THERMAL ANALYSIS OF VENTILATED DISC BRAKE ROTOR FOR UTEM FORMULA VARSITY RACE CAR

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ABSTRACT

A new design of disc brake using ventilated rotor was developed for the UTeM Formula Varsity racing car. Compacted graphite cast iron (CGI) was proposed as the material for the disc brake rotor. Thermal analysis was performed in this project to assess the component performance using ABAQUS/CAE v6.7-1 finite element analysis software both in transient condition. Results from the analysis show that the maximum temperature generated on the disc brake surface at the end of the braking procedure for transient condition was within the allowable service temperature of the ventilated rotor material. Thus, the new disc brake rotor is safe for operation and is expected to perform successfully as per design requirement.

***KEYWORDS**: formula varsity, disc brake rotor, thermal analysis, finite element analysis.*

1.0 INTRODUCTION

Formula Varsity is a student racing competition organized by Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM) (Faieza *et.al,* 2009). The competition was inspired by similar formula style racing competition such as Formula SAE where students compete in the challenge to design, fabricate, and race a single-seat open wheel formula style racing car in real track condition (http://students.sae.org). The UTeM Formula Varsity racing team took part in the Formula Varsity 2008 that was held in Melaka, and successfully emerged as the runner-up in the competition. Based on the valuable experiences gained from the event, design improvements had been initiated for the new version of the UTeM Formula Varsity racing car that would be competing in the upcoming 2010 Formula Varsity competition. One of the improvement taken was to redesign the disc brake rotor for the braking system of the new racing car.

In response towards the above goal, this project was conducted to study the performance of the new disc brake rotor design for the UTeM Formula Varsity racing car. Three dimensional geometrical model of the new component was created using CATIA V5 CAD software while commercial finite element analysis software ABAQUS/CAE was used to determine the thermal distribution and maximum temperature generated on the disc brake rotor surface in transient condition. Load analysis was also performed to determine the heat flux load and surface convection coefficient for the new rotor design.

2.0 LITERATURE REVIEW

The main function of disc brake rotor is for transmission of mechanical force and dissipation of heat produced implies to be functioning at both medium and high temperature. The rotor provides braking surface or friction surface for brake pads to rub against it when brake is applied. A disc brake rotor is generally made from grey cast iron due to cast iron provides good wear resistance with high thermal conductivity and the production cost is low compared to other disc brake rotor materials such as Al-MMC, carbon composites and ceramic based composites (Jang *et.al,* 2003). Currently, there are two types of disc brake rotor used in passenger car which is solid disc and ventilated disc.

A solid rotor is simply a solid piece of metal with friction surface on each side and this type of rotor is light, simple, cheap, and easy to manufacture. A ventilated disc meanwhile refers to the brake disc or rotor with various opening profiles (holes, grooves, etc.) which provide better cooling performance (additional heat transfer function) and weight savings as well as aesthetic appearance (Jacobsson, 2003). Therefore, it is widely used compared to solid disc.

The thermal stability of the disc shape is influenced by the quantity of the material and the heat treatment before machining as well as the basic design for the disc rotor. Some of the thermally most important properties of disc brake rotor are as follows (Jacobsson, 2003):-

i) Thermal capacitance (density and specific heat) is the ability to store the heat. Initially on braking process, a significant amount of frictional heat is stored and during short braking, this thermal capacitance is dominates.

ii) Heat dissipation becomes important consideration at long braking times (above 2-3 minutes). The convection is occurring for more than 90% of the total heat dissipation in most of the braking condition, whereby radiation is almost negligible.

iii) Thermal conductivity is the ability to re-distribute the thermal energy. During long and low intensity braking, the peak temperature is depends largely on the disc material's conductivity. However, the thermal conductivity has a little effect during short braking.

iv) Thermal expansion coefficient (related to location of friction contact due to the thermal deformation) affects the tendency towards hot spotting and thermal disc thickness variation (DTV) generation. The temperature gradients of the disc brake can cause to temporary DTV owing to the uneven thermal expansion of the material.

Heat transfer is energy in transit, which occurs as result of a temperature gradient or difference. This temperature difference is thought of as a driving force that causes heat to flow. Heat transfer for a ventilated disc brake rotor occurs by three mechanism or modes: conduction, convection and radiation. Ventilated disc brake generally exhibit convective heat transfer coefficient that is approximately twice as large as those associated with solid discs. During a continued braking, a ventilated disc usually tends to reach a temperature which is approximately 60% of the temperature of a solid disc.

