Design and Analysis of a Disc Rotor for a Small Race Car's Braking System

by

Azman Bin Aziz
6319

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

DECEMBER 2008

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Approved by:

....

(Ir. Dr. MASRI BIN BAHAROM)

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(AZMAN BIN AZIZ)

ABSTRACT

The purpose of these report is to record the information regarding on Final Year Project. It includes the data gathering, calculations and design stage that had been gone through by author. The objective of the project is to design the disc rotor for a braking system of Formula SAE according to rules and regulation of Formula SAE car.

FSAE car braking system that is designed by author is based on the dual hydraulic circuit, which the standard front to rear split that generally used in rear wheel driven car. Moreover, the braking system uses a disc braking system instead of using drum brakes. Advantages of using disc brakes system are more fade resistant, possible to stop in wet condition, reduce the overall weight of the car and easy to make service during the race.

In the Literature Review, the first stage in designing is made it according by the rules and regulation of Formula SAE guidelines. Moreover, the formulas were identified in getting the right formula of braking performance, component sizing, and adhesion utilizations of the car.

In the Result and Discussion, it shown the target of brake bias setting is 55:45 (front to rear) has been calculated in the Excel form. Also, adhesion utilization curve is generated and shown the both axles will lock up simultaneously at deceleration rate, z=k at 0.58g. Next, the rotor have been designed by using CATIA. Also, the rotor's thermal analysis have been analyzed using ANSYS Workbench. The manufacturing process of the rotor have also been proposed by the author. As conclusion, a certain amount of understanding of the brake system has been obtained.

ACKNOWLEDGEMENT

Alhamdulillah. Thanks and gratitude to Allah S.W.T for the spirit, wisdom, knowledge and understanding for me in journey to complete my final project tasks and report. For the strength and health, He provides me that I am able to go through every single circumstances and problem during the development.

I would like to express my great thanks to my project supervisor, Dr. Abdul Rashid Bin Abdul Aziz and Ir. Dr, Masri Bin Baharom for his advice, my co-supervivisor, Mr Mohd. Saifuddin Bin Mohd. for his guidance and understanding throughout the development of this project. This project development would not have been possible without the assistance and guidance of certain individuals whose contributions have helped in its completion.

Also, to my beloved parents who always provide me with a lot of supports and prayers that strengthen me. Not forgotten, to my friends and peers for their unconditional support and love for me.

Last but not least, I would like to thank all persons who have contributed to this project in one way or another especially the UTP technicians.

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ABBREVIATIONS AND NORMENCLATURES

μ_{pr}	: Coefficient of Friction between pad and rotor
P_{fm}	: Mean calliper actuation pressure (Nm^{-2})
A_{pad}	: Quantity of area under pad at any time (m^2)
ω	: Angular velocity (rad/s)
r_m	: Mean rubbing radius (m)
F	: Force (N)
V	: Speed (rad/s)
m	: Mass (k)
v	: Velocity (m/s)
A	: Conduction Area (m^2)
dT	: Temperature Changes (K)
dX	: Distance (m)
K	: Thermal Conductivity ($Wm^{-1}K^{-1}$)
W	: Energy (Js^{-1})
d_o	: Outer Diameter (m)
d_i	: Inside Diameter (m)

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Society of Automotive Engineers (SAE) has been organizing competitions of engineering designs worldwide. One of the competitions is the Formula SAE (FSAE) where students congregate in a design/race team in developing a Race (formula type) car, and upon completion, race in the autocross event. The team of engineers consists of chassis, power train, aerodynamics, suspension, and many more.

Good handling could be described as going around corners faster while improving control which is commonly associated to how well the suspension and steering of the car being tuned up. However, there are other parameters that always come first before the car is actually tackling the corners, which is the braking system. The braking system will reduce the speed of the car until a safe speed limit, depends on the car itself. In fact, there is no way for the car could deal with the corners without a correct hence a good braking system.

The development process of this braking system consist of several engineering stages which are designing, analyzing and come up with the fabrication steps to reach it best prospective. The study is start from scratch with some guides from internal lecturers as well as external expertise that's willing to show their cooperation in realizing the project. The responsibility is handed over to student as one of the Final Year Project title for each year. The project is expected to develop technical skills along with engineering-wise knowledge in terms of racing technology.

