OPTIMUM DESIGN OF BRAKING SYSTEM FOR A FORMULA 3 RACE CARS WITH NUMERIC COMPUTATIONS AND THERMAL ANALYSIS

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Abstract - *Weight reduction is one of the prime concerns for a formula 3 cars. It was decided to reduce the weight of brake system by using the disc rotor and calipers of a bike instead of using a bulky hat type disc rotor. In this paper, the component selection of braking system is discussed. Various calculations of braking force, braking torque and brake bias are shown. Also, the safety of using bike's rotor is validated by calculations and thermal analysis. This brake system was implemented by team Ojaswat for the event* ***Supra 15*** *organized by* ***SAE, India****.*

Key Words**: Formula 3 Car, Thermal Analysis, Abaqus, Braking System, Ansys.**

1.INTRODUCTION

Brake system is one of the vital systems of a formula 3 race car. It's perfect functioning in all the conditions is a necessity for the safety point of view. Our primary aim was to come up with a braking system that is simple and has an optimized weight along with being reliable. As per the rule book of SAE, India, it was compulsory for the system to consist of two independently operated hydraulic circuits. Also, all the four wheels must lock simultaneously. In order to implement fool proof safety, we also had to keep a brake over travel switch.

Lakkam, Suwantaroj, Puangcharoenchai, Mongkonlerdmanee and Koetniyom [1] determined the film coefficient of convective heat transfers by investigating thermal gradients on the disc rotor. They experimentally determined the convective heat transfer coefficient and used it to perform numerical simulation by finite element method. Thus, they studied the temperature diffusion and heat ventilation of front and back vented brake discs.

Sheikh and Srinivas [2], wanted to study the amount of deformation due to tangential Force and pressure loading. So, in their work, they performed analysis without considering the effects of thermal expansion. They performed thermal + structural analysis of disk rotor of Honda Civic using Ansys.

Iersel [3] used a computer controlled test rig to find out the friction coefficient of brake pads. The brake pads were tested at various conditions and it was shown that optimal operative temperature lies around 220 °C. Also, it was shown that the resulting brake torque depends linearly on brake pressure.

2. SELECTION OF COMPONENTS:

A. Brake rotor and Calipers:

It is beneficial to select a rotor having the diameter as large as can be accommodated in the rims of the car. This is because of the reason that for the transmission of same torque, with the increase in diameter, the respective force decreases. Hence a bike's front rotor with diameter of 200 mm was selected for a 13inch wheel rim. The rotor was petal typed to facilitate heat transfer. The thickness of the disc was 3.5mm and suitable calipers with dual pistons were selected.

B. Master Cylinder:

A tandem type master cylinder was selected so that independent two hydraulic circuits can be obtained and it can be obtained by a single control from brake pedal. It contained DOT3 as brake oil. A diagonally split-connections were given to the wheels so that the car maintains stability in case of failure of one of the circuits. The circuit is made up of rigid pipes followed by flexible brake lines going to the calipers through a Benjo bolt.

C. Brake Pedal:

The brake pedal was machined from checkered Aluminum plate having thickness 5mm. It was designed to withstand a force of 2000N at the footrest. The leverage of the pedal was set to 2.3.

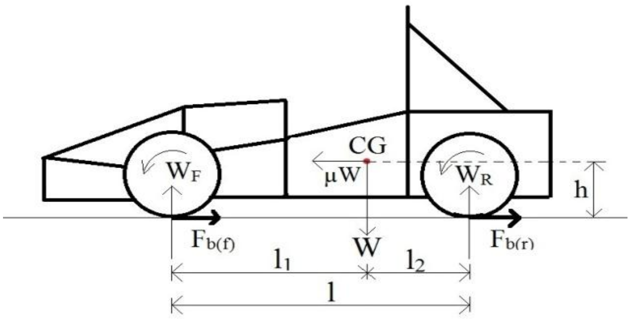
D. Proportioning Valve:

There is a dynamic load transfer during braking which increases the load at front axle than at rear axle. Hence the rear brakes lock earlier than the front brakes. For the simultaneous locking of all four wheels, proportioning valves are required in the brake lines going to the rear wheels so that less pressure is reached there. Proportioning valve helps in setting this brake bias as per the calculated load transfer taking place in the car. The brake bias in our car was 0.51 at the front and 0.49 at rear.