Excessive thermal heat (which in more severe cases where it exceeds the allowable thermal capacity of the disc brake material especially for the rotor), generate undesirable thermal stress with few unfavorable conditions such as surface cracks and permanent disc brake distortion. These defects can give result to failure of the component during operation and may cause life casualties to onboard passenger of the vehicle.

3.0 METHODOLOGY

The overall thermal analysis procedure performed in this project is shown in Figure 1 below.

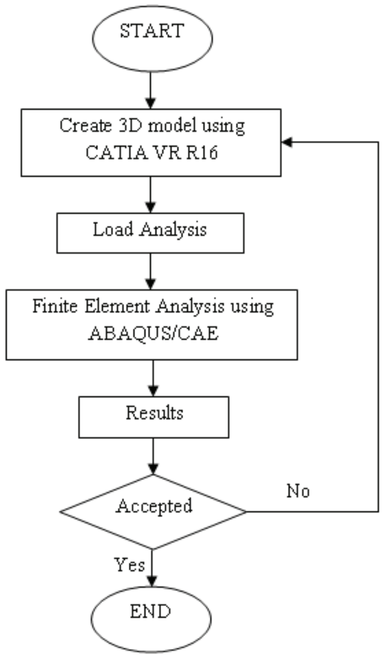


Figure 1 Overall thermal analysis flow chart

The new disc brake rotor design utilized the ventilated concept where ventilation holes were created in symmetrical configuration for the design to enable higher cooling capability and reduce in weight compared to solid rotor disc. A part from that, compacted graphite cast iron or CGI was also proposed as the new material for the rotor design where it offers lower material density and higher specific heat compared to gray cast iron which is used for the current disc brake rotor (http://www.sintercast.com). Compacted graphite cast iron is able to provide the weight saving advantage which can notably contribute in reducing the overall car weight. The 3D model of the new rotor design as shown in Figure 2 below was created using CATIA V5 R16 CAD software and is used as the geometrical model for the finite element modeling during the thermal analysis stage.

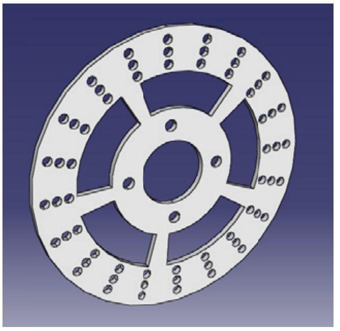


Figure 2 The 3D model of the new ventilated disc brake rotor design

In the load analysis stage, heat flux and convection heat transfer coefficients has been determined based on the minimum overall car load (total car curb weight and one driver) as stated in the 2008 Formula Varsity car design specification which is 200 kg (http://formulavarsity.wordpress.com). Finite element software ABAQUS/CAE v6.7-1 was used during the thermal analysis stage. In this stage, the material properties, load and boundary conditions as well as meshing properties are all assigned to the geometrical disc brake rotor model.

4.0 LOAD ANALYSIS

A total of 10 braking cycles were applied during the transient analysis in this project with vehicle braking patterns as suggested by Gotowicki (2005) as shown in Figure 3.

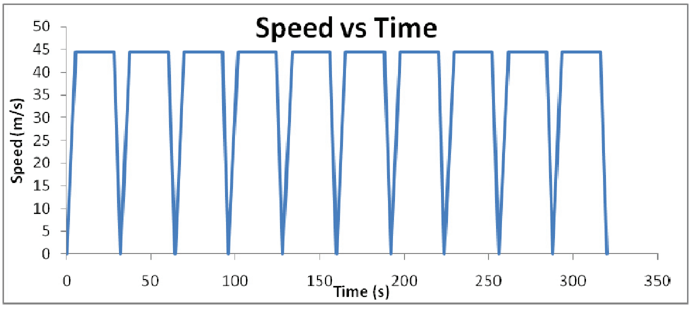


Figure 3 Speed versus time for 10 cycles of braking

The heat flux applied to the disc brake rotor is calculated during the braking stage. Total braking time for each cycle is 2.83 seconds, corresponding to the amount of time the brake rotor is heated during operation. To simplify the analysis, several assumptions have been made as follows:-

i) All kinetic energy at disc brake rotor surface is converted into frictional heat or heat flux.

