International Journal of
Advanced Thermofluid Research

ISSN 2455-1368
www.ijatr.org

Impact of Curved Vents, Holes and Slots on Thermo-mechanical Behavior of Automobile Disc Brake - FEM Simulation and Validation

Asif Afzal [1]* and M. Abdul Mujeebu [2]

[1]*Department of Mechanical Engineering, P. A. College of Engineering, (Visvesvaraya Technological University), Mangaluru, India.*
[2]*Department of Building Engineering, College of Architecture and Planning, Imam Abdulrahman Bin Faisal University, 31451 Dammam, Saudi Arabia.*

Keywords
Disc Brake •
Pressure Pad •
Solid Disc •
Ventilated Disc •
Thermal Analysis •
Contact Pressure •
Total Deformation.

Received
September 18, 2020
Revised
November 20, 2020
Accepted
November 25, 2020
Published
December 01, 2020

Abstract

Ventilated discs have gained significant attraction for automobile disc brake due to enhanced thermal performance, but the optimal choice needs careful analysis of thermal and structural behaviors. Following the previous studies on solid and straight ventilated discs, the present study considers discs with three new ventilation patterns namely curved vents, curved vents with holes and curved vents with holes and slots. Three-dimensional modeling was done by SOLIDWORKS 15, and finite element simulation was performed by ANSYS 15. In the thermal analysis, the temperature history during one braking cycle was studied for each model, and the structural parameters analyzed include total deformation, Von Mises stress and contact pressure. The study shows that changing from straight vents to curved vents improves thermal performance without affecting the mechanical behavior. Moreover, the thermo-mechanical behavior is further improved by adding holes and slots on the surface, along with curved vents.

*Corresponding email: asif.afzal86@gmail.com (Asif Afzal).

DOI: https://doi.org/10.51141/IJATR.2020.6.1.3

1. Introduction

The growing rate of accidents has led to extensive developments in the design of braking systems (A. F. B. Shaik & Srinivas, 2012). Disc brake is a major part of braking system and therefore is responsible in decelerating the vehicle. In order to ensure the best performance, the heat energy generated due to friction in the disc brake has to be dissipated in minimum time. If the disc brake is completely solid, there will be more contact area between the bake pad and the disc. While this is an advantage to improve braking, the excessive heat generation due to friction affects cooling of the disc. Many researchers have focused on improved designs and means to increase the heat transfer rate (A. Belhocine & Bouchetara, 2012; Ali Belhocine & Bouchetara, 2012, 2013a; Das et al., 2013; Reddy et al., 2013; Sushma et al., 2015; Vivek Agnihotri & M.K. Chopra, 2014). Generally, vents or holes are provided in the solid disc to enhance the heat transfer rate as the surface area-to-volume ratio increases. The high temperature causes deformation and thermal stresses, which leads to creep, fatigue failure and cracks. Hence, a careful analysis of the thermo-mechanical performance of the disc brake is very crucial in the design of efficient braking systems.

Gao and Lin (Gao & Lin, 2002) showed that the contact temperature significantly affects the frictional power due to speed, load, durability and thermo-elastic instability of the material. The effect of sliding speed on thermo-mechanical properties of disc brake was studied by Pinto et al. (Pinto et al., 2017) who showed that, increased sliding speed caused non-uniform contact pressure and high temperature, which led to hot spots. Abubakar and Ouyang (AbuBakar & Ouyang, 2008) developed a finite element (FE) model of a real disc brake to predict the frictional wear. The predictions were validated by measured static contact pressure distribution and surface topography of the friction material. Ventilated discs have controlled temperature stresses, owing to their lesser weight and enhanced convective heat transfer coefficient compared to solid discs (Jacobsson, 2003). There have been a couple of different studies on brake disc-crack initiation, thermal distortions in a brake rotor, and ventilated air flow in brake discs. In a study on ventilated disc brake based on 3D thermo-mechanical coupling model, Hwang and Wu (Hwang & Wu, 2010) showed that in a single braking, temperature field affected the thermal expansion, which led to variation of contact pressure distribution. They obtained lower temperature in the vanes, which was due to the effect of disc conductivity and higher convection in the vanes. The maximum contact pressure was observed at the center of contact region due to the thermo-mechanical coupling behavior.

Nouby et al. (Nouby et al., 2011) studied the effect of disc brake material on squeal noise generation by using an FE model. The most commonly used materials were considered for the analysis. It was shown that the pad friction material was the highest contributor (56%) of squeal generation, followed by rotor (22%), caliper (11%) and bracket (11%) materials. Belhocine and Bouchetara (Ali Belhocine & Bouchetara, 2012) performed thermal analysis of non-ventilated and ventilated brake discs by using the FE tool ANSYS. Transient simulations were done with three types of cast iron (AL FG 25, FG 20 and FG 15) for a determined braking mode. They showed that the radial ventilation played significant role in cooling the disc during braking. In a study on the effect of fiber type on the mechanical and tribological properties of brake friction materials, Ozturk et al. (Öztürk et al., 2013) found that the friction coefficient decreased with increasing sliding speed and applied load. However, it increased with increase of disc temperature up to 3000C but decreased thereafter. Among the tested materials, the best performance was obtained for E-glass and steel wool fiber–reinforced composites in terms of friction coefficient and specific wear rate, respectively.

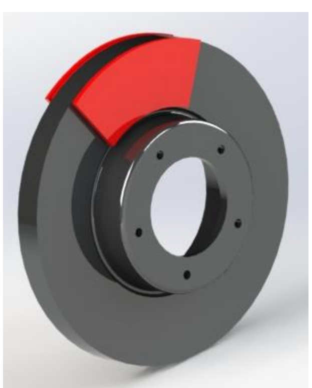
Belhocine et al. (Ali Belhocine et al., 2014) studied the temperature distribution of full and ventilated brake discs during braking operation by using FE analysis. The radial ventilation was found to have significant role in cooling the disc in the braking phase. The critical temperature of the rotor was also observed by considering the material used, the geometric design of the disc and the mode of braking. The dust generated during braking of vehicles leads to staining of wheels and can cause environmental pollution. The brake pad materials, during friction release wear particles which are of some micrometer in size and are inhalable (Mosleh & Khemet, 2006). According to Jang and Ahn (Jang & Ahn, 2007) these hot spots form local stresses of high intensity which causes material degradation and finally failure of the system. The hot spots act as a source of unwanted frictional vibrations known as 'hot roughness' as observed by Barber and Zagrodzki (Yun-Bo et al., 2000). But, in ventilated disc, the hot roughness is mainly due to uneven temperature distribution across the disc brake. Due to reduced area, the thermal capacity is reduced and temperature of the disc increases quickly during frequent braking (Jung et al., 2012).

