THERMAL STRESS ANALYSIS OF HEAVY TRUCK BRAKE DISC ROTOR

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ABSTRACT

While braking, most of the kinetic energy are converted into thermal energy and increase the disc temperature. This project consists of thermal stress analysis on heavy truck brake disc rotor for steady state and transient condition. The heat dissipated along the brake disc surface during the periodic braking via conduction, convection and radiation. In order to get the stable and accurate result of element size, time step selection is very important and all of these aspects are discussed in this paper. The findings of this research provide a useful design tool to improve the brake performance of disc brake system.

Keywords : Disc, transient, FEA, thermal stress

1.0 INTRODUCTION

The brake system are used to ensure the safety control of a vehicle during the braking and enable the vehicle to a smooth stop within the shortest possible distance under the emergency situations, normal operation and also parking conditions. The efficient brake system on any type of vehicle are must be able to provide the necessary braking torque to the wheel to control the vehicle while dissipate the heat flux generated due to the friction between the brake pad with the brake disc rotor. The braking action is usually achieved by mounting the brake on the wheel as known as the foundation brakes that apply a braking torque directly on the wheel. The another type of braking actions is by using the brakes on the transmission shaft of the vehicle that generates higher braking force at the wheel compare to the foundation brakes but can only provide low braking torque at low vehicle speed (T.K. Garrett et. al., 2001).

In order to predict the thermal stress analysis inside the brake rotor, the finite element analysis is used to analyze the thermal distribution behavior along the rotor in steady state and transient condition. During the analysis, all the braking parameters are set to fixed values based on the values that have been stated in the literature review including the parameter of the heavy truck, material properties of the rotor, dimension of the rotor, rotational speed of the disk brake and the cycle of the pressure applied.

The moving of commercial truck has a certain amount of kinetic energy and transferred to the disc rotor through the brake to dissipate the energy in order to stop the vehicle. The brake converts the kinetic energy into heat generated by friction between the pads and the disc rotor. The cooling process due to forced convection is being calculated to the heavy truck at the given speed with the brake disc rotor at the high temperature due to the rotation. The analysis of the brake temperature requires the accurate determination of the total energy absorbed by the front brake disc rotor. This project conducted on the Volvo heavy truck brake disc in order to investigate the thermal stress behavior by using Finite Element Analysis (FEA).

2.0 METHODOLOGY

An overview of the thermal stress analysis is shown in the Figure 1. The dimension of the heavy truck brake disc rotor is translated into 3D drawing by using Solidworks. The methods of load analysis calculation and convectional heat transfer coefficient due to the forced convection along the brake disc surface are adapted from Limpert (1975) (R. Limpert, 1975). The 3D model of heavy truck disc rotor is imported to ABAQUS/CAE software. The simulation was carried out as thermal analysis in transitory regime to determine the temperature distribution of disc brake and analyze the Von-Misses stress distribution.

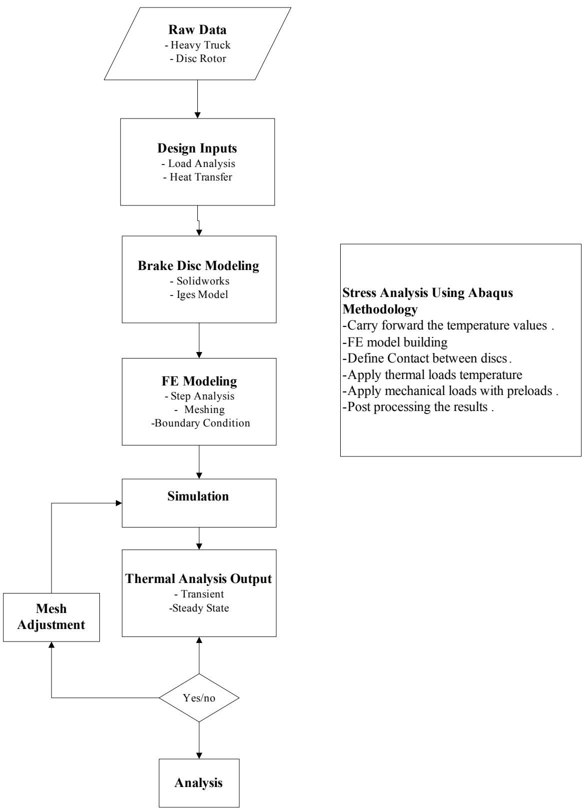

FIGURE 1
An overview of thermal stress analysis

The thermal boundary condition such as the convective heat transfer coefficient of the brake disc rotor and the symmetrical boundary condition are specified to ensure the accuracy of the temperature distribution analysis and the thermal stress analysis. The material properties of the heavy truck brake disc rotor, the applied load at the inboard and outboard surface and the interaction (cooling process) due to the forced convection are applied. The suitable of meshing element are applied before submitted for analysis and monitor the progress. Trials were being made to adjust the meshing element of brake disc rotor in order to minimize the temperature difference between the analytical and simulation.