3. Brakes Calculation:

A. Stopping Distance

All the calculations are performed considering initial velocity of 60 kmph and final velocity of 0 kmph.
During braking, there is a weight transfer due to which load on front axle increases.



By taking the moments about Rear and Front wheels, we get the following respective equations of dynamic load transfers

$W_{Front}= W\frac{l_2}{l} + \frac{h}{l} F_b$; $W_{rear} = W\frac{l_1}{l} - \frac{h}{l} F_b$

Maximum braking force provided between road and tyre is given by

$F_{bmax} = \mu W = W\left(\frac{d}{g}\right)$

$F_{b(f)} = W_f\left(\frac{d}{g}\right)$; $F_{b(r)} = W_r\left(\frac{d}{g}\right)$

Where, W= Weight of the vehicle
F_b = Braking Force (total)

The Equations are for ideal condition where braking efficiency is 100%

Braking Efficiency: $\eta = \left(\frac{d}{g}\right) * \left(\frac{1}{\mu}\right)$

$$\left(\frac{d}{g}\right) = 0.85\mu$$

Now, braking efficiency = 85%

Hence braking forces at axles are:

$$F_{b(f)} = w_f * \left(0\frac{d}{g}\right) = 0.85\mu * \left[W\frac{l_2}{l} + \frac{h}{l} 0.85\mu W\right]$$

$$F_{b(r)} = w_r * \left(\frac{d}{g}\right) = 0.85\mu * \left[W\frac{l_1}{l} - \frac{h}{l} 0.85\mu W\right]$$

Considering the values as per the design of our team's student formula race car:

l= 1.55m; l_1= 0.93m; l_2= 0.62m; h= 0.29m

W= 350*9.81= 3433.5 N

Coefficient of friction (μ) depends on several factors. Let's assume its value= 0.67

$F_{b(f)} = 0.85\mu\left[W\frac{l_2}{l} + \frac{h}{l} 0.85\mu W\right] = 990.49$ N

$F_{b(r)} = 0.85\mu\left[W\frac{l_1}{l} - \frac{h}{l} 0.85\mu W\right] = 964.88$ N

$F_b = 0.85\mu W = 1955.37$ N

Percentage biases on front and rear wheel respectively are:

$K_{b(f)} = \frac{(F_{bf})}{F_b} = 0.506$; $K_{b(r)} = \frac{(F_{br})}{F_b} = 0.493$

Braking torques at front and rear wheels respectively are:

$T_F = \frac{F_{bf}}{2} * R_{wheel}$ = 119.35 Nm…………… (1)

$T_R = \frac{F_{br}}{2} * R_{wheel}$ = 116.26 Nm…………… (2)

Where,
R_{wheel} = 0.241m

Considering that the driver applies pedal force F_P = 250N on a brake pedal having leverage 2.3,

Force on the push rod of master cylinder:

= 2.3*250 = 575N

The diameter of master cylinder is 18mm.
Pressure in master cylinder:

$$= \frac{Force\ on\ master\ cylinder\ push\ rod}{Area\ of\ piston} = 2.26\ MPa$$

The diameter of piston= 25mm

Force at caliper = Pressure in master cylinder * Area of piston Caliper *No. of pistons

= 2.26MPa* 0.00049 * 2
= 2223.03 N

Clamping Force= 2 * force on caliper
= 4446.06 N

Let the co-efficient of friction between the disc and pad (μ_p) in the brake caliper be 0.3

Also,

$$r_{(effective)} = \frac{r1+r2}{2}$$

Where,
r1= Radius of circle formed by inner edge of friction pad
r2= Radius of circle formed by outer edge of friction pad

$$F_{(friction)} = 2 * \mu_p * F_{caliper}$$
$$= 2 * 0.3 * 2223.03$$
$$= 1333.81 \text{ N}$$

$$Torque = F_{(friction)} * r_{(effective)}$$
$$=1333.81*0.095$$
$$= 126.71 \text{ N m} > \text{Req. Braking Torque}$$
$$(\because eq^n\ (1) \text{ and } (2))$$

Hence a pedal force of 250N would provide the sufficient braking torque for all wheels to lock.