The literature shows that several analyses were carried out by many researchers, on solid disc and disc with straight vents (A. Belhocine et al., 2014; A. Belhocine & Bouchetara, 2012; A Belhocine, 2016; A Belhocine et al., 2014; Ali. Belhocine, 2014; Ali Belhocine et al., 2014; Ali Belhocine & Bouchetara, 2012, 2013a, 2013b, 2013c; Bouchetara et al., 2014). However, discs with curved vents, curved vents and holes, and with curved vents, holes and slots, have not been investigated. Accordingly, the present study focuses on the thermal and structural analyses of these three types of brake discs. Solid disc and disc with straight vents are considered as reference models in this study. Solid Works 15 is used to model the disc brakes and ANSYS 15 computing software is used to perform the analysis.

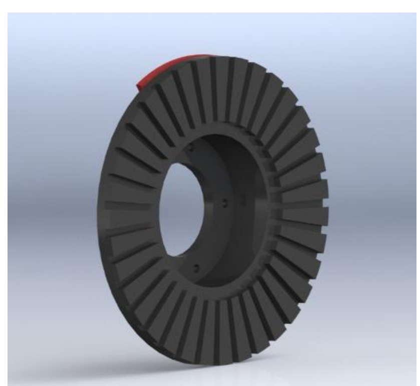
2. Methodology

2.1. Finite Element Model and Boundary Conditions

During the braking of vehicle, the kinetic energy is converted in to heat energy as evident by the high temperature of the disc (300-800°C). The heat generation is due to friction between the disc pad and the disc rotor. The heat is completely absorbed by the disc rotor, and the heat flux emitted is due to and proportional to friction between the surfaces. As soon the brake is applied, due to friction, heat flux reaches its maximum in a short span of time (< 5 seconds) and drops rapidly due to the release of the brake. The heat flux has to be dissipated across the disc rotor cross section. In this work, a 3-D analysis was performed to study the structural and thermal behaviors of solid disc and solid disc with different vents, holes and slots as shown in Figure 1. The models were meshed by using tetrahedral three-dimensional elements with 10 nodes (iso-parametric). The Models 1 and 2 were included for the purpose of comparison with the new models (Models 3, 4 & 5) considered in this study.

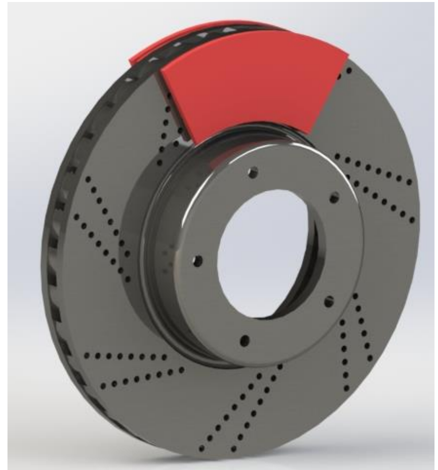


Model 1: Solid disc

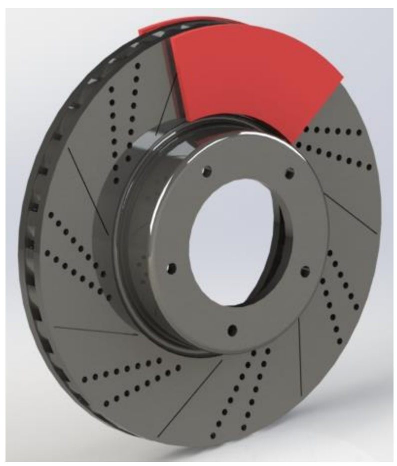


Model 2: Straight ventilated disc

Model 3: Curved ventilated disc



Model 4: Curved ventilated disc with holes



Model 5: Curved ventilated disc with holes and slots on outer surface

Figure 1: The different models built in SOLIDWORKS 15.

The governing equation for the heat conduction in cylindrical coordinate system for the unsteady state is given by,

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r k_r \frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) \tag{1}$$

where ρ stands for density, c is specific heat, k_r is thermal conductivity along radius of the material and k_z is thermal conductivity of the material along z-axis. The boundary conditions considered were $T = T^*$ and $q_n =$

q_n^* where $T^*$is the specified temperature of disc surface, q_n^* is the frictional surface heat flux at the contact of disc and pad. The convective boundary condition was represented by $q_n = h(T - T_\infty)$, where $T = 60°\text{C}$ i.e. initial temperature of the disc at time *(t)* =0 seconds, T_∞ is the surrounding air temperature and h is the convective heat transfer coefficient.

The generated heat is initially transferred by conduction followed by convection to the surrounding air. The heat flux (q_o) entering the disc rotor is estimated by,

$$q_0 = \frac{1-\emptyset}{2}\frac{mgvz}{2A_d\varepsilon_p} \quad (2)$$

where the breaking effectiveness $z = a/g$, a is the deceleration of the vehicle given in m/s^2, g is acceleration due to gravity in m/s^2. m is the vehicle mass in kg, v is initial velocity of the vehicle in m/s, A_d is surface swept by the disc brake pad in m^2, and ε_p distribution load factor.

The dimensions of disc and factors employed in thermal computations are mentioned in Table 1. Gray cast iron (FG15) is the material of disc brake, and its thermo-elastic properties are widely available in the literature (A. Shaik & Srinivas, 2012). Rotors are made of cast iron for three reasons: 1) hard and wear-resistant 2) cheaper than aluminum or steel 3) good heat dissipation and absorption.

The assumptions and boundary conditions of the present analysis are as follows (A Afzal et al., 2017; Asif Afzal & Abdul Mujeebu, 2019; Pinto et al., 2017):

- All kinetic energy at disc brake rotor surface is converted into frictional heat.
- The heat transfer is only by conduction and convection (radiation is only about 5% to 10%, so it is neglected).
- The disc material is homogeneous and isotropic.
- The domain is axis-symmetric.
- Inertia and body force effects are negligible.
- The disc is stress-free before the application of brake.
- the ambient temperature and initial temperature has been set to 20°C
- All other possible disc brake loads are neglected.
- Convection occurs only certain parts of disc brake rotor such as cooling vanes area, outer ring diameter area and disc brake surface
- Uniform pressure distribution by the brake pad onto the disc brake surface
- Thermal conductivity and specific heat are functions of temperature.
- The initial temperature of the disc is constant.

- The boundary conditions for the transient thermal problem are,
  - Heat flux entering the disc is localized in the contact zone of disc-pad in both sides.
  - Heat transfer is by convection on all surfaces of the disc.

2.2 Loading Conditions in ANSYS 15

The meshed models were exported to ANSYS workbench for thermal and structural analyses. For thermal analysis, the temperature distribution depends upon the heat flux entering the disc through both sides of the disc and wall heat transfer coefficient. For analysis, the initial and boundary conditions were introduced in the transient thermal module of ANSYS. The conditions for numerical analysis are summarized in Table 2. For structural analysis, temperature and corresponding stress in disc brake vary under freeway driving conditions. The initial and boundary condition were introduced in the structural module of ANSYS. The initial temperature is 60°C, the pressure applied on both sides was 1 MPa, and the rotational speed of the disc was 157.89 rad/s. The grid sizes chosen and the respective temperature obtained are mentioned in Table 3. As there was no significant variation in % temperature difference with the actual for the last two sizes, the grid size of 286569 was adopted.