2.1 LOAD ANALYSIS

They are several assumptions have been made to simplify the analysis complexity and at the same time allow the reasonable output is obtained from the result of the simulation. In the temperature analysis for repeated braking, the brake disc rotor assumed as a lumped system and the heat transfer coefficient and also the thermal properties are constant. Based on the information of the Vehicle Research & Test Center, East Liberty, Ohio (2004), the average of Volvo heavy truck stopping distance with fully air disc brake (27oC ambient temperature) traveling at a speed of 26.82 ms^{-1} under the best of road conditions, required an average of 73.45 m stopping distance with the deceleration rate 4.89 ms^{-2} in 5.48 second. In this project, the 10 stop periodic braking were adapted from Huang and Cheng (2006) based on the information of the Vehicle Research & Test Center and also from the acceleration lane design for higher truck volumes by Gattis (2008) (Y.M. Huang, et. al., 2006) (J. L. Gattis Christopher Hanning et. al., 2008). The total time for the whole operation is 1167.2 second. From the Figure 2, during the repeated braking applications the heavy truck is decelerated at a given deceleration from 26.82ms^{-1} to zero speed and accelerated again to achieve 26.82ms^{-1} and next braking process are carried out.

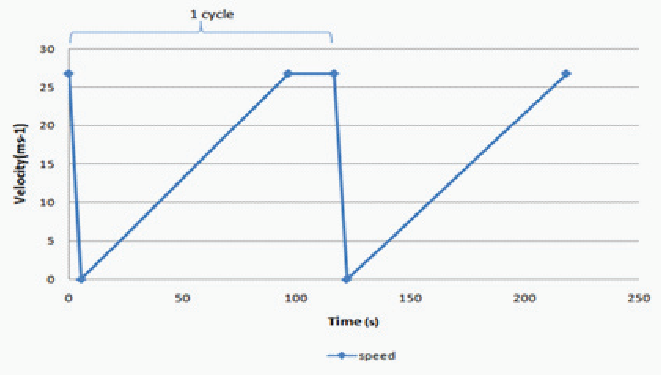

FIGURE 2
First cycle of the braking conditions

The heat dissipated through the brake disc surface during the heat flux applied to the both surface are ignored and only can be considered during the idle time. There are four type of convective heat transfer coefficient are considered in this research such as the braking surface, inner ring surface, outer ring surface and also the inner vane passage that have been exposed to the force convection for the cooling process.

2.2 FINITE ELEMENT MODEL

Finite element model developed to define the heat flux applied into the brake disc surface in order to analyze the thermal stress behavior during the periodic braking. The full model of brake disc rotor is modeled using quadratic tetrahedron with explicit element type in quadratic geometric order which to calculate the each nodal displacement strains and stress.

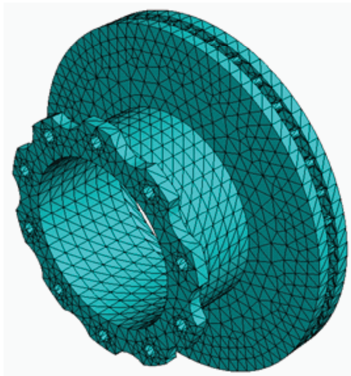

FIGURE 3
Brake disc model (meshing)

3.0 RESULTS AND DISCUSSIONS

The result of the thermal stress on the steady state and transient analysis were discussed. During the repeated braking, thermal stress gradients generated within the brake disc rotor may produce cracks.

3.1 TRANSIENT ANALYSIS

Thermal stresses are created in the disc by differential expansion because the disc is not at a uniform temperature during braking. The thermal stresses generated during the heat flux applied to the brake disc surface are presented on the 2^{nd}, 6^{th} and 10^{th} cycle of braking operation. Figure 4 shows the 2^{nd} cycle of the heat flux applied and the idle time (cooling process) on the disc brake rotor. At the beginning of the braking process the thermal stress generated is fairly low and as the time increases, the thermal stresses start to build up mainly due to the increasing heat flux being applied.