1.2 Problem Statement

1.2.1 Problem identification

The process of designing the suspension system should include the considerations of overall autocross track layout. The competition itself will be divided into static and dynamic events. In the dynamic event, the car will be used many times in its highest speed. Thus, in order to assist the car to complete the entire race, a set-up of well-designed braking system is a must to it. Design inadequacy from the previous design had been identified, where the design application of the braking system could not sustain the excessive heat of the friction force due to the main competition had not been studied. Other than that, the disc rotor of the braking system must be home fabricated as been stated in the regulation of the Formula SAE competition.

1.2.2 Significant of Project

Upon completion of the research and designing, the final design will be absorbed into the racecar. The design and calculation will determine the performance of the vehicle in the event. The FSAE design team provides the knowledge base of the motor sports industry. Students are able to integrate fundamentals of kinematics and mechanics of material.

1.3 Objectives of Study

The main objective of this project is to design a good braking system for UTP Formula SAE car. The main goals of this project are stated as follow:

i. To design and analyze the rotor disc for a small race car's braking system.

ii. To propose manufacturing processes involved for a limited production of the rotor disc.

1.4 Scope of Work

The project consists of designing stages of the braking system of the Formula SAE car which constrained by 2007 Formula SAE Rules. This stage is focused on the verification process of the previous calculation on braking performance. After that, the process is continued by performing new calculation on braking performance and based on the previous UTP FSAE car.

The next stage is the designing process of a new rotor which must has a significant weight reduction as well as the heat ventilation capabilities and high material strength. The design process includes the usage of CAD modeling software such as CATIA. By using the capability of CATIA, this will ensure better communication of design during packaging process. The thermal and structural analysis of the design will be analyzed using ANSYS and ANSYS Workbench. The analysis is expected to be able to justify the new design of rotors.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Formula SAE Braking System Layout

The components and the braking system of a Formula SAE car are much more different than the regular passenger car. The main difference between these two cars is the Formula SAE has a balance bar as one of the component. The balance bar functions as a tuning component to tune the braking force for the front and rear tire. Figure 2.1 and 2.2 shows the Formula SAE braking system that will be described one by one.

Figure 2.1: UTP Formula SAE Car2008

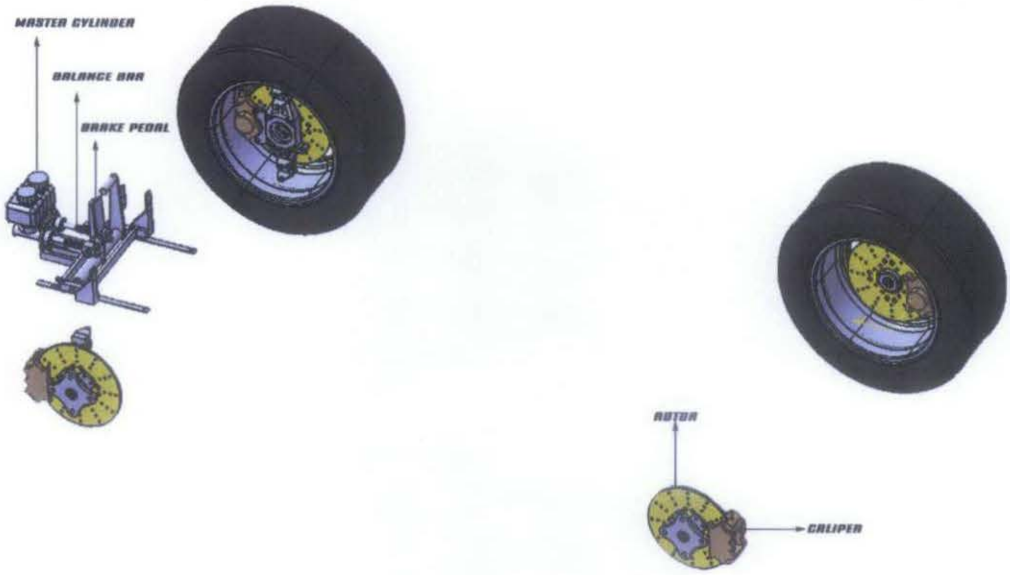


Figure 2.2: Brake System Layout for Formula SAE Car

Additionally, the braking system will also be equipped with an over-travel kill switch. The function of this switch is that when in the braking system fails during an event where the brake pedal over travel, the switch will be activated and stops the engine from running. This switch must kill the ignition and cut down the power to any electrical fuel pumps. Repeated actuation of the switch must not restore power to these components, and it must be designed so that the driver cannot reset it. The switch must be implemented with an analog component and not through recourse to programmable logic controllers, engine control units, or similar functioning digital controllers. The switch is located at the back side of the brake pedal in the pedal box.