Table 1 Input parameters

Parameter	**Values**
Disc diameter	318 mm
Disc thickness	28 mm
Overall height of disc	67 mm
Centre diameter	98 mm
Mass of automobile	1380 kg
Top speed of automobile	160 mph
Effective radius of rotor	110 mm
Deceleration	12.9 ms^{-2}

Table 2 Step control inputs

Number of steps	5
Current step number	4
Step end time	30s

Auto time stepping	On Time
Carryover time step	Off
Initial Time step	0.25s
Time integration	On
Initial temperature of disc	60 °C
Material of disc	Grey Cast Iron FG15

Table 3. Grid independence study

Grid size	Peak temperature	% difference
253467	485.65	4.5 %
286569	502.71	1.5%
306589	505.85	0.65%

2.3 Validation

The present FE simulation was validated by the results (temperature distribution) of previous works on solid disc and straight ventilated disc (Belhocine et al., 2012, 2013a, 2013b, 2013c, 2014, 2015). Figures 2 and 3 show that the temperature distributions of Models 1 and 2 are consistent with the previous works on solid and straight ventilated discs respectively. The discrepancies may be attributed to the variations in assumptions; for instance:

- The present analysis has considered only one braking cycle time from 0.1s to 45s, whereas in the previous works continuous cycles were considered.
- This study assumed uniform convective heat transfer coefficient for all the surfaces whereas it is variable for different surfaces of disc-pad assembly in the previous works.
- The dimensions for the models were considered from the manufacturer data which slightly varies compared to previous works.

The above assumptions were made basically to reduce the computing time, because unlike the previous works, the present analysis has considered coupled thermal and structural analysis for 5 models, which incurs huge computational cost for ANSYS.

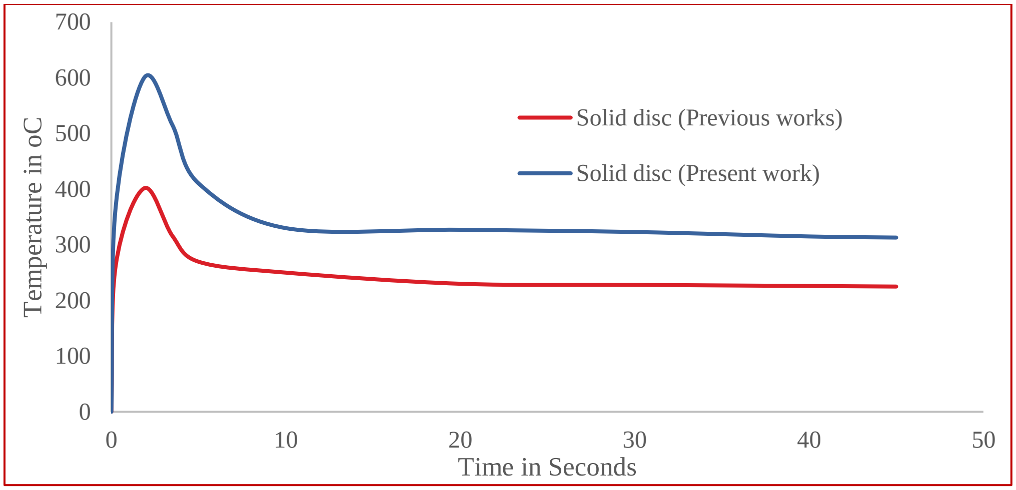


Figure 2: Validation for solid disc (Model 1).

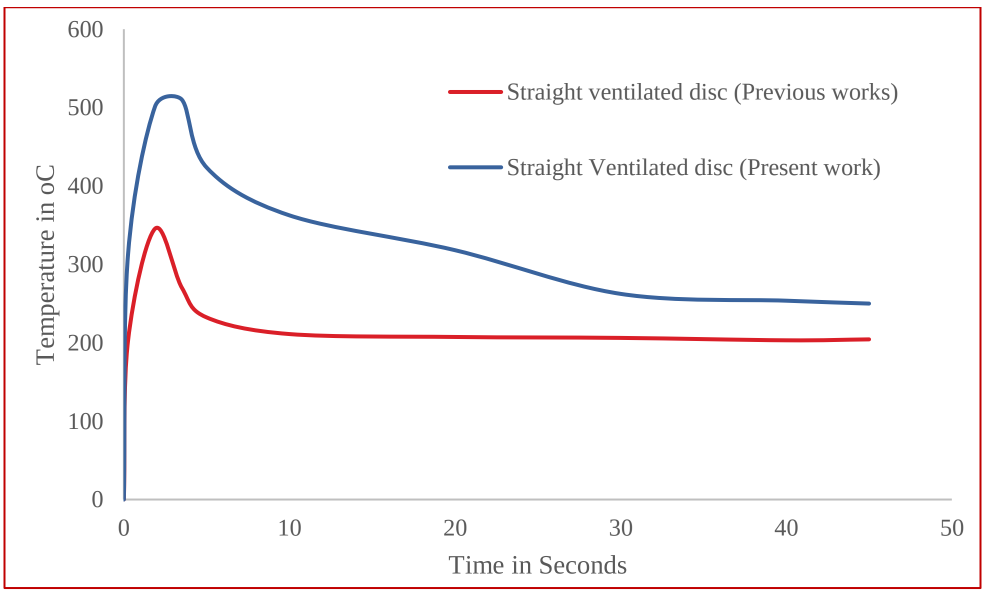


Figure 3. Validation for straight ventilated disc (Model 2).

3. Results and Discussion

3.1 Thermal analysis

In the thermal analysis, the temperature distribution in time and space for all the models are studied to compare their peak temperatures and cooling patterns. Figure 4 compares the temperature distribution and history of the tested models from 0.1s to 45s. It is well known that the temperature is indicative of heat generation, and the heat dissipation is enhanced by increasing the surface-area-to-volume ratio. This is evident from the peak temperature and cooling patterns of the models, wherein the solid disc (Model 1) has the highest peak temperature (592^{0}C) and it decreases with the extent of ventilation. Similarly, the effect of ventilation on the cooling pattern is also obvious. As can be seen in Figure 1, the geometry of the curved vents (Model 3) allows easier and rather more effective entry of air into the disc surface compared to the straight vents (Model 2), which reduces peak temperature and enhances cooling. Further enhancement in heat transfer could be achieved by adding holes (Model 4) and slots (Model5). This approves Model 5 as the best choice in terms of thermal behavior. The heating and cooling patterns are similar to those obtained in previous works with solid and straight ventilated discs (A. Belhocine & Bouchetara, 2012; Ali Belhocine & Bouchetara, 2012).

