Redesign of Disc Brake Assembly with Lighter Material

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Abstract

The project Titled "Redesign of Disc Brake assembly with lighter material" is aimed at evaluating the performance of disc brake of a car under severe braking conditions and there by assist in disc rotor design and analysis. An attempt is made to suggest an alternative material for disc brake by comparing the results obtained for different materials Cast Iron, Carbon fibre reinforced ceramic composite, based on which yields a low temperature variation across the rotor, less deformation, good heat dissipation and minimum von-misses stress possible.

The simulation for the thermo elastic behaviour of disk brake is obtained in the repeated brake condition. The computational results are presented for the distribution of temperature on the friction surface between the contacting bodies. Also, thermo elastic instability (TEI) phenomenon (the unstable growth of contact pressure and temperature) is investigated in the present study, and the influence of the material properties on the thermo elastic behaviours (the maximum temperature on the friction surfaces) is investigated to facilitate the conceptual design of the disk brake system

1. Introduction

A brake is a device by means of which artificial frictional resistance is applied to moving member, in order to stop the motion of a machine.

In the process of performing this function, the brakes absorb either kinetic energy of the moving member or the potential energy given up by objects being lowered by hoists, elevators etc. The energy absorbed by brakes is dissipated in the form of heat.

In the course of brake operation, frictional heat is dissipated mostly into pads and a disk, and an occasional uneven temperature distribution on the components could induce severe thermo elastic distortion of the disk. The thermal distortion of a normally flat surface into a highly deformed state, called thermo elastic transition. It sometimes occurs in a sequence of stable continuously related states as operating conditions change. At other times, however, the stable evolution behaviour of the sliding system crosses a threshold whereupon a sudden change of contact conditions occurs as the result of instability.

2. Design methodology

The design methodology adapted for the current work is shown in the following figure 1.

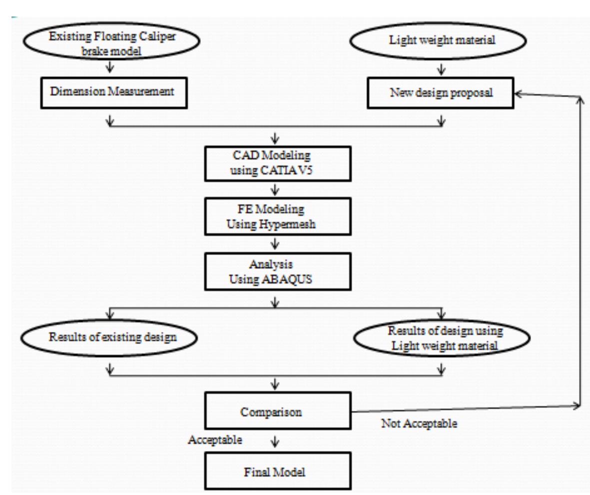


Figure 1: Design methodology

3. Disc Brake Geometry

Figure 2 shows the picture of rear disc brake assembly of Ford Mondeo GLX Sedan vehicle.

Figure 2: Disc Brake Geometry

4. CAD Model

Figure 3 shows the CAD model of the Disc brake assembly created using CATIA software.

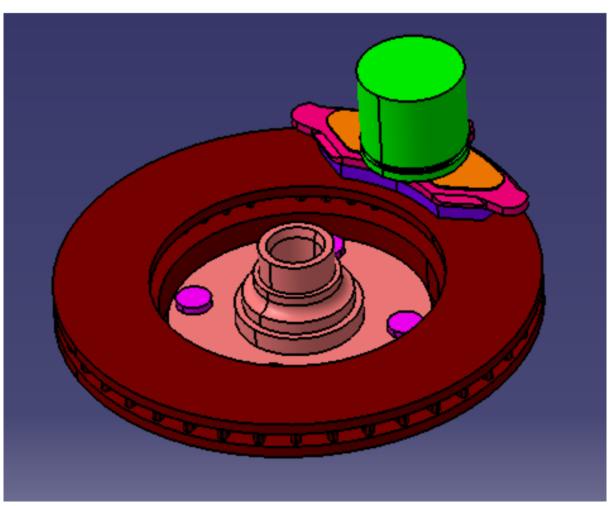


Figure 3: CATIA Model

5. Finite Element Model

Figure 4 shows the Finite Element model of the Disc brake assembly modelled using Hypermesh software.