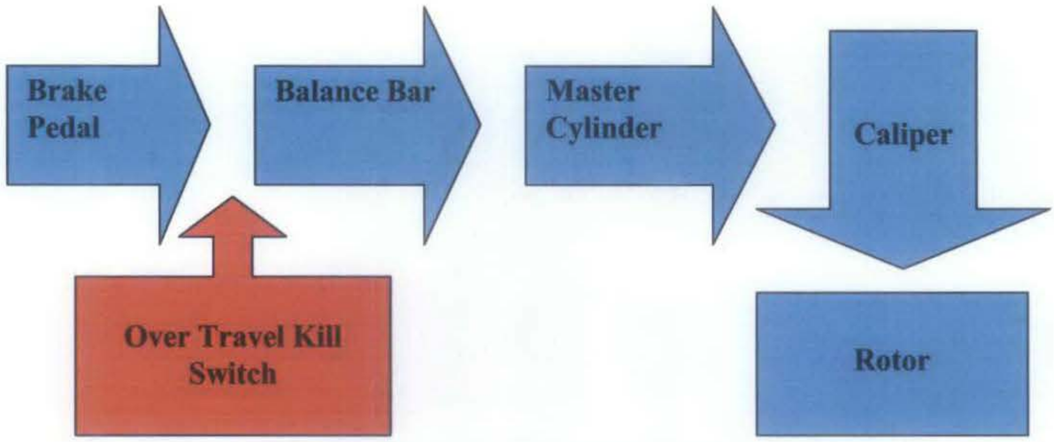


Figure 2.3: Hydraulic System Flow in Formula SAE

2.1.1 Pedal Box

The sole function of the pedal box assembly is to harness and multiply the force exerted by the driver's foot by using leverage concept. It can be learned by the leverage on a teeter-totter concept which the farther they sit from the pivot; the more weight can be lift on the other end. In the case of the braking system, the pivot is at the top of the brake pedal arm, the pad is on the opposite end, and the output rod is somewhere in between.

2.1.2 Balance Bar

The balance bar takes the force applied to the brake pedal and distributes it to the front and rear master cylinders. The percentage of the force that goes to the master cylinder depends on the position adjustment of the balance bar. If the center spherical joint is positioned exactly in the center of the two master cylinder pushrod clevises, them each master cylinder will get the same amount of pushrod force. If the shaft and the spherical joint moves are turned closer to the left clevis, then the left clevis will see more force from the pedal than the right clevis. It also works vice versa.

2.1.3 Master Cylinder

The next step in the braking system is to convert the amplified force from the brake pedal into hydraulic fluid pressure. The master cylinder, consisting of a piston in a sealed bore with the brake pedal output rod on one side and brake fluid on the other, performs this task. As the pedal assembly output rod pushes on the piston, the piston moves within the cylinder and pushes against the fluid, creating hydraulic pressure. The pressure generated at the master cylinder is equal to the amount of force from the brake pedal output rod divided by the area of the master cylinder piston.

For the Formula SAE car, the master cylinder is divided internally into two sections, each of which pressurizes a separate hydraulic circuit. Each section supplies pressure to one circuit. A front or rear split system uses one master cylinder section to pressurize the front slave cylinders, and the other section to pressurize the rear slave cylinders. A split circuit braking system is now required by for safety reasons. If one of the circuit fails, the other circuit can stop the vehicle.

2.1.4 Tube and Hoses

The brake tubes and hoses transport the pressurized brake fluid away from the master cylinder to the four corners of the car. It would be ideal to use the most rigid material possible to minimize the compliance in the system.

2.1.5 Caliper

Like the master cylinder, the caliper is just a piston within a bore with pressurized fluid on one side. While the master cylinder used mechanical force on the input side to create hydraulic force on the output side, the caliper is vice versa.