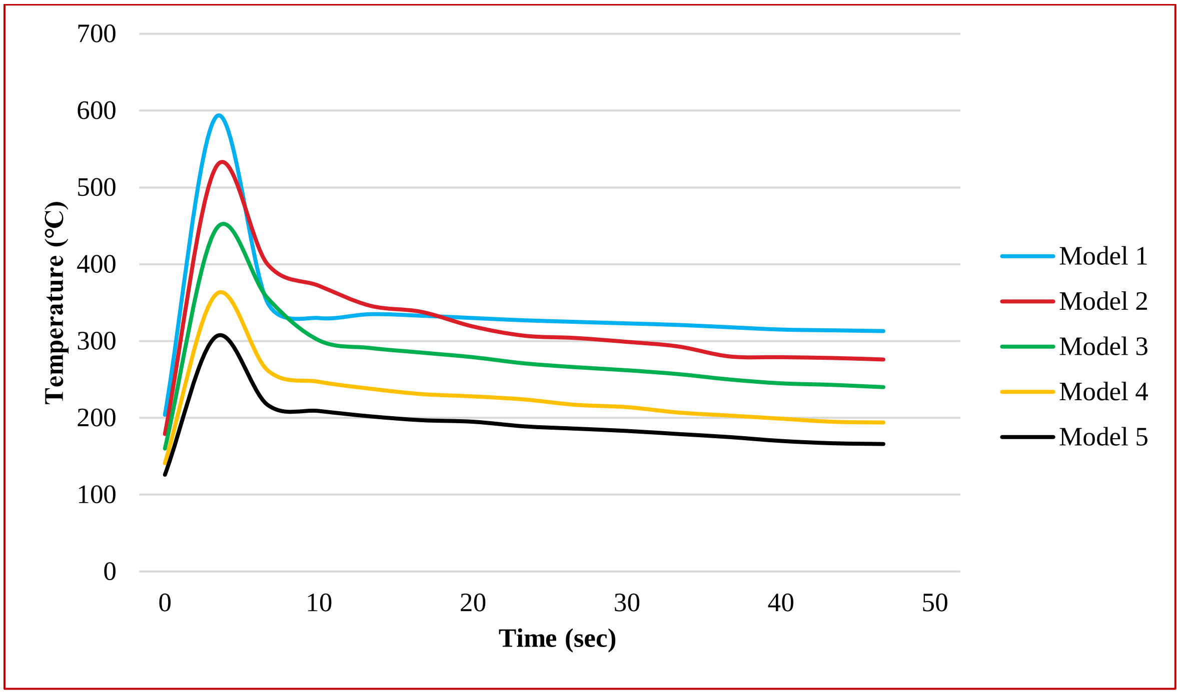


Figure 4: Comparison of temperature vs time.

3.2 Structural Analysis

3.2.1 Total Deformation

Total deformation is a prime parameter that indicates the structural behavior of the disc. The extent of deformation within the disc material during the braking is observed for all the models with a time interval of 1s, up to the stop of brake (4s). Figure 5 compares the deformation patters of the tested models and Figure 6 shows the deformation contours obtained from ANSYS at 4s. The deformation gradually increases almost linearly with time (due to increase of pressure applied) and reaches to maximum at stopping (4s). While comparing different models, it is worth noting that, the deformation in Model 4 is highest followed by Model 5. Models 2 and 3 show a common pattern while Model 1 has the least deformation.

In general, vents, holes and slots induce more deformation, due to the reduced strength caused by reduction in mass. Models 2 and 3 have similar deformation patterns, which indicates that changing the type of vent (from straight to curved vent) does not influence deformation. Nevertheless, by considering the better thermal performance, Model 3 would be a promising alternative to Model 2. When holes are added to the curved vents (Model 4), the deformation is increased to maximum. However the deformation is reduced by adding slots at the disc surface. This can be explained by the coupled thermo-mechanical behavior of the disc material. For instance, lesser ventilation yields higher strength and hence lesser deformation. On the other hand, enhanced heat transfer reduces peak temperature and also contributes to reduction in deformation. This is evident from Model 4 wherein the presence of holes increases deformation due to reduced strength. But interestingly, adding slots with curved vents and holes (Model 5) could reduce the deformation (compared to Model 4) even though there is reduction in mass. This is obviously due to the enhanced heat transfer by slots, which might have dominated the potential hike in deformation due the reduction in mass.

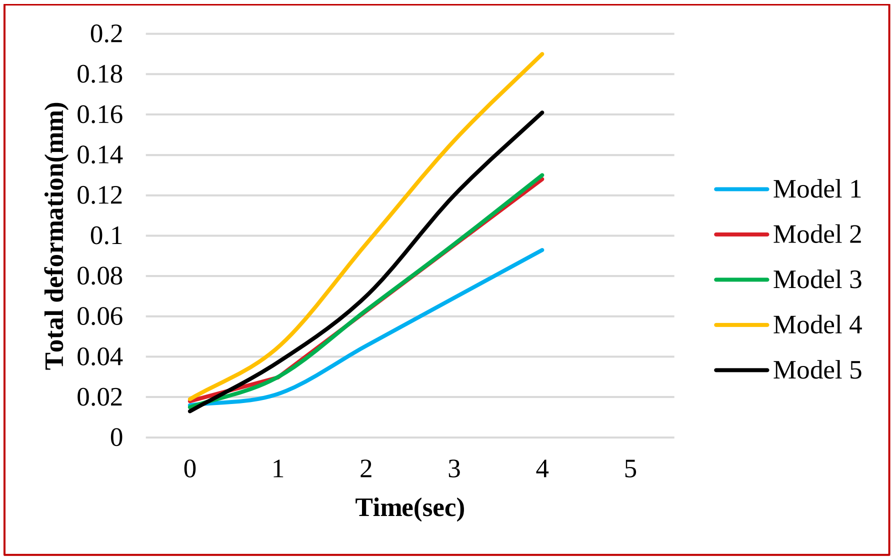
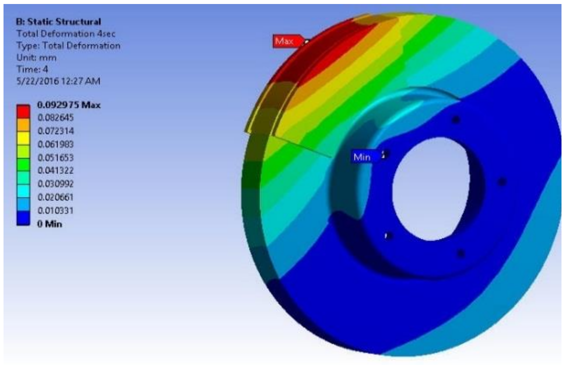
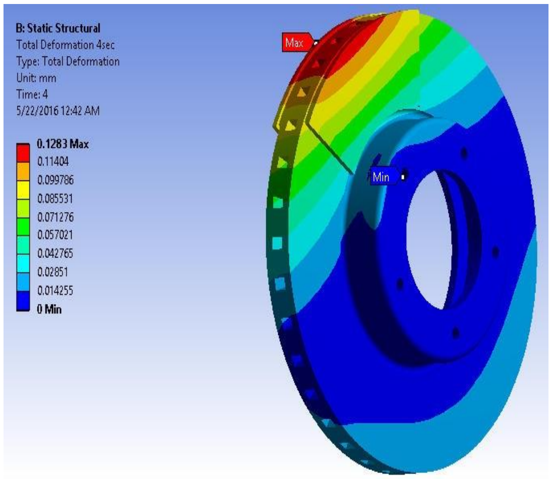


Figure 5: Comparison of total deformation vs time.