Deceleration:

$$d= \frac{F(total)}{M} = \frac{(947.39+1007.98)}{350} = 5.58 \frac{m}{s^2}$$

$$\text{Stopping Distance} = \frac{V^2}{2*d} = \frac{16.66^2}{2*5.58} = 24.87 \text{ m}$$

B. Calculations for the front rotor of bike:

As bike's front wheel brake rotors are used in the car, it is essential to find out the forces that act upon the rotor during the braking conditions of the bike. Taking the value of weight from the bike's specifications as 121kg and assuming driver's weight to be 60kg,

$W = 181 \text{ kg} = 181*9.81 = 1775.61\text{N}$;

$F_b = 0.85\mu W = 1011.2 \text{ N}$

Assuming, the brake bias in bike is 60:40, let 60% of the braking force is at the front wheel,

$F_{b(f)} = 0.6 * F_b = 606.72\text{N}$.

$T_f = F_{b(f)} * R_{wheel} = 606.72 * 0.3059 = 185.59\text{N}$

Where,
R_{wheel} = 305.9mm for 100/90-17" front tyre

$$F_{(friction)} = \frac{T_f}{R_{effective}} = 1953.6\text{N}$$

$$\text{Clamping Force} = \frac{F_{(friction)}}{\mu p} = 6512.19\text{N}$$

This is 1.46 times the clamping force in braking in the above car. Hence, it is safe to use this disc rotor for the formula 3 car.

C. Thermal Considerations:

Rotor Diameter= 200mm
Area of brake pad= 1675 mm^2
Mass of brake disc m_1 = 0.56 kg
Area of disc= 24463 mm^2

$$K.E = \frac{mv^2}{2} = \frac{350*16.66^2}{2} = 48572.23 \text{ J}$$

Heat Generated = K.E. = 48572.23 J

Nathi, Charyulu, Gowtham and Reddy [1] have calculated the heat flux for rotor by the following equation in their work, Assuming 70% energy on the front wheel and considering the energy of the one wheel, we get;

$$\text{Heat Flux} = \frac{\text{Heat Generated}*.7}{\text{Stopping time} * \text{Area of rubbing}*2}$$

$$= \frac{48572.23*.7}{2.92*0.0213*2} = 273333.38 \frac{W}{m^2}$$

Film Co-efficient:

$$P_r = \frac{Cp\ \mu_v}{k} = \frac{1007*1.983*10^{-5}}{0.024} = 0.8320 > 0.6$$

Where,
C_p= Specific heat of air at constant pressure
μ_v = Dynamic viscosity of air
k= Thermal Conductivity of air = 0.024 W/m°C

$$R_e = \frac{V\,x}{\nu} = \frac{1*16.66*(2\pi*0.1)}{2*10^{-5}} = 502400$$

Where,
V = Velocity of air = 60kmph = 16.66m/s
x = Distance travelled by air = 2πr
r = radius of disc = 100mm = 0.1m
ν = kinematic viscosity = $2*10^{-5}$ m^2/s

As, $R_e > 5 * 10^5$, for a flow over flat plate, the flow is considered to be turbulent.

$$Nu = 0.0296 * P_r^{\frac{1}{3}} * R_e^{\frac{4}{5}} = 36378$$

$$Nu = \frac{h\,x}{k} = 36378$$

$$\text{Film Coefficient} = h = \frac{Nu*k}{x} = 1390 \text{ W/m}^2\,°\text{C}$$

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4.Thermal Analysis:

A. Ansys:

Steady state thermal analysis coupled with static structural analysis was performed in Ansys 15. The CAD model of rotor was created in PTC Creo 2.0 as per the real rotor of Bajaj discover 125m and then was exported for analysis.