The hydraulic force on the input side of the caliper will be converted into a squeezing or clamping force on the output side of the caliper. In order to calculate the amount of clamping force generated in the caliper, the incoming pressure is multiplied by the area of the caliper piston.

2.1.6 Brake Pad

The brake pads have the responsibility of squeezing on the rotor with the clamping force generated by the caliper. There is a lot of material composition and formulation for the friction pad, but what really matters is the effective coefficient of friction between the pad and the rotor face. By knowing the clamp load generated by the caliper and the coefficient of friction between the pad and rotor, one can calculate the force acting upon the rotor.

2.1.7 Rotor

The rotor is a device that slows or stops the rotation of a wheel. A rotor usually made of cast iron or ceramic, is connected to the wheel or axle. To stop the wheel, the brake pads are forced mechanically and hydraulically against both sides of the rotor generating friction. The friction causes the rotor and attached wheel to slow or stop.

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

2.2 Braking Calculation

The calculation for the braking system is formulated by governing equations from stopping force developed on tires to the force exerted by the foot of the driver. This comprehensive way of calculation is being used to determine the correct component sizing of all braking components. All equations are then inserted into Microsoft Excel in purpose to manage the equation as well as determining various outputs from several input trials. All equations used are listed out in figure in the next sub section.

2.2.1 Governing Equations

TIRE

$$N_1 = P_1 + \frac{P \times z \times h}{E}$$

$$F_1 = \frac{F_{Front}}{2} = \frac{\mu N_1}{2}$$

$$T_{1(Tire)} = F_1 R$$

↓

ROTOR

$$T_{1(Tire)} = T_{1(Rotor)}$$

$$T_{1(Rotor)} = (f_1 r_1)(\sum calipers \times \sum pads)$$

$$\therefore f = \frac{T_{1(Rotor)}}{(r)(\sum Calipers \times \sum Pads)}$$

↓

PISTON

$$\mu_{pad} = 0.56$$

$$N_{atPiston} = \frac{f_1}{\mu_{pad}}$$

↓

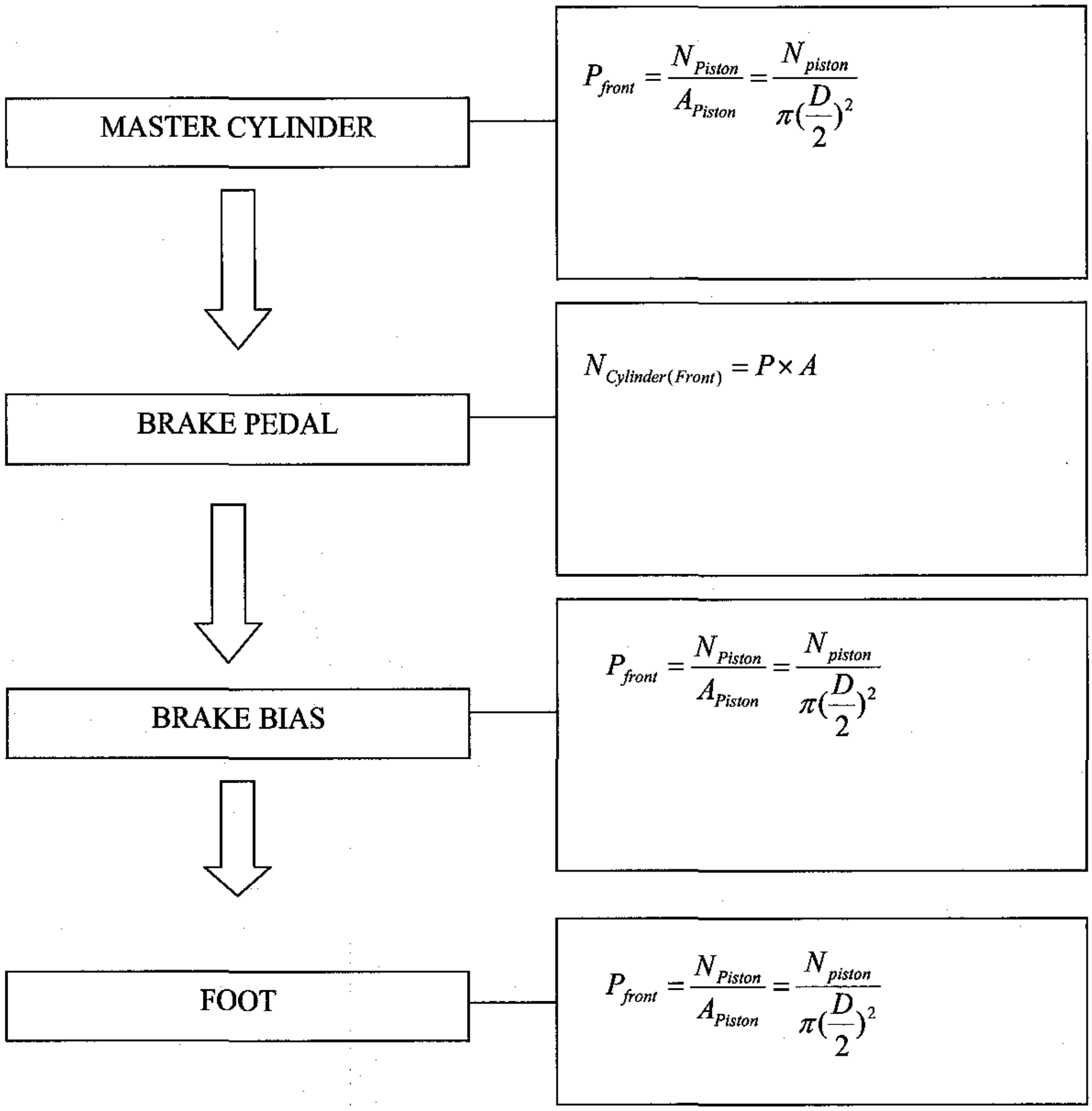


Figure 2.4: Governing Equation for Braking Calculation

2.2.2 Adhesion Utilization

Adhesion utilization, f, is the theoretical coefficient of adhesion that would be required to act at the tire-road interface of a given axle for a particular value of deceleration. It is there fore the minimum value of tire-ground adhesion required to sustain a given deceleration and is defined as the ratio of the braking force to the vertical axle load during braking. The governing equations that lead to the determination of adhesion utilization parameter, for each front and both axle, stated as follows:

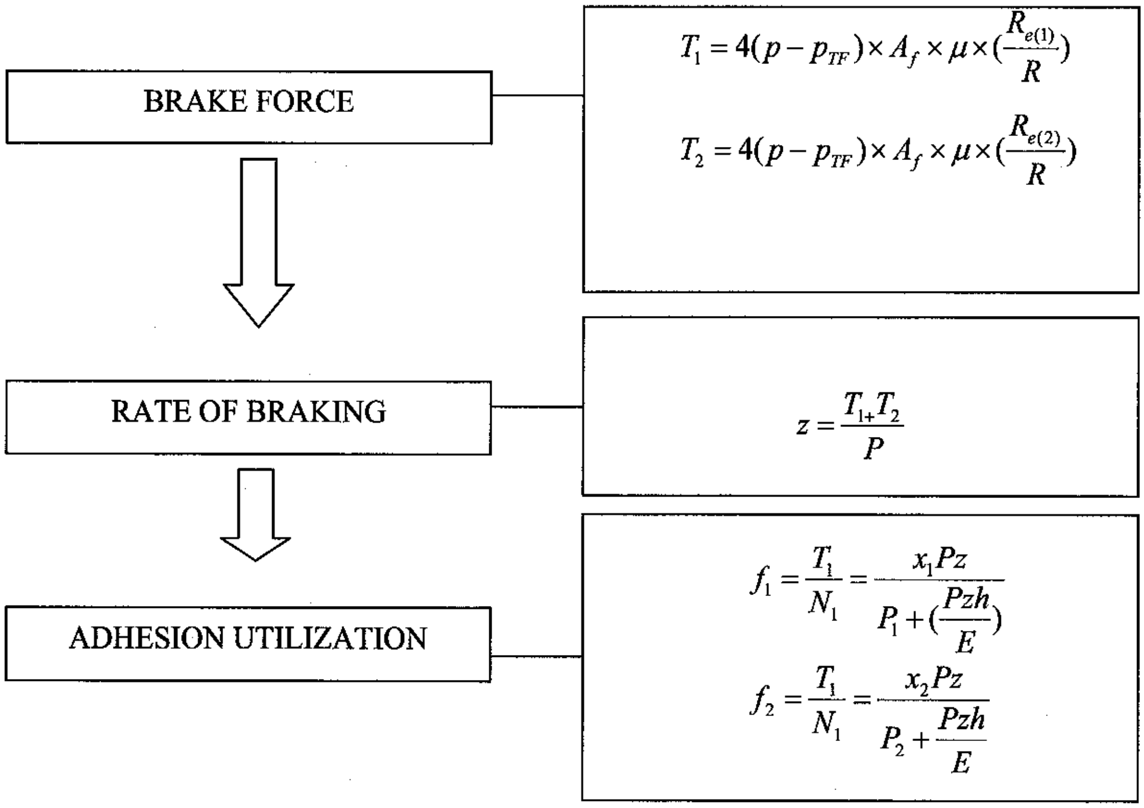


Figure 2.5: Governing Equation to Determine Adhesion Utilization

2.3 Braking Thermodynamics

Brakes are designed to slow a vehicle down from a moving condition. It is technically done by its thermodynamics mechanism which the capabilities in changing energy types. Theoretically, when a vehicle traveling at speed, it developing an amount of kinetic energy. This significant energy type keep on vary in respect to the vehicle's speed. When brakes are applied, the pads that press against the rotor convert that energy into thermal energy. Then, the cooling characteristic of the brakes dissipates the heat and the vehicle slow down.

In the scope of this study, the conservation of energy principle occurs as the kinetic energy is converted to thermal energy.

2.3.1 Brake Fade

In reality, as the vehicle is moving, braking processes will take place repetitively in order to tackle the corner or stop in the traffic. This condition is hence to be more severe in racing condition where brakes applied to slow down the vehicle from high speed to a safe speed range in handling a corner or turn. However, what is like to be highlighted here is the interval between each braking process which is in racing; definitely really small since the corner will come from one after another continuously. This caused the braking components has no chance to cool down. Thus, in terms, of braking thermodynamics principle, as the number of braking attempts increases, the braking components, especially the rotor and pads, experienced a relatively high temperature rise which sometimes up to $600^{o}c$. At this stage, they cannot absorb much more heat and the braking performance will reduced. This is defined as 'brakes fade' which always related to reduction in braking performance as the temperature of braking components especially friction material getting so hot.

In order to further explain the concept lies behind brake fade phenomenon, a closer look into a material perspective is needed. Brake pads are constructed by combining friction materials together with some sort of resins. As the rubbing process take place, this surface will first experienced a temperature rise. As a result, the resin which holding the pad material together, starts to vaporize and forming a gas. Because of the configuration of the pads that 'clamping' the rotor, the gas forms a layer between the two components. Therefore, friction contact area between pads and rotor has been abolished and caused the reduction in braking performance

2.3.2 Combating Brake Fades

Brake fade is a term that refers to the reduced effectiveness of many dry brakes as they become heated. If a brake rotor was a single cast chunk of steel, it would have terrible heat dissipation properties and leave nowhere for the vaporized gas to go. Because of this, brake rotors are typically modified with all manner of extra design features to help them cool down as quickly as possible as well as dissipate any gas from between the pads and rotors. The following diagram shows some examples of rotor types with the various modifications that can be done to them to help them create more friction, disperse more heat more quickly, and ventilate gas. There are four types of rotors that compared the significant of having optimization in terms of thermodynamics principle:

i. Basic brake rotor.

ii. Grooved rotor

The grooves give more bite and thus more friction as they pass between the brake pads. They also allow gas to vent from between the pads and the rotor.

iii. Grooved, drilled rotor.

The drilled holes again give more bite, but also allow eddy currents to blow through the brake disc to assist cooling and ventilating gas.

iv. Dual ventilated rotors.

Same as before but it has two rotors instead of one. It has vanes in between them to generate a vortex which will cool the rotors even further whilst trying to actually 'suck' any gas away from the pads.