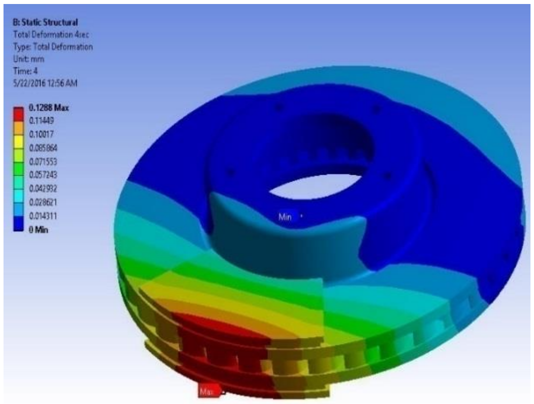
Thus, the choice could now be reduced between Models 3 and 5. Since Model 5 has better thermal performance and the increase in total deformation with respect to Model 3 is only 3μm (fairly acceptable), it can be considered as the best choice. This will be verified further in terms of stress and contact pressure. The deformation is also affected by the variation in contact surface area between the disc and pressure pads. For instance, the reduction in contact area due to holes in Models 4 and 5 caused increase of deformation, but this can be controlled by reducing the number of holes. However, since reducing the number holes compromises the thermal performance to some level, further thermo-mechanical analysis is required to arrive at the optimal number of holes.



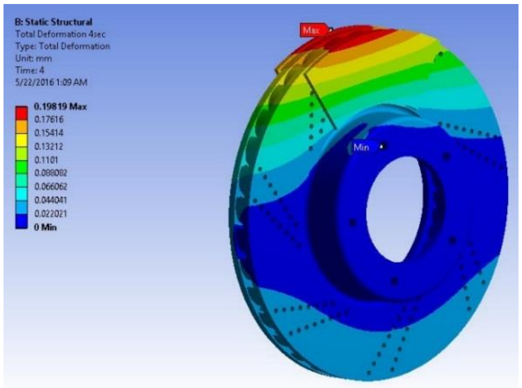
Model 1



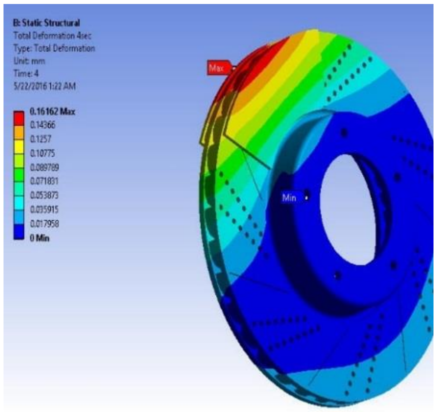
Model 2



Model 3



Model 4



Model 5

Figure 6: Total deformation contours for the models at 4s.

3.2.2 Von-Mises Stress

The Von-mises stress distribution for the models from 1s to 4s is shown in Figure 7. For the braking period considered, the maximum equivalent stress is seen at 4s, which varies between 130 MPa and 185 MPa for all the models considered. This variation is absolutely due to their geometry and thermo-mechanical coupling (Ali Belhocine & Bouchetara, 2014). The high temperature distribution and hence highest stress concentration in the solid disc is due to the least surface-area-to-volume ratio. The contours of von-mises stress distribution in Figure 8 indicate that the maximum stress occurs at the bolt-hole area, which is attributed to the enhanced shear and torsion as this part is fastened to the wheel hub by screws, preventing any relative motion between the hub and wheel.

While comparing the models based on stress distribution, it is obvious that the maximum stresses for Models 3, 4 and 5 fall between those of Model 1 (185 MPa at 4s) and Model 2 (130 MPa at 4s). It is well known that the stress development in solid disc (Model 1) is always higher than ventilated discs, so it would be meaningful to compare Models 3, 4 and 5 with Model 2. It can be observed that the stress distributions in the new models increase slightly (maximum 14%) compared to Model 2, but this variation is not detrimental. Slots are commonly known for enhanced stress concentration around the edges (Dongbin et al., 2016; Rees et al., 2012), hence Model 5 has slightly more stress concentration compared to Model 4; however, this is overcome by its better thermal behavior.

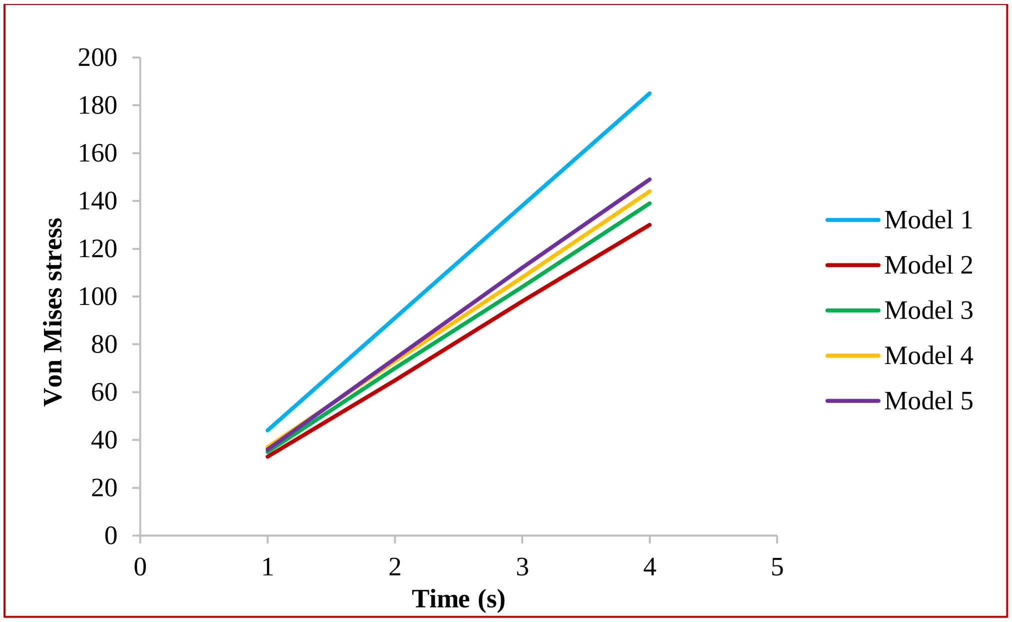
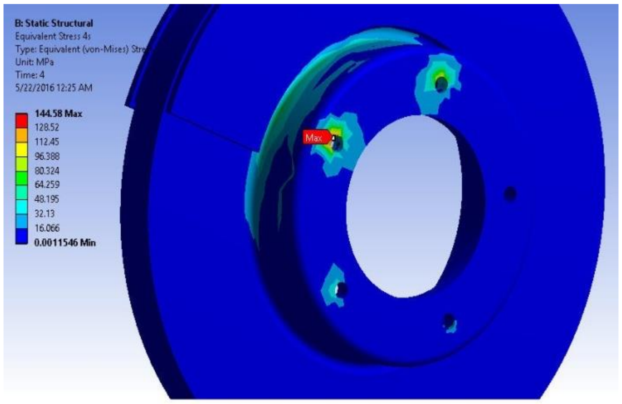
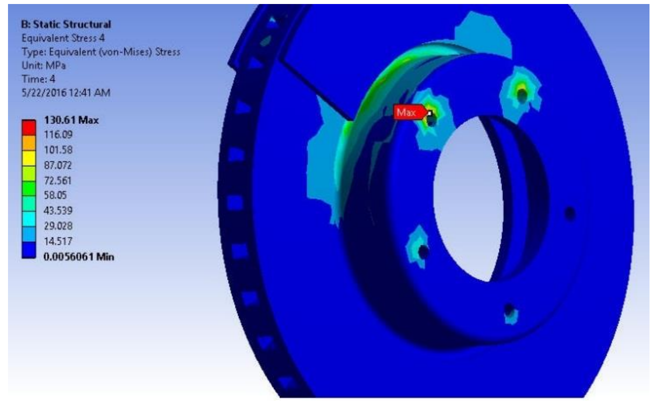