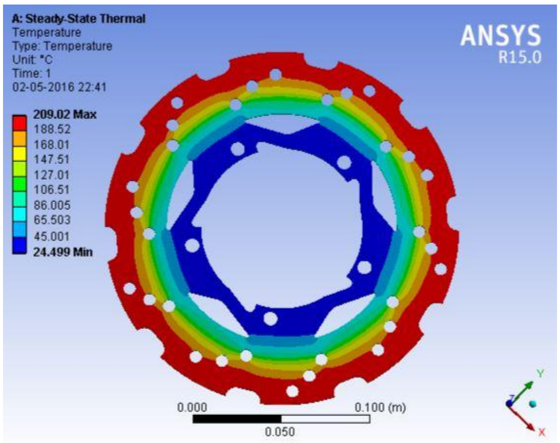

Fig. 1: Temperature

Figure 1 shows the maximum and minimum temperature zones in the disc rotor with the values being in °C.

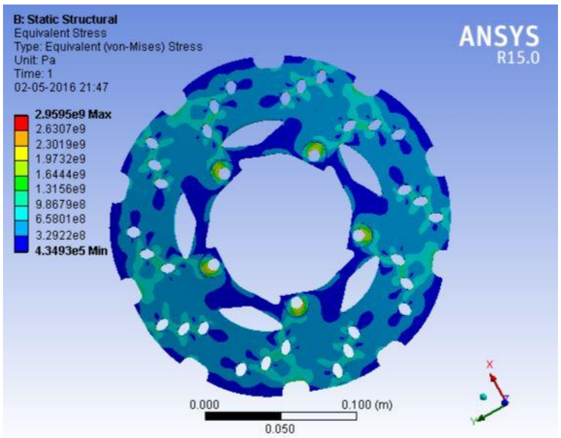

Fig. 2: Equivalent Stress

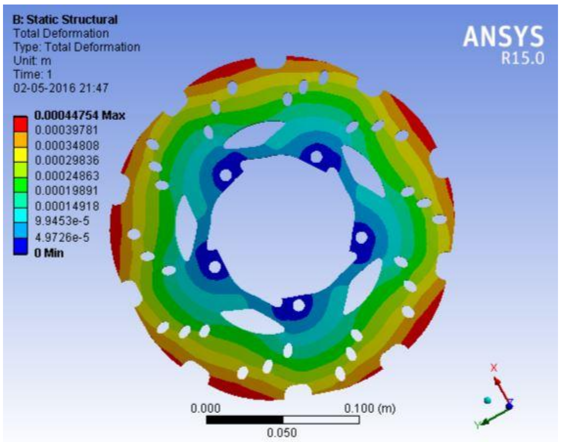

Fig. 3: Total Deformation

B. Abaqus:

In order to see how the disc behaves under dynamic conditions, Abacus was used to perform an Explicit Coupled Thermo-mechanical analysis. The results of this analysis are shown below.

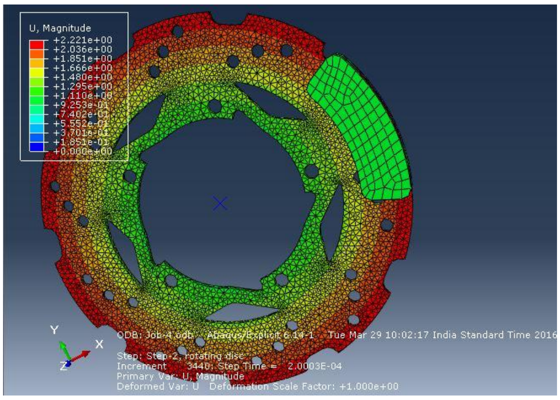

Fig. 4: Translations and Rotations (Deformations)

