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STRUCTURAL AND THERMAL ANALYSIS OF DISC BRAKE OF RACE CAR

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Abstract— **The disc brake is a device for slowing or stopping the rotation of a wheel. Friction causes the disc and attached wheel to slow or stop. Brakes convert friction to heat, but if the brakes get too hot, they will cease to work because they cannot dissipate enough heat. This condition of failure is known as brake fade. Disc brakes are exposed to large thermal stresses during routine braking and extraordinary thermal stresses during hard braking.**

The aim of the present work is to model a disc brake used in Honda Civic. Coupled field analysis (Structural + Thermal) is done on the disc brake. The materials used are cast iron and aluminum. Analysis is also done by changing the design of disc brake. Actual disc brake has no holes, design is changed by giving holes in the disc brake for more heat dissipation. Modeling is done in CATIA and Analysis is done in ANSYS.

Introduction

The disc brake is a device for slowing or stopping the rotation of a wheel. A brake disc (or rotor) usually made of cast iron or ceramic composites (including carbon, kevlar and silica), is connected to the wheel and/or the axle. To stop the wheel, friction material in the form of brake pads is forced mechanically, hydraulically, pneumatically or electromagnetically against both sides of the disc. Friction causes the disc and attached wheel to slow or stop. Most modern cars have disc brakes on the front wheels, and some have disc brakes on all four wheels. This is the part of the brake system that does the actual work of stopping the car. In today’s growing automotive market the competition for better performance vehicle in growing enormously. The racing fans involved will surely know the importance of a good brake system not only for safety but also for staying competitive, so the brakes should have very high braking efficiency. The wear and tear of the pads or the cost is not of great concern to the manufacturer of the racing car brakes.

1. B. Brown stated that in order to increase the efficiency of a brake caliper, introduction of modular brake caliper in the place of currently used conventional caliper may results in increase in performance.
2. Thomas J. mentioned in his study of Thermal Analysis in Disc Brakes that failure in disc brakes is mainly due to brake fade. The use of ventilated rotors helps in more heat dissipation compared to the solid discs.
3. Davis, J.R. stated in his hand book of Aluminum and Aluminum Alloys, that maximum stress was lower for Al 2219 than the Al 6061. So in the present work Al 2219 is considered for the design of modular caliper in order to reduce the stress levels.

Problem Description

These brakes offer better stopping performance than comparable drum brakes, including resistance to "brake fade" caused by the overheating of brake components, and are able to recover quickly from immersion (wet brakes are less effective). Unlike a drum brake, the disc brake has no self-servo effect and the braking force is always proportional to the pressure placed on the braking pedal or lever.

Many early implementations for automobiles located the brakes on the inboard side of the driveshaft, near the differential, but most brakes today are located inside the wheels. (An inboard location reduces the unsparing weight and eliminates a source of heat transfer to the tires, important in Formula One racing.). Disc brakes were most popular on sports cars when they were first introduced, since these vehicles are more demanding about brake performance. Discs have now become the more common form in most passenger vehicles, although many (particularly light weight vehicles) use drum brakes on the rear wheels to keep costs and weight down as well as to simplify the provisions for a parking brake. As the front brakes perform most of the braking effort, this can be a reasonable compromise. The picture of disc brake will be as shown in Fig: 1

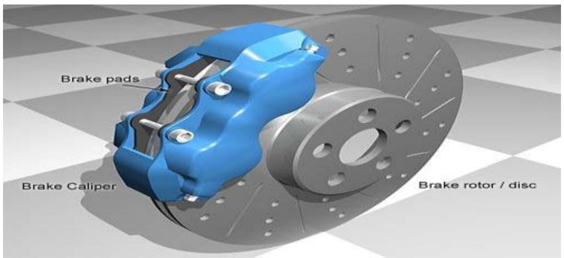

Fig: 1 Disc brake

Working

A disc brake assembly consists of

1. Cast-iron disc (disc rotor) that rotates with the wheel.
2. Caliper assembly attached to the steering knuckle.
3. Friction materials (disc pads) that are mounted to the caliper assembly