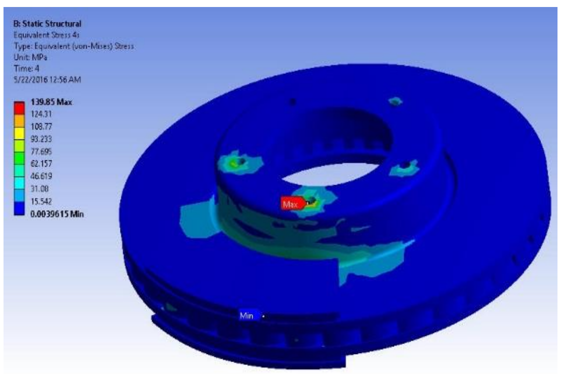
Figure 7: Comparison of Von Mises stress vs time.



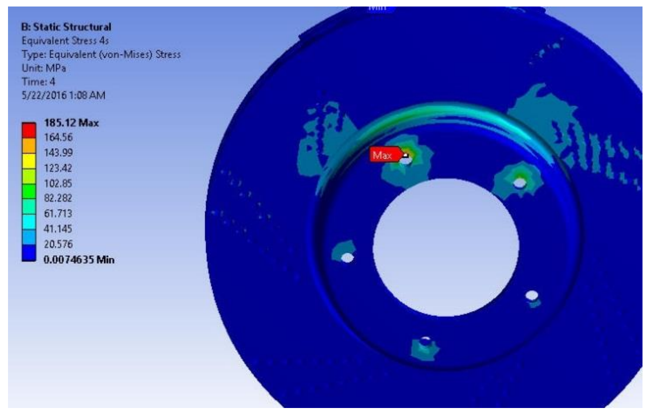
Model 1



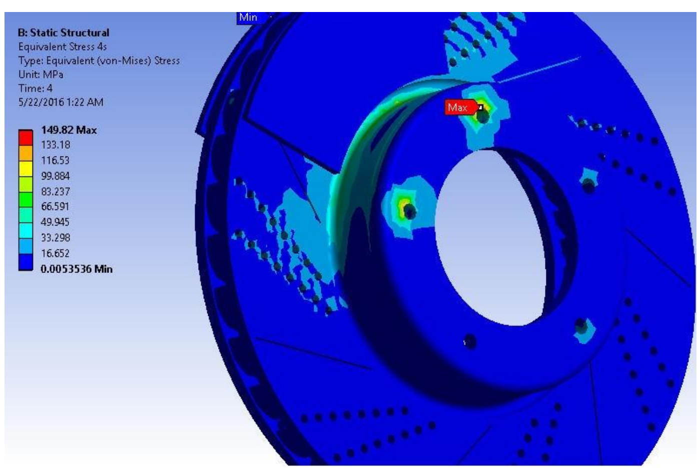
Model 2



Model 3



Model 4



Model 5

Figure 8: Von Mises stress distribution contours for the models at 4s.

3.3.3 Contact Pressure

Figure 9 shows the pressure variation for all the models due to contact between the pad and disc assembly coupled with thermal and mechanical effects of friction, and Figure 10 shows the corresponding contours at 4s. In all the 5 cases, the contact pressure increases linearly with breaking time (from 0 to 2.9 MPa) and reaches its maximum (1.9MPa to 2.9MPa) at t=4s. The maximum contact pressure is seen at the leading edge owing to the maximum contact, and it decreases towards the trailing edge; at the same time the pressure distribution shows a symmetric pattern (Ali Belhocine & Bouchetara, 2013c).

The contact between pad and hole-area in Models 4 and 5 causes wear in the pressure pads due to their cyclic expansion and contraction, which leads to debris accumulation on the disc surface and eventual deterioration of the pad. This can be compromised at certain level as the pads are easily replaceable and are cheaper than the main disc. Moreover, the slots in Model 5 accommodate some of the debris, which increases the pad life and reduces the extra noise or vibration caused (Mo et al., 2013; Wang et al., 2016). It is well known that higher contact pressure is always desirable for better braking performance. In this perspective, Model 5 seems to be the best, followed by Models 2 and 3 respectively. It is worth noting that Model 4 shows the least contact pressure, hence further study is needed to explore the scientific reason.

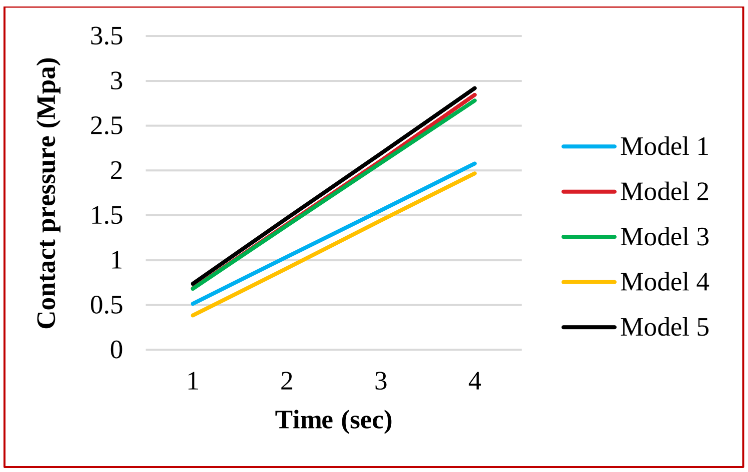
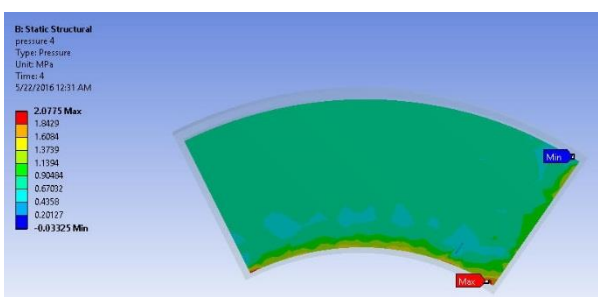
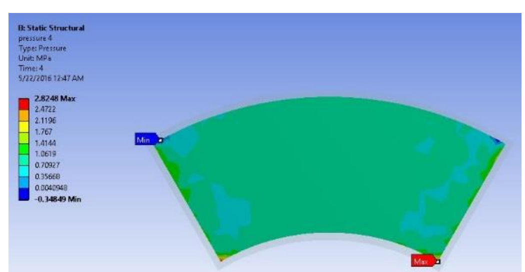