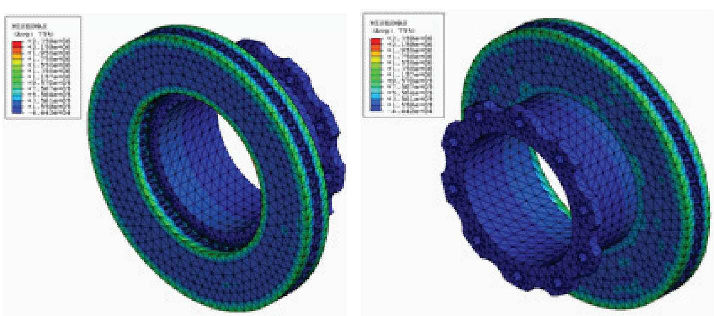

FIGURE 4
Thermal stress analysis at 2nd cycle (heating)

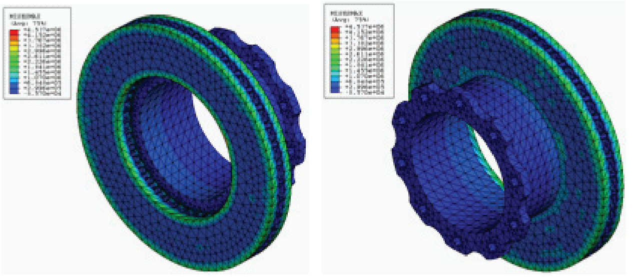

FIGURE 5
Thermal stress analysis at 2nd cycle (cooling)

From the Figure 4 and 5, the maximum temperature at the braking surface is 355K during the heat flux applied and increase to 406K during the idle time. The maximum thermal stress at the braking surface is 2.35MPa during the heat flux applied and increase to 4.53MPa during the idle time.

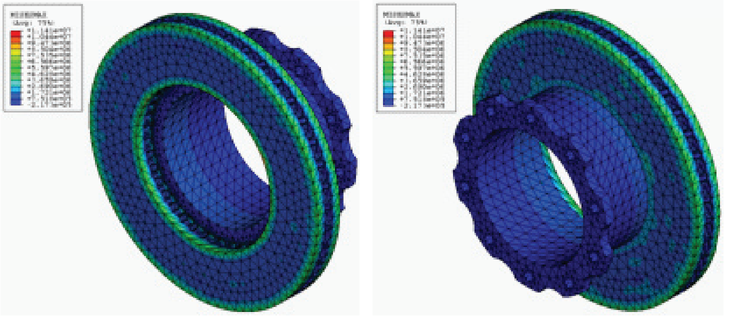

FIGURE 6
Thermal stress analysis at 6th cycle (heating)

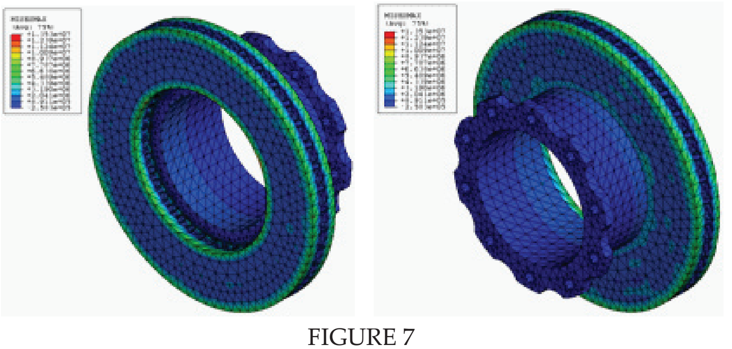

FIGURE 7
Thermal stress analysis at 6th cycle (cooling)

From the Figure 6 and 7, the maximum temperature at the braking surface is 567K during the heat flux applied and increase to 617K during the idle time process to decrease the temperature rise rate. The maximum thermal stress is 11.4MPa at disc rotor surface and increase to 13.5MPa due to the cooling process.

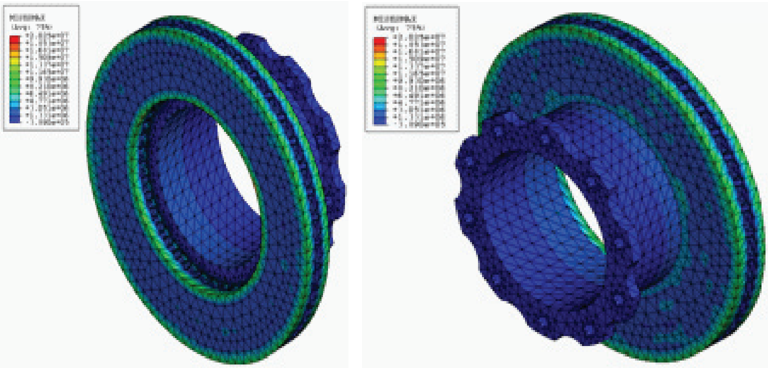

FIGURE 8
Thermal stress analysis at 10th cycle (heating)