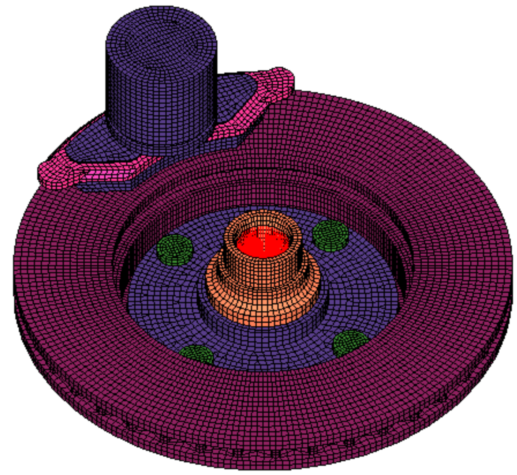


Figure 4: Finite Element Model

6. Thermoelastic analysis of the given disc brake assembly

Disc brakes operate by pressing a set of brake pads against a rotating brake disc; the frictional forces cause deceleration. The dissipation of the frictional heat generated is critical for effective braking performance. Temperature changes of the brake cause axial and radial deformation; and this change in shape, in turn, affects the contact between the pads and the disc. Thus, the system should be analyzed as a fully coupled thermo-mechanical system.

6.1 Assumptions

The assumptions which are made while modelling the process are given below:

1. The domain is considered as axis-symmetric.

2. Inertia and body force effects are negligible during the analysis.

3. The disk is stress free before the application of brake.

4. Brakes are applied on the entire four wheels.

5. The analysis is based on pure thermal load and pressure load. The analysis does not determine the life of the disk brake.

6. Only ambient air-cooling is taken into account and no forced Convection is taken.

7. The kinetic energy of the vehicle is lost through the brake disks i.e.no heat loss between the tyre and the road surface and deceleration is uniform.

8. The thermal conductivity of the material used for the analysis is uniform throughout except in the case of composite rotor disc where the condition is orthotropic.

9. The specific heat of the material used is constant throughout and does not change with temperature.

6.2 Fade test procedure from FMVSS 105-75

The fade test procedure FMVSS 105-75, applied to the hydraulic and electric brake systems, specifies the following conditions. A Vehicle travelling at a speed of 97 kmph reduces its speed at 0.6g for 4.57 seconds, accelerates for 25 seconds until speed is back to 97 kmph, and then continues with the same speed for 5.43 seconds. This process is shown in figure 5. Each cycle lasts 35 seconds.

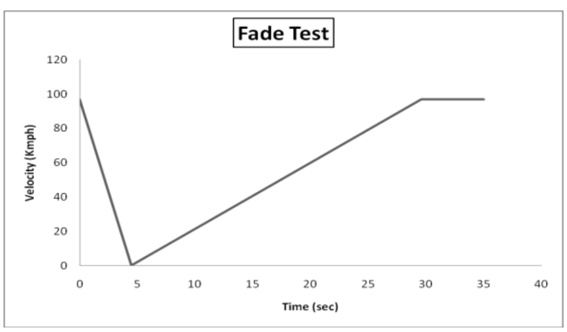


Figure 5: Braking conditions for FMVSS 105-75

6.3 Boundary and loading conditions

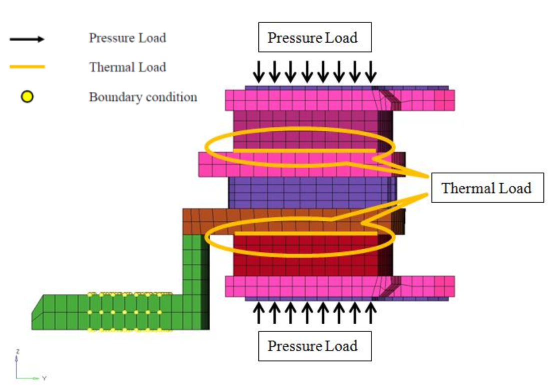


Figure 6: Boundary and loading condition

The boundary and loading conditions are represented in the figure 6.

Pressure load of 1481400 N/m^2 is applied on both inner shim and outer shim. Thermal load of 659745 watt/m^2 is applied between the pad and the rotor disc. The model in constrained in all DOF at the hat region of rotor as shown in the figure 6. Since only sector model is used symmetric boundary condition is also considered in the analysis.

The initial temperature of the disc brake is set to 20^o C.