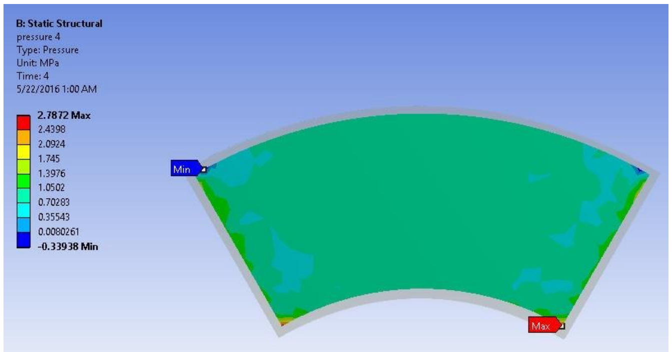
Figure 9: Comparison of contact pressure vs time.



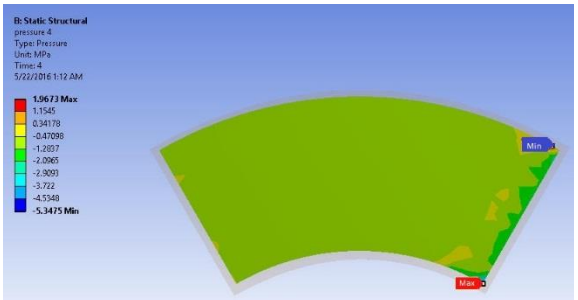
Model 1



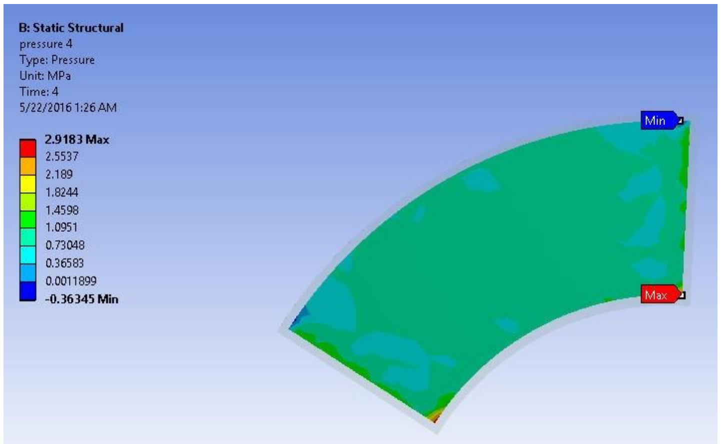
Model 2



Model 3



Model 4



Model 5

Figure 10. Contact pressure distribution of models at 4s.

4. Conclusion

Finite element simulation and analysis (by using ANSYS 15) was performed to verify the individual and combined influences of curved vents, holes and slots on the thermo-mechanical behavior of automobile brake disc made of gray cast iron. The new ventilation strategies studied are curved vents, curved vents with holes, and curved vents with holes and slots. Discs with these configurations were compared with solid and straight ventilated discs. The results were validated with those of previous works for slid and straight ventilated discs. The study has revealed the following:

- Changing from straight vents to curved vents improves thermal performance owing to enhanced heat dissipation, while the mechanical behavior is not affected
- Presence of holes with curved vents further improves the thermal behavior, but this is offset by decline of mechanical characteristics.
- The thermo-mechanical behavior is improved by addition of slots on the disc surface

Thus, it can be deduced that discs with curved vents, holes and slots are promising in terms of thermal and structural performances. However further analysis is needed to identify the optimal choice with respect to thermo-mechanical behavior, cost and reliability. Straight vents with holes, different disc and pad materials, and other pad configurations are also worth exploring. These are considered in the authors' future work.

References

AbuBakar, A. R., & Ouyang, H. (2008). Wear prediction of friction material and brake squeal using the finite element method. 264, 1069–1076. https://doi.org/10.1016/j.wear.2007.08.015

Afzal, A, Ansari, Z., Faizabadi, A., & Ramis, M. (2017). Parallelization strategies for computational fluid dynamics software: state of the art review. Archives of Computational Methods in Engineering, 24(2), 337–363. https://doi.org/https://doi.org/10.1007/s11831-016-9165-4

Afzal, Asif, & Abdul Mujeebu, M. (2019). Thermo-Mechanical and Structural Performances of Automobile Disc Brakes: A Review of Numerical and Experimental Studies. Archives of Computational Methods in Engineering, 26(5), 1489–1513. https://doi.org/https://doi.org/10.1007/s11831-018-9279-y

Pinto, R., Afzal, A., D'Souza, L., Ansari, Z., & Mohammed Samee, A. D. (2017). Computational Fluid Dynamics in Turbomachinery: A Review of State of the Art. Archives of Computational Methods in Engineering, 24(3), 467–479. https://doi.org/https://doi.org/10.1007/s1183

Belhocine, A., & Bouchetara, M. (2012). Thermal behavior of full and ventilated disc brakes of vehicles. Journal of Mechanical Science and Technology, 26(11), 3643–3652. https://doi.org/10.1007/s12206-012-0840-6

Belhocine, A., Ghazali, N. M., & Abdullah, O. I. (2014). Structural and contact analysis of a 3-dimensional disc-pad model with and without thermal effects. Tribology in Industry, 36(4), 406–418.

Belhocine, A. (2016). FE prediction of thermal performance and stresses in an automotive disc brake system. The International Journal of Advanced Manufacturing, 1–16. http://link.springer.com/article/10.1007/s00170-016-9357-y

Belhocine, A, Bouchetara, M., Bakar, A. R. A., & Nouby, M. (2014). Modeling of thermal contact problem of disc brake system with frictional heat generation. World Journal of Engineering, 11(4), 373–390. https://doi.org/10.1260/1708-5284.11.4.373

Belhocine, Ali. (2014). Structural and Contact Analysis of Disc Brake Assembly during Single Stop Braking Event. American Journal of Mechanics and Applications, 2(3), 21. https://doi.org/10.11648/j.ajma.20140203.12

Belhocine, Ali, Bakar, A. R. A., & Bouchetara, M. (2014). Numerical modeling of disc brake system in frictional contact. Tribology in Industry, 36(1), 49–66.