When hydraulic pressure is applied to the caliper piston, it forces the inside pad to contact the disc. As pressure increases the caliper moves to the right and causes the outside pad to contact the disc. Braking force is generated by friction between the disc pads as they are squeezed against the disc rotor. Since disc brakes do not use friction between the lining and rotor to increase braking power as drum brakes does, they are less likely to cause a pull. The friction surface is constantly exposed to the air, ensuring good heat dissipation, minimizing brake fade. The assembly of disc brake will be as shown in Fig: 2

Unlike drum brakes, disc brakes have limited self-energizing action making it necessary to apply greater hydraulic pressure to obtain sufficient braking force. This is accomplished by increasing the size of the caliper piston. The simple design facilitates easy maintenance and pad replacement.

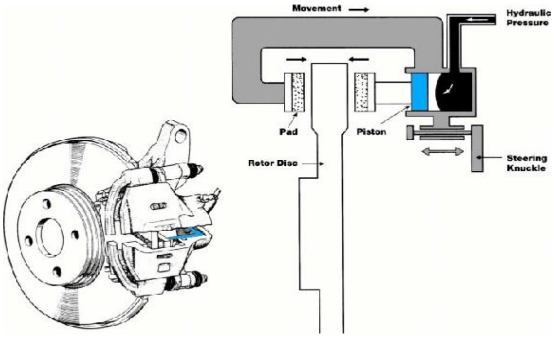

Fig: 2 Disc brake assembly

Disc Rotor

Generally, the disc rotor is made of gray cast iron, and is either solid or ventilated. The ventilated type disc rotor consists of a wider disc with cooling fins cast through the middle to ensure good cooling. Proper cooling prevents fading and ensures longer pad life. Some Ventilated rotors have spiral fins which creates more air flow and better cooling. Spiral finned rotors are directional and are mounted on a specific side of the vehicle. Ventilated rotors are used on the front of all late model Toyotas.

The solid type disc rotor is found on the rear of four wheel disc brake systems and on the front of earlier model vehicles.

A third style rotor can be either the ventilated or solid type which incorporates a brake drum for an internal parking brake assembly.

Caliper

The caliper, also called the cylinder body, houses one to four pistons, and is mounted to the torque plate and steering knuckle or wheel carrier. It is found in floating caliper designs or fixed caliper designs on Toyotas.

Brake Pad

Different brake design applications require different kinds of friction materials. Several considerations are weighed in development of brake pads; the coefficient of friction must remain constant over a wide range of temperatures, the brake pads must not wear out rapidly nor should they wear the disc rotors, should withstand the highest temperatures without fading and it should be able to do all this without any noise. Therefore, the material should maximize the good points and minimize the negative points.

Materials which make up the brake pad include friction modifiers, powdered metal, binders, fillers and curing agents.

Conventional Brake Caliper

Structural Analysis of Conventional Brake Caliper

A pressure loading of 1500 N is used for all the cylinders. The two bolts are bolted to the suspension system so a fixed boundary condition was used to represent them. The model used for analysis is shown in figure.

There are two forces acting on the surface of the brake pads one is the normal force due to the hydraulic pressure and the other is the tangential force. Al properties required for the analysis are given in Table: 1

Table: 1 Physical properties of Al 2219

Mass Density (kg/mm3)	2.688 x 10-4
Modulus of Elasticity (N/mm2)	10.7 x 106
Poisson's Ratio	0.33
Shear Modulus (N /mm)	3.92 x 106
Thermal coefficient of Expansion	12.5 x 10-6

The displacement of the total caliper body can be obtained by obtaining the total displacement of the caliper body. Fig: 3 shows the displacement in the caliper. The displacement is in one direction as the caliper is fixed on one side. The total value of displacement is 0.002925mm.