6.4 Thermal loading condition

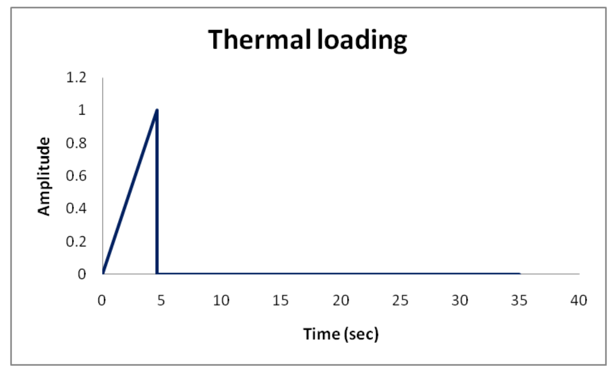


Figure 7: Thermal loading condition

Figure 7 shows the thermal loading history, which defines the thermal loading condition for one cycle. The cycle lasts for 35 seconds. Initially heat flux is linearly ramped in small steps to its maximum value for the first 4.57 seconds and is reduced to 0 immediately. The heat is conducted through the model for remaining time.

6.5 Mechanical loading condition

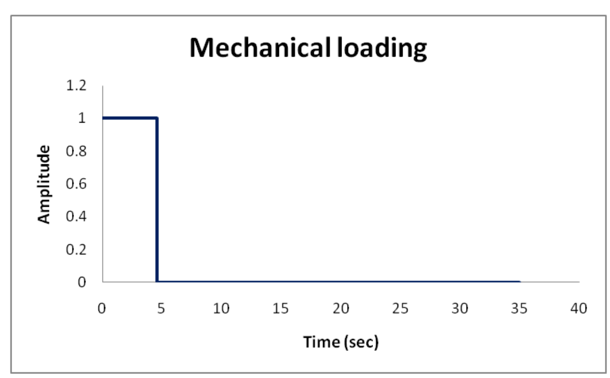


Figure 8: Mechanical loading condition

Figure 8 shows the mechanical loading history, which defines the mechanical loading condition for one cycle. The cycle lasts for 35 seconds. Initially pad force is increased to its maximum value at the start of the first increment and is retained at this magnitude for 4.57 sec and is reduced to 0 immediately. The heat is conducted through the model for the rest 30 seconds and the pad force acting on the disc as 0.

6.6 Material information:

The material properties of the given disc brake are shown in table 1.

Rotor is made up of Cast Iron. Shim and back plate is made up of Cast carbon steel. Pads are made of Ceramic porcelain material.

Table 1: Material properties of disc brake assembly

Material	Ceramic Porcelain	Cast Iron	Cast Carbon Steel	
Property Name	Value	Value	Value	Units
Elastic modulus	2.2059E+11	6.6178E+10	2.0000E+11	N/m^2
Poisson's ratio	0.22	0.27	0.32	NA
Mass density	2300	7200	7800	kg/m^3
Compressive strength	5.5149E+08	5.7219E+08	2.4817E+08	N/m^2
Thermal expansion coefficient	1.0800E-05	1.2500E-05	1.2500E-05	/Kelvin
Thermal conductivity	1.4949	45	30	W/(m.K)
Specific heat	877.96	510.00	500.00	J/(kg.K)

6.7 Results for given Disc brake

6.7.1 Temperature plots

The following figures show the temperature distribution plot for the given disc brake model at 1st braking cycle.

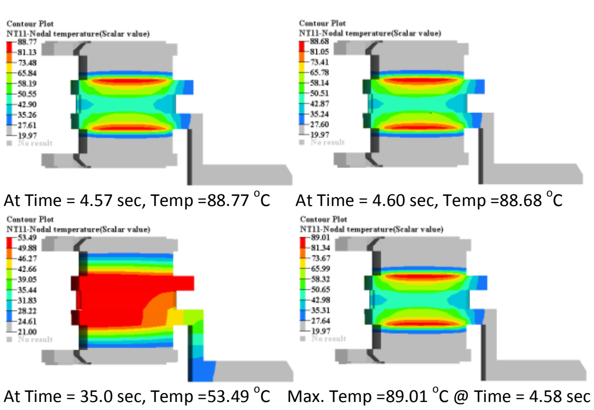


Figure 9: Temperature plot for one cycle

Figure 10 shows the variation of temperature with respect to time for one braking cycle. During the first braking cycle the max temperature of 89.01 °C is attained at 4.58 seconds.