Belhocine, Ali, & Bouchetara, M. (2012). Thermal analysis of a solid brake disc. Applied Thermal Engineering, 32(1), 59–67. https://doi.org/10.1016/j.applthermaleng.2011.08.029

Belhocine, Ali, & Bouchetara, M. (2013a). Investigation of temperature and thermal stress in ventilated disc brake based on 3D thermomechanical coupling model. Ain Shams Engineering Journal, 4(3), 475–483. https://doi.org/10.1016/j.asej.2012.08.005

Belhocine, Ali, & Bouchetara, M. (2013b). Thermal- mechanical coupled analysis of a brake disc rotor. Elixir Publisher, 55(A), 13244–13250. https://doi.org/10.1007/s11668-012-9634-5

Belhocine, Ali, & Bouchetara, M. (2013c). Thermomechanical behaviour of dry contacts in disc brake rotor with a grey cast iron composition. Thermal Science, 17(2), 599–609. https://doi.org/10.2298/TSCI110826141B

Belhocine, Ali, & Bouchetara, M. (2014). Thermal Analysis of Automotive Brake Rotor. Archive of Mechanical Engineering, LXI(1), 89–113.

Bouchetara, M., Belhocine, A., Nouby, M., Barton, D. C., & Bakar, A. (2014). Thermal analysis of ventilated and full disc brake rotors with frictional heat generation. Applied and Computational Mechanics, Volume 8, pp 5-24.

Das, A. D., Raj, V. C. R., Preethy, S., & Bharani, G. R. (2013). Structural and Thermal Analysis of Disc Brake in Automobiles. International Journal of Latest Trends in Engineering and Technology, 2(3), 18–25.

Dongbin, Z., Xin, N., Peng, P., Mengzi, W., Kailai, D., & Yabin, C. (2016). Experimental study and fi nite element analysis of a buckling-restrained brace consisting of three steel tubes with slotted holes in the middle tube. Journal of Constructional Steel Research, 124, 1–11. https://doi.org/10.1016/j.jcsr.2016.05.003

Gao, C., & Lin, X. (2002). Transient temperature field analysis of a brake in a non-axisymmetric three-dimensional model. Journal of Materials Processing Technology, 129(1), 513–517. http://www.sciencedirect.com/science/article/pii/S0924013602006222

Hwang, P., & Wu, X. (2010). Investigation of temperature and thermal stress in ventilated disc brake based on 3D thermo-mechanical coupling model. Journal of Mechanical Science and Technology, 24(1), 81–84. https://doi.org/10.1007/s12206-009-1116-7

Jacobsson, H. (2003). Aspects of disc brake judder. Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 217(6), 419–430. http://pid.sagepub.com/content/217/6/419.short

Jang, Y., & Ahn, S. (2007). Frictionally-excited thermoelastic instability in functionally graded material. Wear, 262(9), 1102–1112. http://www.sciencedirect.com/science/article/pii/S0043164806004418

Jung, S., Kim, Y., & Park, T. (2012). A study on thermal characteristic analysis and shape optimization of a ventilated disc. International Journal of Precision Engineering and Manufacturing, 13(1), 57–63. https://doi.org/10.1007/s12541-012-0008-4

Mo, J. L., Wang, Z. G., Chen, G. X., Shao, T. M., Zhu, M. H., & Zhou, Z. R. (2013). The effect of groove-textured surface on friction and wear and friction-induced vibration and noise. Wear, 301, 671–681. https://doi.org/10.1016/j.wear.2013.01.082

Mosleh, M., & Khemet, B. (2006). A surface texturing approach for cleaner disc brakes. Tribology Transactions, 49(2), 279–283. http://www.tandfonline.com/doi/abs/10.1080/05698190600639913

Nouby, M., Abdo, J., Mathivanan, D., & Srinivasan, K. (2011). Evaluation of Disc Brake Materials for Squeal Reduction. Tribology Transactions, 54(4), 644–656. https://doi.org/10.1080/10402004.2011.587634

Öztürk, B., Arslan, F., & Öztürk, S. (2013). Effects of different kinds of fibers on mechanical and tribological properties of brake friction materials. Tribology Transactions, 56(4), 536–545. http://www.tandfonline.com/doi/abs/10.1080/10402004.2013.767399

Pinto, R., Afzal, A., D'Souza, L., Ansari, Z., & Mohammed Samee, A. D. (2017). Computational Fluid Dynamics in Turbomachinery: A Review of State of the Art. Archives of Computational Methods in Engineering, 24(3), 467–479. https://doi.org/https://doi.org/10.1007/s1183

Reddy, V. C., Reddy, M. G., & Gowd, G. H. (2013). Modeling And Analysis of FSAE Car Disc Brake Using FEM. International Journal of Emerging Technology and Advanced Engineering, 3(9), 383–389.

Rees, D. W. A., Bahai, H., & Taylor, S. (2012). Stress Concentrations for Slotted Plates in Bi-Axial Stress. Engineering, 4, 69–75.

Shaik, A. F. B., & Srinivas, C. L. (2012). Structural and thermal analysis of disc brake with and without crossdrilled rotar of race car. International Journal of Advanced Engineering Research and Studies (IJAERS), Volume IV(Issue July-Sept), pp 39-43.

Shaik, A., & Srinivas, C. (2012). Structural and thermal analysis of disc brake with and without crossdrilled rotar of race car. International Journal of Advanced Engineering Research and Studies, 1(4), 39–43. http://technicaljournalsonline.com/ijaers/VOL I/IJAERS VOL I ISSUE IV JULY SEPTEMBER 2012/202.pdf

Sushma, C. V, Reddy, P. R., Reddy, P. S., & Ramayee, L. (2015). Thermal and Structural Analysis of Disc Brake with Square / Circular Groove for Two Wheeler. 2(7), 74–79. https://doi.org/10.17148/IARJSET.2015.2716

Vivek Agnihotri & M.K. Chopra. (2014). Optimized thermo-structural analysis of solid and vented disc brake using finite element method (A case study). IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE), 11(4), 40–49. http://www.iosrjournals.org/iosr-jmce/papers/vol11-issue4/Version-5/G011454049.pdf

Wang, D. W., Mo, J. L., Liu, M. Q., Ouyang, H., & Zhou, Z. R. (2016). Noise performance improvements and tribological consequences of a pad-on-disc system through groove-textured disc surface. Tribology International, 102, 222–236. https://doi.org/10.1016/j.triboint.2016.05.030

Yun-Bo, Y. I., Barber, J. R., & Zagrodzki, P. (2000). Eigenvalue solution of thermoelastic instability problems using Fourier reductionf. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences, 456(2003), 2799–2821. https://doi.org/10.1098/rspa.2000.0641