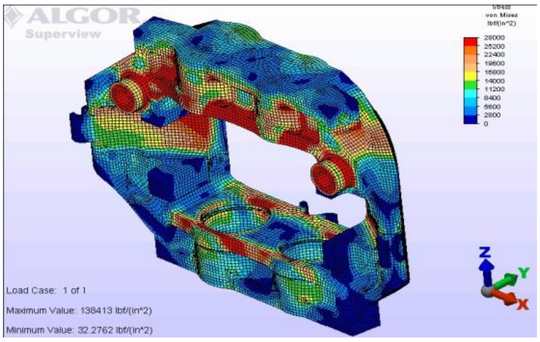

Fig: 3 Displacement in conventional caliper

The caliper undergoes two major deformations one is in the Z direction and the other in the X direction. The Z direction displacement is a sort of bulging effect while the X displacement occurs due to the tangential forces acting due to friction and pressure. The maximum Z -direction displacement corresponds to the loading in axial direction is shown in figure .The maximum displacement is 0.00105mm inch in z direction. The maximum displacement in negative Z direction is 0.002025mm. The maximum X -direction displacement is shown in figure. The maximum displacement is 0.00036mm in X direction. The maximum displacement in negative X direction is 0.00108mm

Structural Analysis of Conventional Caliper with Thermal Effects

Tremendous amount of heat is generated in braking action. The same boundary conditions and loads were applied to the new design. Brake caliper was analyzed at a nodal temperature of 3000 F. Figure shows the stress levels in the caliper. By applying fixed boundary conditions zero displacement is allowed on those nodes. When stress is applied to these elements it will try to elongate in one direction and contract in the other in accordance to poisons rule. Therefore artificial stress is induced near the mounting bolts. These stresses can be neglected.

Stresses in conventional caliper including thermal:

The displacement is in one direction as the caliper is fixed on one side. Fig: 4 shows the displacement in the caliper. The total value of displacement is 0.0135 mm. This displacement is a addition of displacements in X and Z directions.

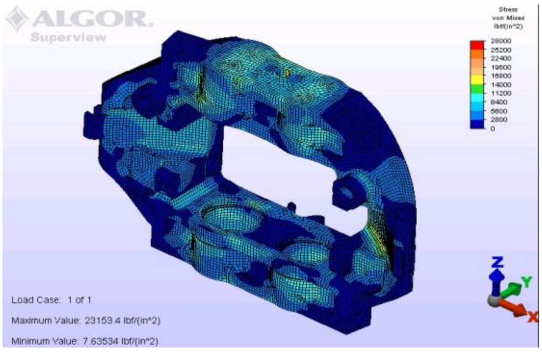

Fig: 4 Displacement in conventional caliper including thermal

The displacement is in one direction as the caliper is fixed on one side. Figure shows the displacement in the caliper. The total value of displacement is 0.0135mm this displacement is an addition of displacements in X and Z directions.

The maximum Z -direction displacement corresponds to the loading in axial direction is shown in figure. The maximum displacement is 0.005625mm in z direction. The maximum displacement in negative Z direction is 0.048 inch. The maximum X -direction displacement is shown in figure. The maximum displacement is 0.002925mm in X direction. The maximum displacement in negative X direction is 0.004725mm.

Modular Caliper

The new modular caliper used the base of conventional brake caliper. The main objective of the design was to increase the strength of the caliper without increasing the weight of the caliper by a large amount, taking displacement and stress into account and also making a brake caliper with an assembly instead of a single block manufacturing. This concept of is proposed in the new design. Al 2219 and Titanium is used for the new caliper design.

The assembly consists of two different side blocks housing the pistons. The material for side blocks is Al 2219. The Side plates supporting the side blocks are made of titanium. The left part and the right part of the caliper are assembled together using titanium stoppers. The Z-shaped stoppers were used specifically to increase the assembly resistance against loading due to rotation of the rotor. Properties of aluminum and titanium are specified in the Table: 2

Table: 2 Physical Properties of Aluminum and Titanium

	Al 2219	Titanium
Mass Density (kg/mm3)	2.688 x 10-4	4.21 x 10-4
Modulus of Elasticity (N /mm2)	10.7 x 106	16.825 x 106
Poisson's Ratio	0.33	0.34
Thermal coefficient of Expansion	12.5 x 10-6	4.9444 x 106

Design Of Disc Brake Rotor

The design or capacity of a brake depends upon the following factors

1. The unit pressure between the braking surfaces.
2. The coefficient of friction between the braking surfaces.
3. The peripheral velocity of the brake drum.
4. The projected area of the friction surface
5. The ability of the brake to dissipate heat equivalent to the energy absorbed.