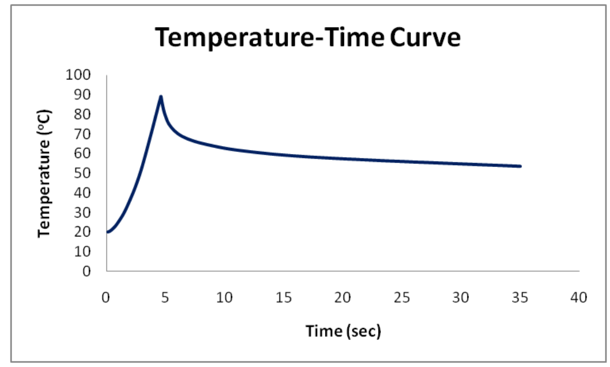


Figure 10: Temperature plot for one cycle

The following figures show the temperature distribution plot for the given disc brake model at 10th braking cycle

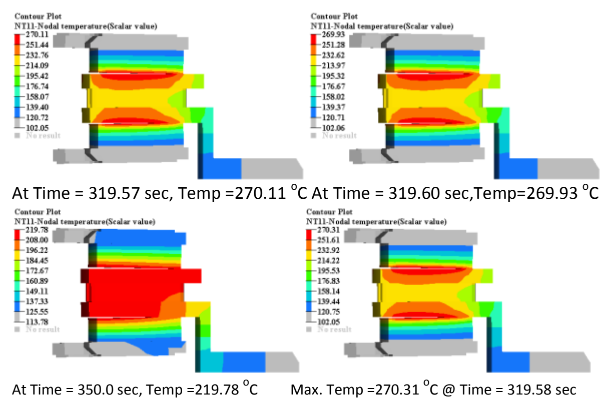


Figure 11: Temperature plot for ten cycles

Figure 12 shows the variation of temperature with respect to time for Ten braking cycles. During the 10th braking cycle the max temperature of 270.31 °C is attained at 319.58 seconds.

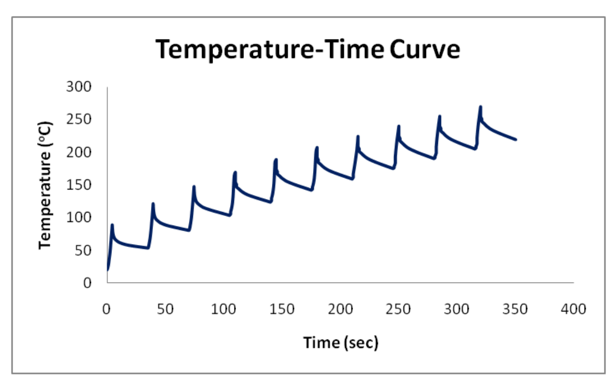
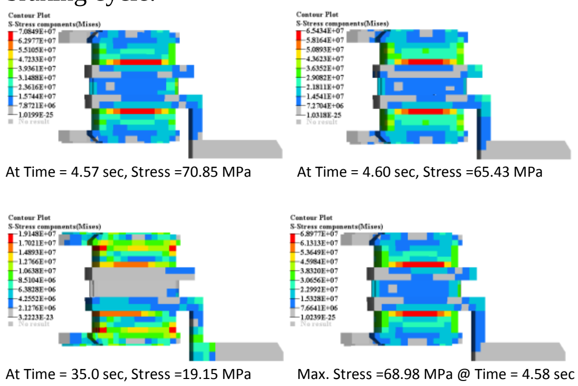


Figure 12: Temperature plot for ten cycles

6.7.2 Stress plots

The following figures show the Stress distribution plot for the given disc brake model at 1st braking cycle.

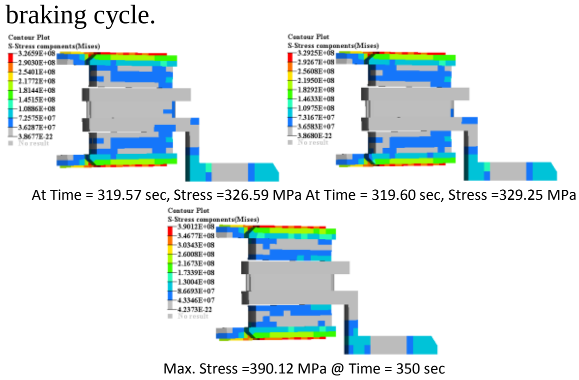


At Time = 4.57 sec, Stress =70.85 MPa At Time = 4.60 sec, Stress =65.43 MPa

At Time = 35.0 sec, Stress =19.15 MPa Max. Stress =68.98 MPa @ Time = 4.58 sec

Figure 13: Stress plot for one cycle

The following figures show the Stress distribution plot for the given disc brake model at 10th braking cycle.



