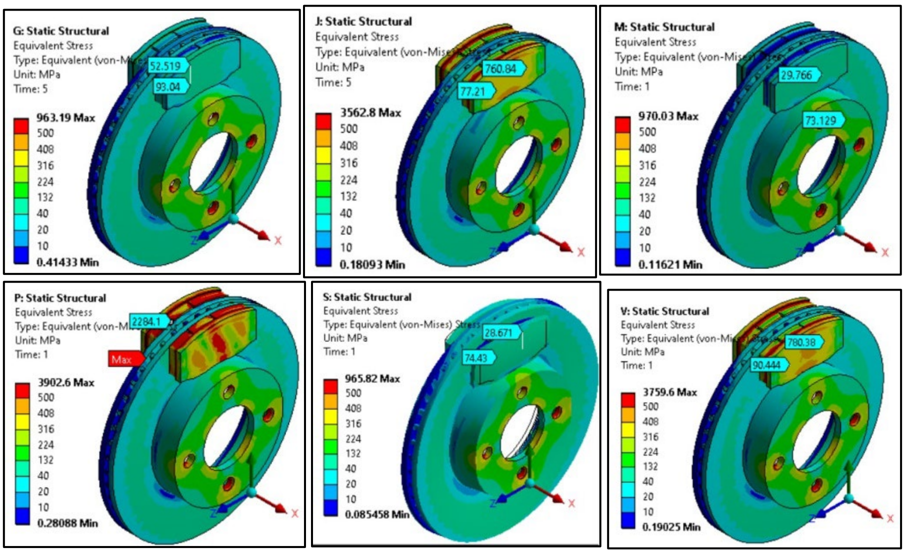


Fig. 13 stress plot with thermal effect

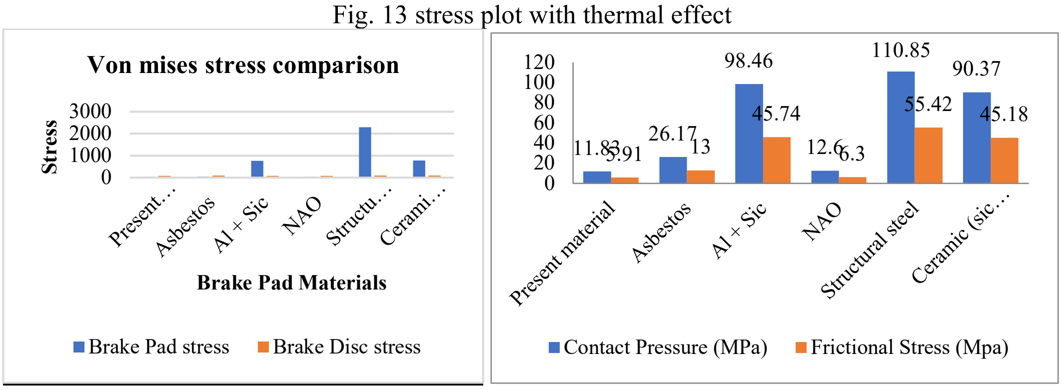


Fig.14 Comparative Von Mises stress, Frictional Stress and Contact pressure

6. Conclusion

The study investigated thermo-mechanical aspects of various friction materials utilized in brake pads. The analysis considered responses such as deformation, von-Mises stresses, heat flux, and temperature distribution to determine the most suitable friction material, with the goal of enhancing brake effectiveness and providing significant strength to the braking system during the design phase.In thermo-mechanical analysis, Non-Asbestos Organic (NAO) based friction material and the current brake pad material exhibited 30-45% less stress and 22% less deformation compared to other conventional materials. Metal-based friction composites exhibited higher stress, heat flux, and deformation. NAO-based composites demonstrated sufficient contact pressure at the disc-brake pad interface. The lower thermal conductivity of NAO and Asbestos composite brake pads resulted in a minimum holding temperature. The research underscores the importance of considering thermal effects in the analysis of brake pad materials. The findings highlight the superior performance of NAO-based composites, suggesting their suitability for enhancing brake system effectiveness. These insights can inform the design process, contributing to the development of more robust and efficient brake systems.

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