ii) The heat transfer involved for this analysis only conduction process and convection. This heat transfer radiation can be neglected in this analysis because of small amount which is 5% to 10% (Limpert, 1999).

iii) In this analysis, the ambient temperature has been set to 22°C while for initial temperature for disc brake rotor is 50oC (Hwang *et.al*, 2007).

iv) All other possible disc brake loads are neglected.

v) Only certain parts of disc brake rotor will apply with convection heat transfer such as the cross-drilled area, cooling vanes area, outer ring diameter area and disc brake surface.

The overall load analysis result is shown in Table 1 below.

Table 1 Load analysis results

Description	Value
Stopping Distance,	62.90 m
Braking Time,	2.83 s
Mass of new disc brake rotor	0.879 kg
Kinetic Energy,	169842.57 J
Braking Energy, L	46706.71 J
Thermal Flow, q	16504.14 J/s
Braking Surface, S_{flux}	0.017078 m²
Heat Flux, $q_{specific}$	193280 W/m²
Heat transfer coefficient by convection for Disc Brake Surface, h_R	Reynolds number = 71.473 x 10³ h_R = 39.03 W/m²K
Heat transfer coefficient by convection for Outer Diameter of Disc Brake Rotor, h_R	Reynolds number = 71.473 x 10³ h_R – 221.58 W/m²K
Heat transfer coefficient by convection for Cross-drilled Holes, h_R	Reynolds number = 545.08 h_R = 90.80 W/m²K
Heat transfer coefficient by convection for Cooling Vanes of Disc, h_R	Reynolds number = 1730.93 h_R = 133.45 W/m²K

5.0 FINITE ELEMENT MODELING

The overall finite element modeling process can be divided into three stages which are pre-processing, solution and post-processing as shown in Figure 4. In the pre-processing stage, linear transient thermal analysis option was selected and the geometrical model was imported into the ABAQUS/CAE software. Load and boundary condition values are defined for the model using heat flux and convection heat transfer coefficient values determined earlier during the load analysis stage. During the meshing stages, DCC3D8 hex-element type was chosen, with global seeds of 0.002m for better meshing result. The final component after meshing yields 22 380 number of elements and is shown in Figure 5. Two steps are defined for every braking cycle, which are 2.83 seconds for braking and 29.17 seconds for cooling. Thus, each cycle comprise of 32 seconds or a total of 320 seconds for all 10 cycles.

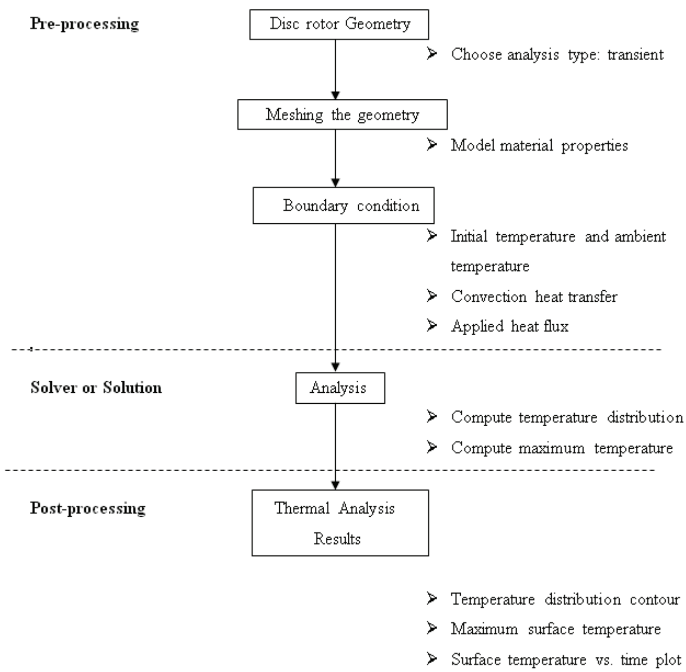
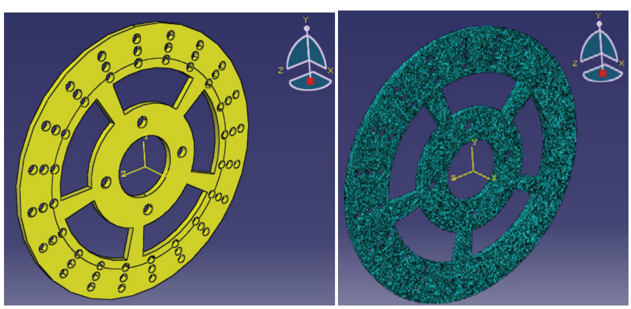