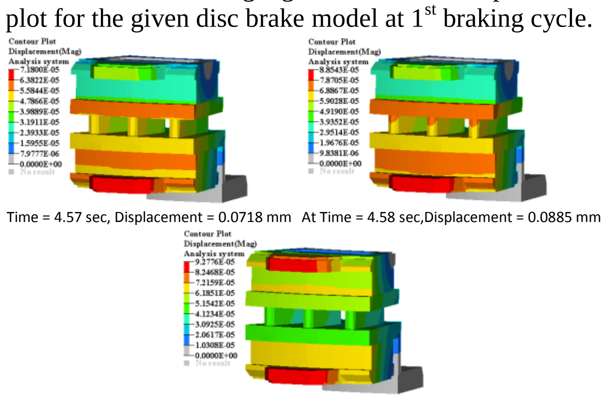
At Time = 319.57 sec, Stress =326.59 MPa At Time = 319.60 sec, Stress =329.25 MPa

Max. Stress =390.12 MPa @ Time = 350 sec

Figure 14: Stress plot for ten cycles

6.7.3 Displacement plots

The following figures show the Displacement plot for the given disc brake model at 1st braking cycle.

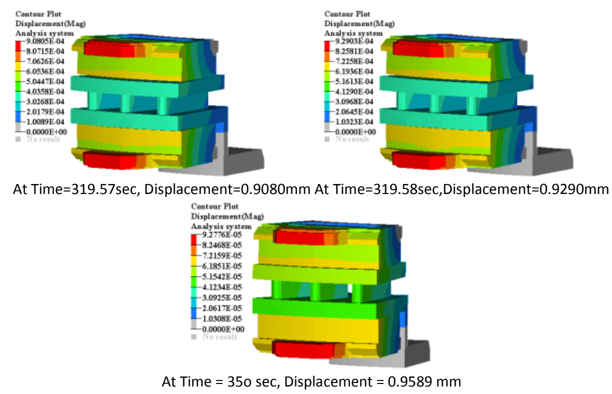


Time = 4.57 sec, Displacement = 0.0718 mm At Time = 4.58 sec,Displacement = 0.0885 mm

At Time = 35 sec, Displacement = 0.09277 mm

Figure 15: Displacement plot for one cycle

The following figures show the Displacement plot for the given disc brake model at 10th braking cycle.



At Time=319.57sec, Displacement=0.9080mm At Time=319.58sec,Displacement=0.9290mm

At Time = 35o sec, Displacement = 0.9589 mm

Figure 16: Displacement plot for ten cycles

7. Thermoelastic analysis of conceptual disc brake assembly

7.1. Rotor design

The Brake rotor of the disc brake assembly is conceptualised to be made of two parts, Hat region and Disc region. The hat region made of Cast carbon steel. The inner cheek, outer cheek and vane are made as an integral part called disc and is made of material Carbon fibre reinforced carbon/ SiC hybrid matrix composite. The bolt-nut arrangement is used to join the parts to form rotor as a whole.

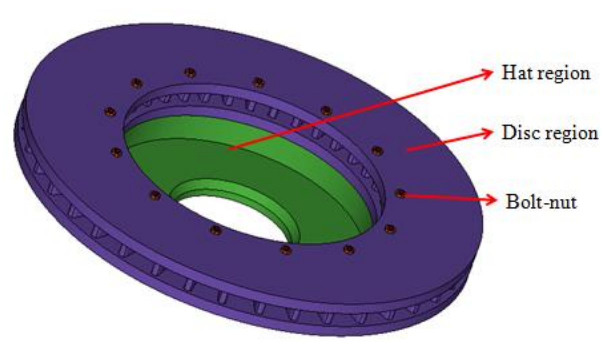


Figure 16: Composite disc brake assembly

7.2. Composite modelling details

The disc is made of unidirectional Carbon fibre reinforced C/ SiC hybrid matrix composite. The composite is considered to be made of continuous carbon fibres reinforced in hybrid matrix. The thickness of each layer of composite is assumed to be 1mm and the thickness of each ply is taken as 0.1111 mm. The composite lay-up sequence is 0, +45, -45, +90, 0, +90, -45, +45, 0.