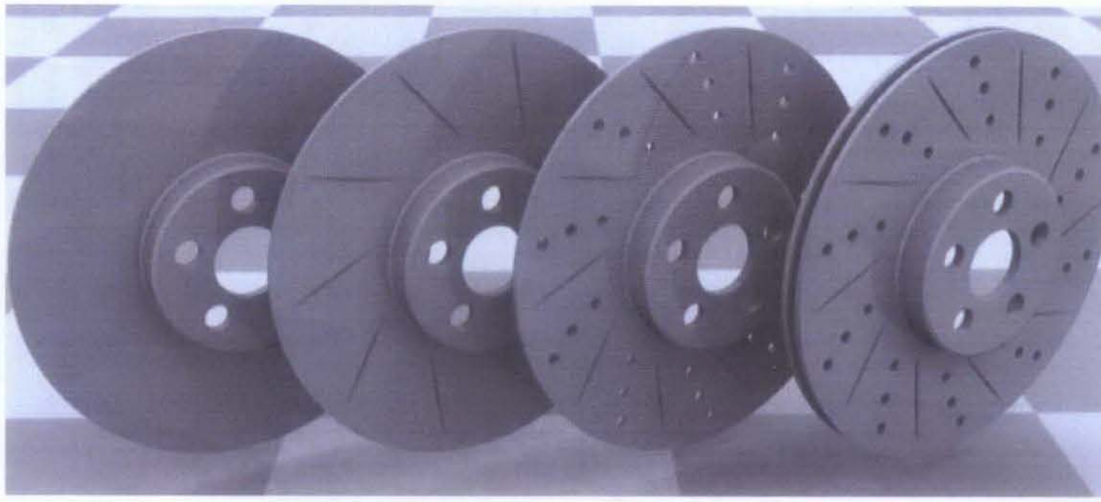


Figure 2.6: Types of Rotors

2.3.3 Thermal Effect

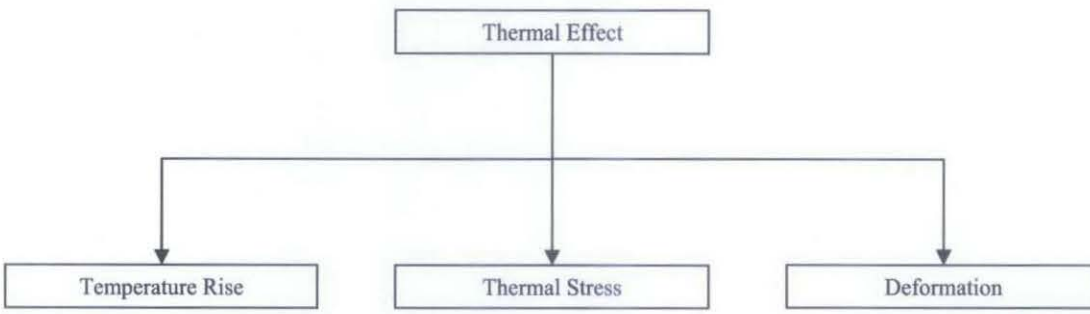


Figure 2.7: Types of thermal effects to rotor

Based on figure 2.4 above, there are 3 significant effects caused by the thermal energy created during braking process on the rotor which are the temperature rise, thermal stress and minor deflection as the consequences of the thermal stress. The temperature rise is the direct upshot of the thermal energy created on the rotor. This change in temperature is caused by conduction effects as well as the convection from the rotor surface which governed by following equations:

Heat transfer during conduction, $Q = kA\frac{dT}{dX}$

Heat Transfer during convection, $Q = hAdT$

During braking, both conduction and convection occurs simultaneously which conduction applies at the rubbing surface whilst convection occurs at exposed surfaces of rotor. Thus, the temperature variation explain how the thermal energy being handle by rotor which assisted by the design itself.

On the other side, as the consequences of temperature variance during braking, thermal stresses is generated during braking. Thermal stress is defines as the residual stress developed in a particular materials as a result of changes in temperature. It is frequently caused by rapid heating and cooling which the exterior of materials is hotter and tend to expand more than the cooler, inner portion of materials. Hence the tensile surface stresses are induced and are balance by the compress interior stresses. This phenomenon is relatively similar to the braking process during braking where rapid heating of the rotor (nearly less than 2 seconds) is followed by rapid cooling utilized by convection by movement of air. The amount of stress developed is defined by following formula:

Thermal Stress, $\sigma = E\alpha\Delta T$

The third effect that will be taken into consideration of this study is the level of deformation of the material due to the thermal stresses generated. This deformation is related to the level of mechanical properties of the material such as yield strength and tensile strength.