Figure 4 Finite element modeling stages



(a) (b)

Figure 5 Disc brake rotor (a) before meshing, (b) after meshing

6.0 RESULTS AND DISCUSSION

In practice, typical service condition for automotive brake discs consist of frequent and quick engagement cycles therefore making it predominantly in transient scheme. Therefore, the results from transient analysis are often more desirable in predicting the actual performance of the disc during operation. The overall temperature versus time for ten cycles of braking operation in transient mode is shown in Figure 6.

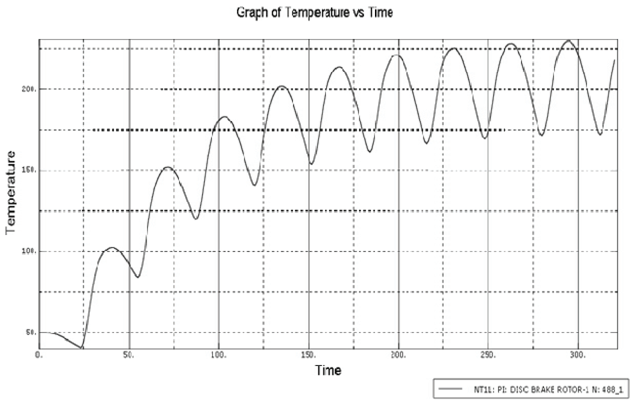


Figure 6 Surface temperature of the new disc brake rotor for 10^{th} cycles of braking

From Figure 6, it can be seen that the maximum temperature generated at the end of the 10^{th} cycle is about 288.4°C. The above graph also shows the behavior of the ventilated rotor during continuous braking, where the surface temperature on the disc surface increased as the number of subsequent braking is increased. For compacted graphite cast iron, the allowable service temperature of the material is between -160°C to 550°C. Thus, the maximum temperature recorded at the end of 320 seconds of braking operation is still within the acceptable service temperature for the CGI material, and therefore the new disc brake rotor is able to withstand the thermal load subjected to it safety without overheating and failure

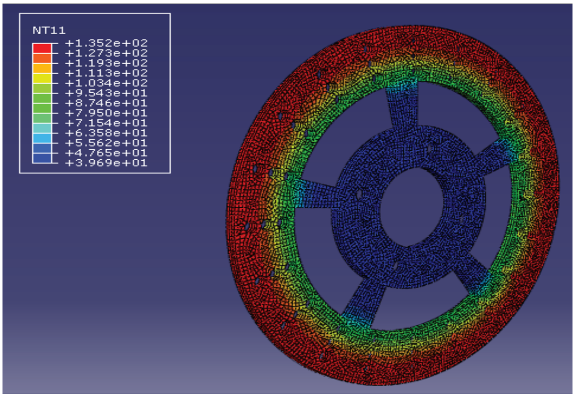


Figure 7 Temperature distribution of the rotor surface at the end of 1st cycle of braking

The thermal analysis result also reveals the behaviour of rotor when subjected frictional load during braking as shown in Figure 7 above. The temperature distribution on the disc surface varies according to the location of contact between the brake caliper and the rotor. It can be seen that that highest temperature is generated on the exact point of contact between the brake caliper and the rotor, and the temperature gradually decreases when it become nearer to the brake disc hub. The temperature decrease is observed due to the cooling effect that took place through convection process.

7.0 CONCLUSION

In conclusion, thermal analysis for the new ventilated disc brake rotor design of the UTeM Formula Varsity racing car has shown that the new design is able to withstand the heat generated during braking without failure. Thus, the new disc brake rotor is expected to function successfully as per design requirement for the new UTeM Formula Varsity racing car.

8.0 ACKNOWLEDGEMENT

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