7.3 Material information:

The Properties of unidirectional (1D) carbon fiber reinforced C/SiC hybrid matrix is shown in the table 2.

Table 2: Properties of unidirectional (1D) carbon fiber reinforced C/SiC hybrid matrix

Total carbon fiber volume fraction (%)		45
C/SiC matrix ratio		60/40
E11 (N/m2)		1.56 E+11
E22 (N/m2)		3.50E+10
E33 (N/m2)		3.50E+10
G12 (N/m2)		2.10E+10
G23 (N/m2)		1.40E+10
G13 (N/m2)		2.10E+10
υ12		0.18
υ13		0.18
υ23		0.25
K (W/mK)	K11	50
	K22	30
	K33	30
α (10-6/°K)	α11	0.7
	α22	0.34
	α33	0.34

7.4 Design proposals:

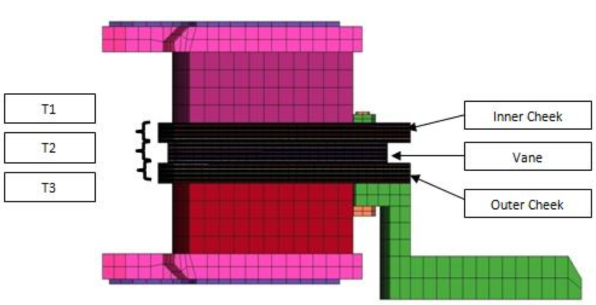


Figure 17: Thickness parameters for design proposal

Various combinations of the thickness are considered and subjected for one braking cycle. The results of the corresponding stress and temperature for a particular combination of the thickness has been presented in the evaluation of mechanical performance.

A set of 27 configurations has been analysed to find out the optimal configuration. It has been considered that the minimum thickness which can be assigned to Inner cheek or Vane or Outer cheek is 4 mm.

Total Disc thickness (Dt) is summation of T1, T2 and T3 as depicted from figure 17. Dt is varied in steps of 2 mm from 12 mm to 22 mm for the study. In each of Disc thickness considered T1, T2, T3 is varied to evaluate a total of 27 configurations of design proposal.

Table 3: Configurations of design proposal

Total disc thickness (Dt), mm	Inner cheek thickness (T1), mm	Vane thickness (T2), mm	Outer cheek thickness (T3), mm
12	4	4	4
	6	0	6
14	4	6	4
	5	4	5
	7	0	7
16	4	8	4
	5	6	5
	6	4	6
	8	0	8
18	4	10	4
	5	8	5
	6	6	6
	7	4	7
	9	0	9
20	4	12	4
	5	10	5
	6	8	6
	7	6	7
	8	4	8
	10	0	10
22	4	14	4
	5	12	5
	6	10	6
	7	8	7
	8	6	8
	9	4	9
	11	0	11

7.5 Results of proposed design

7.5.1 Results sheet of proposed design configurations

The results of conceptual disc brake are shown in the table 4. Maximum temperature attained in the braking cycle, temperature retained in the component at the end of braking cycle, maximum stress obtained in the braking cycle and the stress level at the end of braking cycle is reported. A note of maximum displacement at the end of braking cycle is also provided.

Table 4: Result table of composite disc brake configurations

Disc thickness (Dt), mm	T1_T2_T3	Max temp @ cycle, °C	Temp @ cycle end, °C	Temp. Difference, oC	Max stress, N/m²	Stress, N/m2	Displacement, mm
12	4_4_4	147.32	77.16	70.16	#########	#########	#########
	6_0_6	131.92	71.49	60.43	#########	#########	#########
14	4_6_4	144.94	75.65	69.29	#########	#########	#########
	5_4_5	136.36	72.72	63.64	#########	#########	#########
	7_0_7	126.01	67.48	58.53	#########	#########	#########
16	4_8_4	151.53	74.8	76.73	#########	#########	#########
	5_6_5	141.34	71.29	70.05	#########	#########	#########
	6_4_6	134.61	68.41	66.2	#########	#########	#########
	8_0_8	126.90	63.92	62.98	#########	#########	#########
18	4_10_4	143.03	73.56	69.47	#########	#########	#########
	5_8_5	140.15	70.39	66.76	#########	#########	#########
	6_6_6	133.49	67.47	66.02	#########	#########	#########
	7_4_7	129.02	64.98	64.04	#########	#########	#########
	9_0_9	123.85	61.1	62.75	#########	#########	#########
20	4_12_4	149.62	71.87	77.75	#########	#########	#########
	5_10_5	139.49	69.19	70.3	#########	#########	#########
	6_8_6	132.86	66.58	66.28	#########	#########	#########
	7_6_7	128.42	63.89	64.53	#########	#########	#########
	8_4_8	125.40	61.97	63.43	#########	#########	#########
	10_0_10	121.92	58.14	63.78	#########	#########	#########
22	4_14_4	154.54	70.67	83.87	#########	#########	#########
	5_12_5	143.97	67.7	76.27	#########	#########	#########
	6_10_6	137.21	65.26	71.95	#########	#########	#########
	7_8_7	131.60	63.02	68.58	#########	#########	#########
	8_6_8	128.37	61.17	67.2	#########	#########	#########
	9_4_9	126.16	59.06	67.1	#########	#########	#########
	11_0_11	123.62	56.06	67.56	2.16E+08	#########	#########