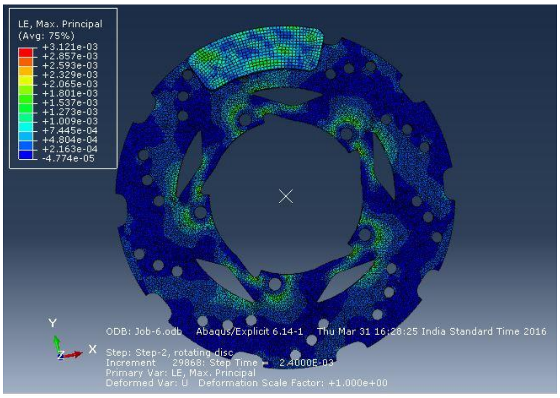

Fig. 5: Logarithmic strain Components

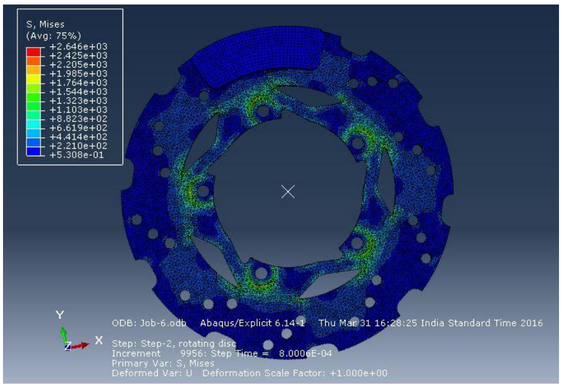

Fig. 6: Stress Components and Invariants

5. Real time fabrication of Brake assembly:

Hubs and Uprights were designed accordingly as per the disc rotor and the rims. The assembly of Upright- Hub mounted with disc and Caliper is shown in figures 7 and 8.

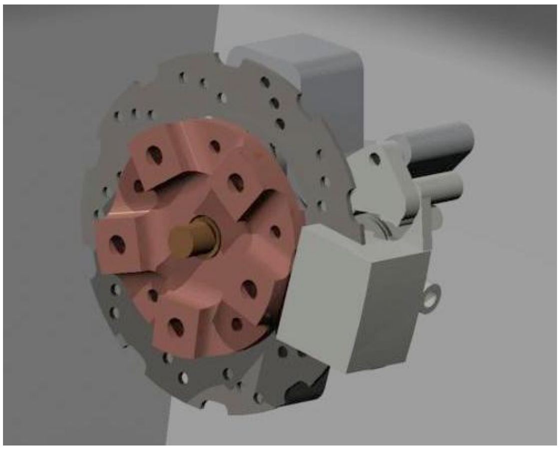

Fig. 7: Brake Rotor Assembly

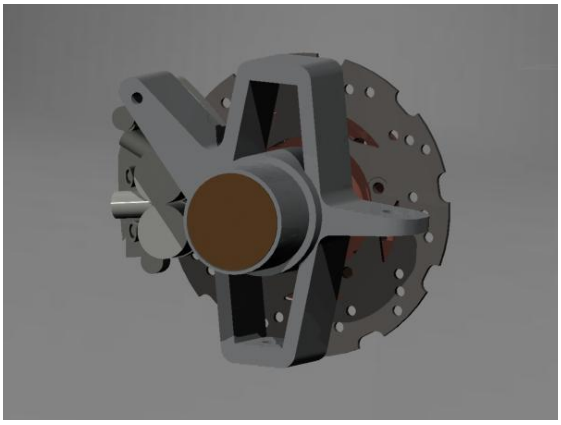

Fig. 8: Brake Rotor Assembly

5. Conclusion:

In this paper, numeric computations have been done to obtain braking forces, braking torque, clamping forces at calipers, brake bias and other important parameters in a braking system. Comparison has been done between the clamping force in the front wheel of bike and the clamping force in one of the front wheels of car. It shows that it is safe to use the rotors of bike in a formula car with the mentioned specifications. Normal brake assemblies used in commercial cars with hat type rotors weighs around 17kg per wheel. On implementing bike's brake assembly in the formula car, this weight reduces to 6kg per wheel. Thus, considerable weight reduction is achieved. Thermal Calculations for heat flux are done and film coefficient is determined which helps in the thermal analysis. The results of coupled steady state thermal and static structural analysis in Ansys as well as dynamic explicit thermo-mechanical analysis in Abaqus have been shown. These results are quite satisfactory.

6. Acknowledgment

Here, we would firstly like to thanks our college to allow us to take participation in such a wonderful brainstorming event in which our technical knowledge escalated. Secondly, our professors Mr. Kalpesh Vaghela and Mr. Sujal Dadhaniya for lending us a hand in all aspects without which this would have been just a castle in air.

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