Design strap of rotor

Axial force = pressure * area

The area of the elemental ring will be = r* θ*dr

$$\therefore W = \int_{r2}^{r1} pr\theta dr \qquad \ldots (1)$$

Assuming that wear is uniform,

$$P_1 r_1 = P_2 r_2 = P.r$$

$$\therefore W = c\theta \int_{r_2}^{r_1} dr \qquad \ldots (2)$$

$$= c\theta\,(r_1 - r_2)$$

$$C = P_{MAX} * r_2 \qquad \ldots (3)$$

$$= 2.709 * 90$$

$$= 243.81$$

$$w = 243.81 * 1.5\,(120 - 90)$$

$$= 10971.45\ N$$

Frictional torque, MT = μ * w * r … (4)

$$= \mu\,\theta \int_{r2}^{r1} pr2\,dr$$

$$= \frac{\mu\,\theta\,C\,(r1 - r2)}{2}$$

Now,

$$MT = \frac{\mu W\,(r_1^2 - r_2^2)}{2(r_1 - r_2)} \qquad \ldots (5)$$

$$MT = \frac{\mu W\,(r_1 + r_2)}{2} \qquad \ldots (6)$$

$$= \mu W\, r_m$$

$$M_T = .35 * 10971.45 * 105$$

$$= 403.200\ N.m$$

Modular caliper design

Modular caliper consists of

- Vented disc brake rotor
- Side block
- Backing Plate
- Piston
- Stopper

Modular Caliper Assembly

The two side blocks that enclose piston cylinders are attached to the side plates using titanium nut bolts. The left hand side housing is bolted from two holes to suspension assembly. The four pistons two on each side push the brake pads on to the rotor when the brake is applied. The tube is fixed to the caliper leading edge with the help of tube nuts and a sleeve to guide it. The tube is useful for circulation of brake fluid inside the cylinder bores.

Fig: 5 shows the internal structure of brake caliper. Here we can see the pistons/seal arrangement and the holes provided for brake fluid to pass in the piston cylinders

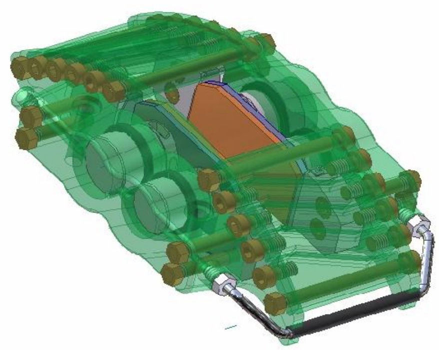

Fig: 5 Internal structure of modular brake caliper assembly

Analysis of new modular caliper

Thermal Study of Modular Brake Caliper:

To reduce the analysis time half model was analyzed. The model used for thermal analysis is shown in figure. The parts included into the model were the side block, side plate, pad blocks, abutments plates, and pistons, titanium inserts, backing plate, brake pad and nut-bolts. The stoppers were eliminated to reduce analysis time. The design parameters used were mass density, specific heat and thermal conductivity. The surface pad temperature was known to be 16000 F.

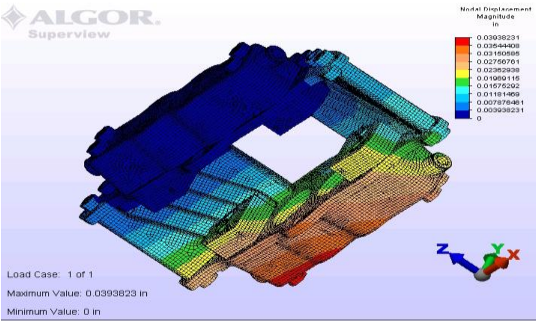

Fig: 6 Temperature analysis results

The temperature of inside diameter of the caliper body (the lower part of the caliper) was assumed to be 2000 F. The temperature of outside diameter of the caliper body (the upper part of the caliper) was assumed to be 1400 F. In Fig: 6, it can be seen that how well the titanium inserts play a role of temperature isolator. They insulate the heat developed at the pad surface from the rest of the caliper body parts effectively as shown in figure. The temperature of 16000 F is reduced to around 3000 F at the pistons and beyond.