7.5.2 Results Interpretation

To find out the optimum design out of 27 configurations Temperature v/s Disc thickness plot is taken for each Cheek thickness category.

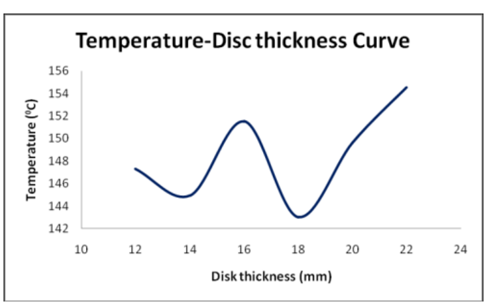


Figure 18: Temperature-Thickness plot for 4mm cheek thickness

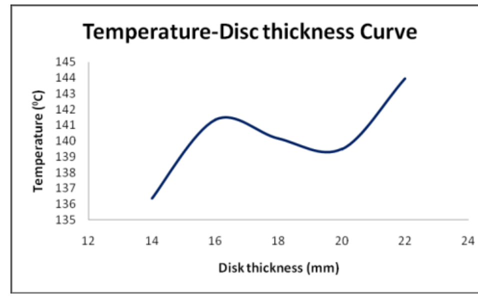


Figure 19: Temperature-Thickness plot for 5mm cheek thickness

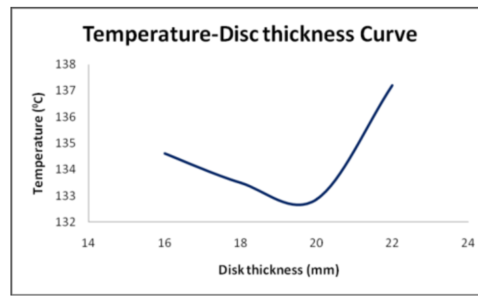


Figure 20: Temperature-Thickness plot for 6mm cheek thickness

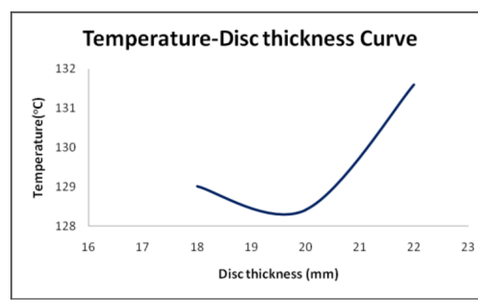


Figure 21: Temperature-Thickness plot for 7mm cheek thickness

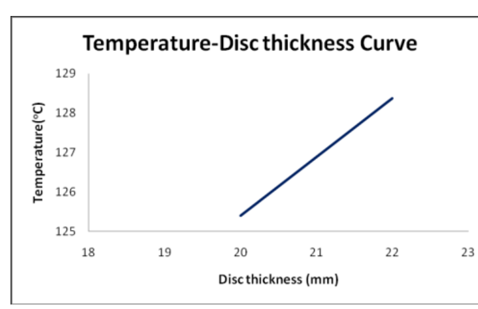


Figure 22: Temperature-Thickness plot for 8mm cheek thickness

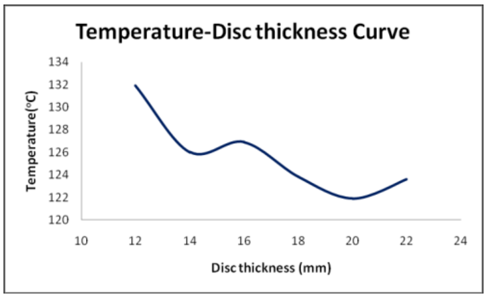


Figure 23: Temperature-Thickness plot for No-Vane configurations

From the curve in figure 18, we can interpret that for 4mm cheek thickness the minimum temperature is observed for disc thickness 18mm and the temperature value is 143.03 ^{o}C.