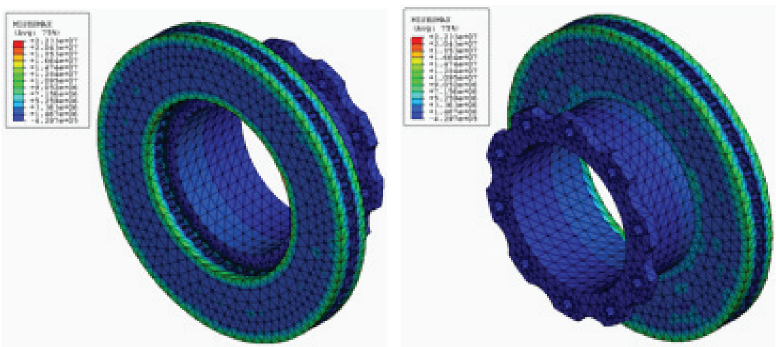

FIGURE 9
Thermal stress analysis at 10th cycle (cooling)

From the Figure 8 and 9, the maximum temperature at the braking surface is 775K during the heat flux applied and increase to 823K during the idle time process to decrease the temperature rise rate. The maximum thermal stress is 20.2MPa at disc rotor surface and increase to 22.3MPa due to the cooling process. While increasing the temperature of the braking surface, the hot spot can be seen at the brake disc rotor surface which shows hard, slightly raised, dark-colored spots on the braking surface with uneven wear material changes of the structure. The discolored swept braking surfaces can also been seen due to the excessive heat that exceeding more than 533 K for grey cast iron material.

3.2 STEADY STATE ANALYSIS

The temperature distribution of the disc rotor under steady state loading condition and the heat storage effect change over the period of time is ignored. During the steady state condition, the cooling process due to the forced convection only occurred at the inner vane passage, outer ring surface, inner ring surface and also the lower inner ring surface. The cooling on the braking surface is ignored due to the heat flux applied is constant during the simulation.

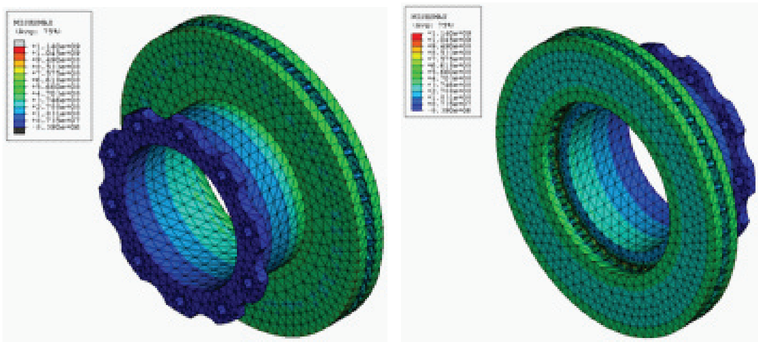

FIGURE 10
Thermal stress analysis steady state condition

From the Figure 10 show the maximum temperature is 9781K which is exceeds the melting temperature of the grey cast iron 35000C at the braking surface. The maximum thermal stress is 1.14GPa the edge on the disc rotor surface. While increasing the temperature of the braking surface, the hot spot can be seen at the brake disc rotor surface which shows hard, slightly raised, dark-colored spots on the braking surface with uneven wear material changes of the structure. The discolored swept braking surfaces can also been seen due to the excessive heat that exceeding more than 533 K for grey cast iron material.