Structural Analysis of Modular Brake Caliper

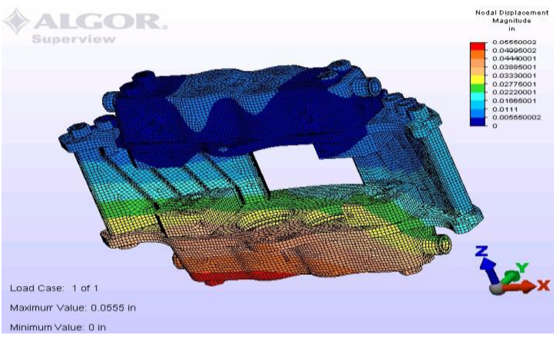

Fig: 7 Overall displacements in the modular caliper

The overall displacement of the caliper is shown in Fig: 7. The maximum displacement in the brake caliper is 0.008775mm. The displacement on the left hand side is zero because of the fact that the caliper is fixed with the steering knuckle (vehicle body) through the mounting holes. The maximum displacement occurs around the trailing edge area which is not fixed with the vehicle body.

The maximum Z direction displacement corresponds to the loading in axial direction is shown in figure. The maximum displacement is 0.0009mm in Z direction. The maximum displacement in negative Z direction is 0.0045mm. The maximum X -direction displacement corresponds to the loading in axial direction is shown in figure. The maximum displacement is 0.00022mm in X direction. The maximum displacement in negative X direction is 0.00225mm.

Structural Analysis of Modular Caliper with Thermal Effects

The overall displacement of the caliper is shown in Fig: 8. The maximum displacement in the brake caliper is 0.0112mm. The displacement on the left hand side (mounting holes side) is zero because of the fact that the caliper is fixed with the steering knuckle (vehicle body) through the mounting holes. The maximum displacement occurs around the trailing edge area which is not fixed with the vehicle body.

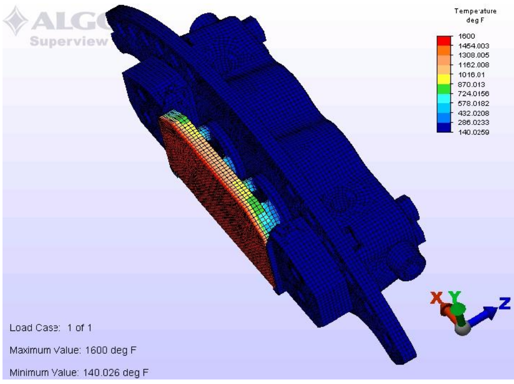

Fig: 8 Displacement in the modular brake caliper including thermal

The maximum Z direction displacement corresponds to the loading in axial direction is shown in figure. The maximum displacement is 0.00135mm in z direction. The maximum displacement in negative Z direction is 0.009mm. The maximum X -direction displacement corresponds to the loading in axial direction is shown in figure. The maximum displacement is 0.00157mm in X direction .The maximum displacement in negative X direction is 0.0045mm.

ROTOR DESIGN

Rotors are made of cast iron for three reasons

1. It is relatively hard and resists wear.

2. It is cheaper than steel or aluminum.
3. It absorbs and dissipates heat well to cool brakes.

Material: Cast Iron

Outer disc diameter	: 258 mm
Inner disc diameter	: 90 mm
Disc thickness	: 10 mm
Disc hole diameter	: 8 mm
Pad thickness	: 10 mm
Hub hole diameter	: 10mm
Hub length	: 58 mm
Hub diameter	: 90 mm
Mass of the disc	: 10 kg