From the curve in figure 19, we can interpret that for 5mm cheek thickness the minimum temperature is observed for disc thickness 14mm and the temperature value is 136.36 ^{o}C.

From the curve in figure 20, we can interpret that for 6mm cheek thickness the minimum temperature is observed for disc thickness 20mm and the temperature value is 132.86 ^{o}C.

From the curve in figure 21, we can interpret that for 7mm cheek thickness the minimum temperature is observed for disc thickness 20mm and the temperature value is 128.42 ^{o}C.

From the curve in figure 22, we can interpret that for 8mm cheek thickness the minimum temperature is observed for disc thickness 20mm and the temperature value is 125.40 ^{o}C.

From the curve in figure 23, we can interpret that for No-Vane configuration the minimum temperature is observed for disc thickness 20mm and the temperature value is 121.92 ^{o}C.

8. Result summary

Table 5 shows the result summary in the tabulated form.

Table 5: Result summary

Rotor Material	Cheek Thickness mm	Optimum disc thickness @ Cheek thickness mm	Maximum Temperature ^{o}C	Temperature @ cycle end ^{o}C	Temperature drop ^{o}C	Maximum stress Mpa	Maximum displacement mm
Composite	4	18	143.03	77.16	69.47	249.1	0.0317
	5	14	136.36	72.72	63.64	232.5	0.0279
	6	20	132.86	66.58	66.28	227.36	0.0299
	7	20	128.42	63.89	64.53	218.32	0.0287
	8	20	125.4	61.97	63.43	211.99	0.0273
	No vane	20	121.92	58.14	63.78	204.35	0.025
Cast iron	6	20	89.01	53.49	35.52	68.98	0.0927

The heat dissipation capacity is higher in case of configuration with 4 mm Cheek thickness and Disc thickness of 18 mm as the temperature drop in the braking cycle is higher. But the maximum temperature attained in the cycle is higher compared to other configurations.

The maximum temperature attained in the configuration having Cheek thickness 5mm and Disc thickness 14 mm is comparatively higher and also the heat dissipation capacity is lower as the temperature drop in the braking cycle is comparatively lower.

The configuration having Cheek thickness of 6 mm and Disc thickness of 20 mm has good heat dissipation capacity and also the maximum temperature attained is comparatively low.

The configuration having Cheek thickness of 7 mm and Disc thickness of 20 mm has comparatively good heat dissipation capacity and also the maximum temperature attained is comparatively low.

With the configuration having Cheek thickness 8 mm and disc thickness the maximum temperature attained is low but the heat dissipation capacity is poor.

In the configurations having no Vane the maximum temperature attained is lower but the heat dissipation capacity is lower. Above that due the absence of the vanes the disc should be modeled as complete solid which will result in increase of weight.

9. Conclusion

As a conclusion the configuration having Cheek thickness of 6 mm with Disc thickness of 20 mm and the configuration having Cheek thickness of 7 mm with Disc thickness of 20 mm are considered to perform better in the given operating conditions.

Among these configurations the configuration with 7 mm Cheek thickness and the Disc thickness 20 mm will provide best results in multiple braking cycles.

Table 6 shows the comparison between Given disc brake and the proposed configuration of Disc brake assembly.

Table 5: Result comparison between Grey Cast Iron and Composite disc brake.

	Grey Cast Iron	Composite	Units
Ultimate / Yield strength	250	1800	MPa
Max. temp @ 10 cycle	270.31	334.36	°C
Max. Stress @ 10 cycle	148.8	500.42	MPa
Max. Displacement @ 10 cycle	0.9589	0.3232	mm

In both the cases the Max stress at 10th braking cycle is well within the ultimate/ yield strength of the material. Comparatively Yield strength of carbon fiber reinforced carbon/SiC hybrid matrix composites is higher and hence the Maximum stress obtained is low for the material. The maximum displacement achieved is also lower in case of composite brake. Thus conclusion is made stating that the Brake disc of configuration having Cheek thickness of 7 mm and Disc thickness of 20 mm is best alternative for the Brake disc made of Grey cast iron material.

8. Reference

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