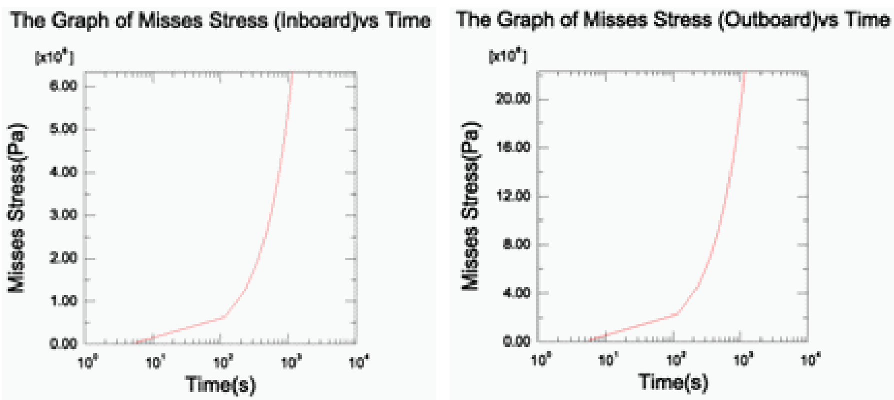

FIGURE 11
Von Misses stress at the inboard and outboard surface

After 10 cycle of repeated braking, the high amounts of thermal stresses are generated along the edge of the outboard braking surface. However, the maximum thermal stress generated are still lower compare to the maximum tensile strength of the brake disc material which is 217MPa while the results of simulation show the maximum stress produced is 22.3MPa. The tensile stress at the brake disc surface at the end of the periodic braking is not exceeding more than half of the maximum compressive stress of the grey cast iron 35000C and unlikely to cause cracking of the disc rotor surface. Brake disc rotor surface cracking will only occur when the thermal stress exceeds the strength of the material. The occurrence of surface rupture is affected by thermal stress, surface condition due to machining, number and frequency of braking cycles, corrosion and brake disc rotor geometry.

The expansion of the outer ring surface due to the increasing temperature is restricted by the cooling process at braking surface and the outer ring surface. The compressive radial stresses generated throughout the disc, compressive hoop stresses in the bore and inner regions and tensile hoop stresses in the rotor. The excessive heat flux applied to the surface of brake disc rotor are not a severe consequence to the rotor material due to the heat dissipated along the surface of brake disc rotor and also the thermal stress generated do not exceed the maximum allowable compressive strength of brake disc rotor material. As the result, the selection of the brake disc rotor material is significant to decrease the surface thickness variation.

3.3 VALIDATION OF RESULTS

The analytical solutions are used to validate the simulation result by adapting the equation from Limpert (1975) (R. Limpert, 1975). The brake disc rotor treated as a lumped system where the temperature assumed to be uniform throughout the rotor, the both heat transfer coefficient and the thermal properties are constant, Limpert (1975) (R. Limpert, 1975). The comparison of transient results with the steady state of thermal stress behaviors was performed. If the transient solution for this operation condition converges to the steady solution as time elapse, it can be regarded as validation of the applied transient scheme.

The lumped equation during the repeated braking adapted from Limpert (1975) (R. Limpert, 1975)

$$\frac{T(t)-T_i}{T_i-T_\infty}=e^{(-h_R A_R t)/(\rho_R c_R v_R)}$$

where;

A_R = rotor surface
h_R = heat transfer coefficient
t = cooling cycle time
$T\infty$ = ambient temperature, K
T = temperature at time, K
T_i = initial temperature, K
ρ_R = rotor density
c_R = specific heat
v_R = rotor volume

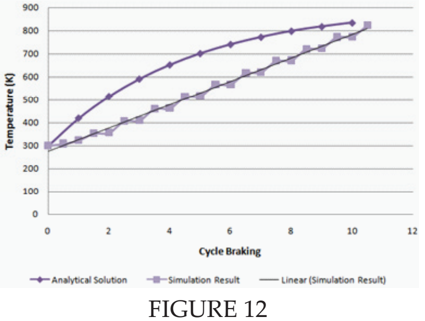

FIGURE 12

Temperature rise of brake disc rotor

Based on the results of the simulation, the maximum temperature generated along the brake disc rotor surface is 824K and the analytical solution is 835.2K. The results of the simulation are proven to be accurate as the difference between the maximum temperatures analytical is smaller. Based on the results of the experiment, thermal stress analysis on brake disc heavy truck has been succesfully achieved.

4.0 CONCLUSION

In this research, the thermal stress analysis of the transient and the steady state condition of disc brakes during periodic braking that were performed are achieved. The maximum of thermal stress generated along the brake disc surface is 22.3MPa which is lower than the maximum tensile strength of the brake disc material 217MPa which unlikely to cause cracking of the disc rotor surface. The temperature of the braking surface are still increasing during the cooling process but in slower rate, the heat dissipation through convection at brake disc rotor surface of the commercial vehicle have smaller impact on decreasing the temperature of braking surface due to the lower speed angular velocity of commercial vehicle tyre. The thermal stress due to the heat flux generation has a major influence on the fatigue stress and thermal cracking by proven to be strongly localized and possesses a sharp gradient in the both axial and radial directions.

5.0 ACKNOWLEDGEMENT

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