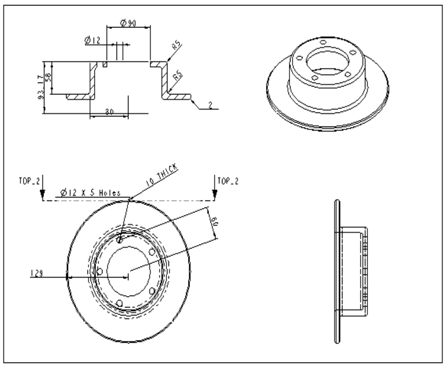

Fig: 9 Draft model of a solid disc

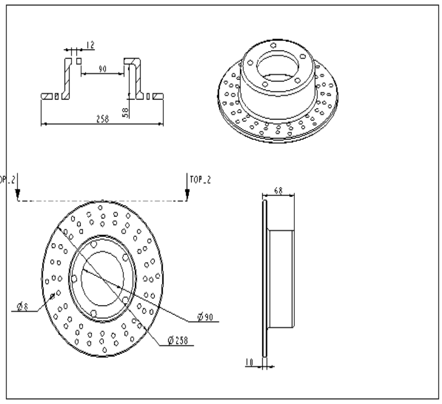

Fig: 10 draft model of a ventilated disc

Drafted models of solid and ventilated discs are shown in figures Fig: 9 and Fig: 10 respectively.And the solid model, pressure analysis, heat input to the solid disc are shown in figures Fig: 11, Fig: 12, Fig:13 respectively.

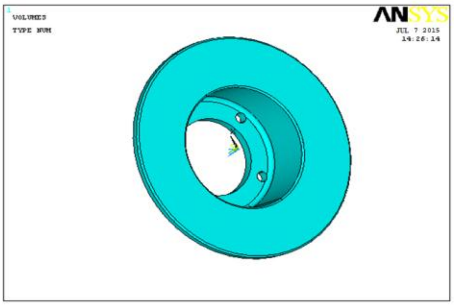

Fig: 11 solid model of a disc brake

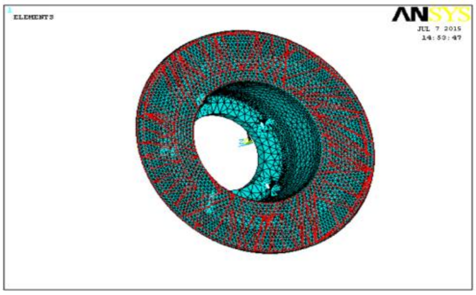

Fig: 12 pressure analysis of a solid disc

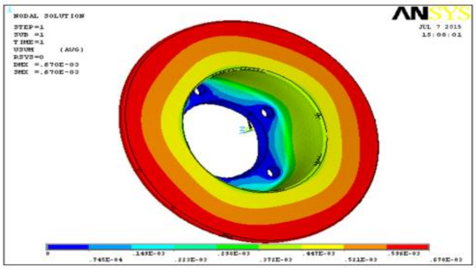

Fig: 13 heat input to the solid disc

Conclusion

The detail review of the thesis will lead one to understand that essentially a new conceptual caliper design was proposed to decrease the thermal deformation at high temperatures The Existing caliper was first analyzed at cold working conditions without taking into account the effects of thermal expansion. The stresses and displacements were noted. The maximum stress was lower for Al 2219 than the Al 6061 brake caliper. This result confirms the use of Al 2219 for the new brake caliper. The existing brake was analyzed at 3000F. The caliper showed high thermal stresses and displacement as compared with the previous case. This is due to the thermal expansion of caliper body.

The modular design was analyzed without considering the effects of thermal expansion. This is done to study the amount of deformation due to tangential Force and pressure loading. These results were used to study the increase in deformation in the caliper at high temperatures. The modular brake was then analyzed using a nodal temperature of 3000F.

The displacement increased as compared with the previous case. This is due to the thermal expansion of the individual parts in the assembly. Since race cars brakes always operate at high temperature the thermal deformation /displacement results are important. The thermal displacement in the modular caliper is lower than the conventional caliper by 8.56 %. This is shown in below Table: 3

Table: 3 Thermal displacements of conventional and modular calipers

condition	**displacements**
Modular brake caliper without temperature	0.008775mm
Modular brake calipers with temperature	0.0123mm
Conventional caliper Al 2219 without temperature	0.00306mm
Conventional caliper Al 2219 with temperature	0.01353mm

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