2.3.4 Heat Flux Density

The amount of energy apply to the rubbing surface between rotor and brake pads is defined as heat flux density which carried by the following calculation

Heat flux density, $Q'_b = (\mu_{pr}\ P_{fm}\ A_{pad}\ \omega\ r_{fm}) / A_{pad}$

$= (F \times V) / A_{pad}$

This energy is calculated based on the worst case braking scenario where the constant g braking process take place. This model is the most similar model that could reflect the actual racing conditions.

2.3.5 Distribution of Heat Flux Density

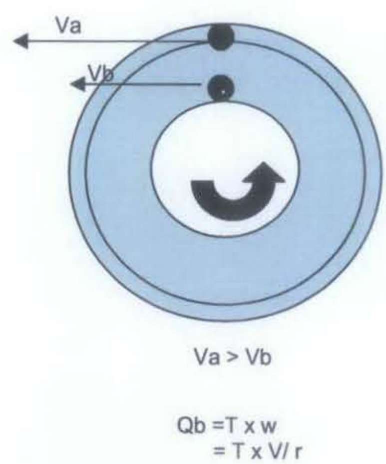


Figure 2.8: Concept on Heat Flux Density Distribution.

For any mass that rotates about central axis, a point on that mass will move faster if it is further away from the axis of rotation. This is because a point has to travel around circumference when it is moved away from the centre. From figure above, it is clearly stated that the point A which located more towards outer side of the rotor is having a larger velocity value compared to point B. The brake discs on SAE car adhere to this phenomenon and as greater energy is created when sliding velocity is increased, the disc are subjected to a non-uniform heat flux input over the discs rubbing surface. Thus, in order to simulate this in the analysis, the rotor rubbing surface is divided in radial direction, forming a number of smaller sequential discs (Refer to Figure below). The heat flux entering the rotor can then be split according to the mean rubbing radius of the section. As the heat flux is a function of sliding velocity (and thus radius), the sections further from the centre receive a larger proportion of energy.

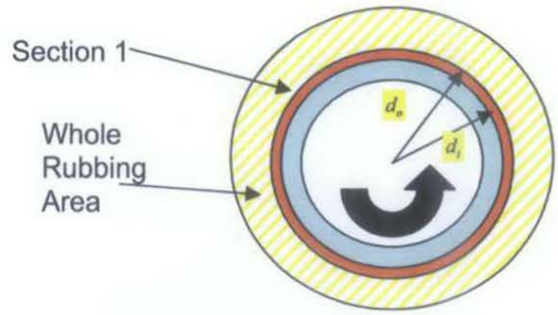


Figure 2.9: Rotor Section Analysis

2.4 Material Properties

There are few types of materials which are commonly used for vehicle's brake rotors, either for commercial purposes or racing objectives. Generally, cast iron has been widely used for motoring due to its desirable qualities. It covered all aspects including ease to manufacture, thermal shock resistance, strength and low cost compared to other alternatives such as MMC (metal matrix composite). Thus, a custom, factory fabricated cast iron is chosen for the project.

2.4.1 Cast Iron Properties – FCD 450

Table 2.1: Material Properties for Cast Iron

Properties	Value
Density	$7228kgm^{-3}$
Thermal Conductivity	$54Wm^{-1}K^{-1}$
Specific Heat	$419Jkg^{-1}$
Film Coefficient	0.17
Young Modulus	165E9 Pa
Poisson Ratio	0.275
Coefficient of thermal expansion	12.6E-6
Bulk Modulus (convection)	$100Wm^{-1}K^{-1}$
Yield Strength	280 Mpa
Tensile Strength	450 Mpa

CHAPTER 3
METHODOLOGY

3.1 Process Flow

The project started with the understanding of the whole project including the studies, theories and the competition's needs. Just after that the design will start using CATIA as a medium to design. Then the FEA analysis will be tested on the design for the material selection and also the properties. If it meets specification, we will continue with the critical design review before assembling all designs. After that the cost analysis will be analyze before completing the final design.

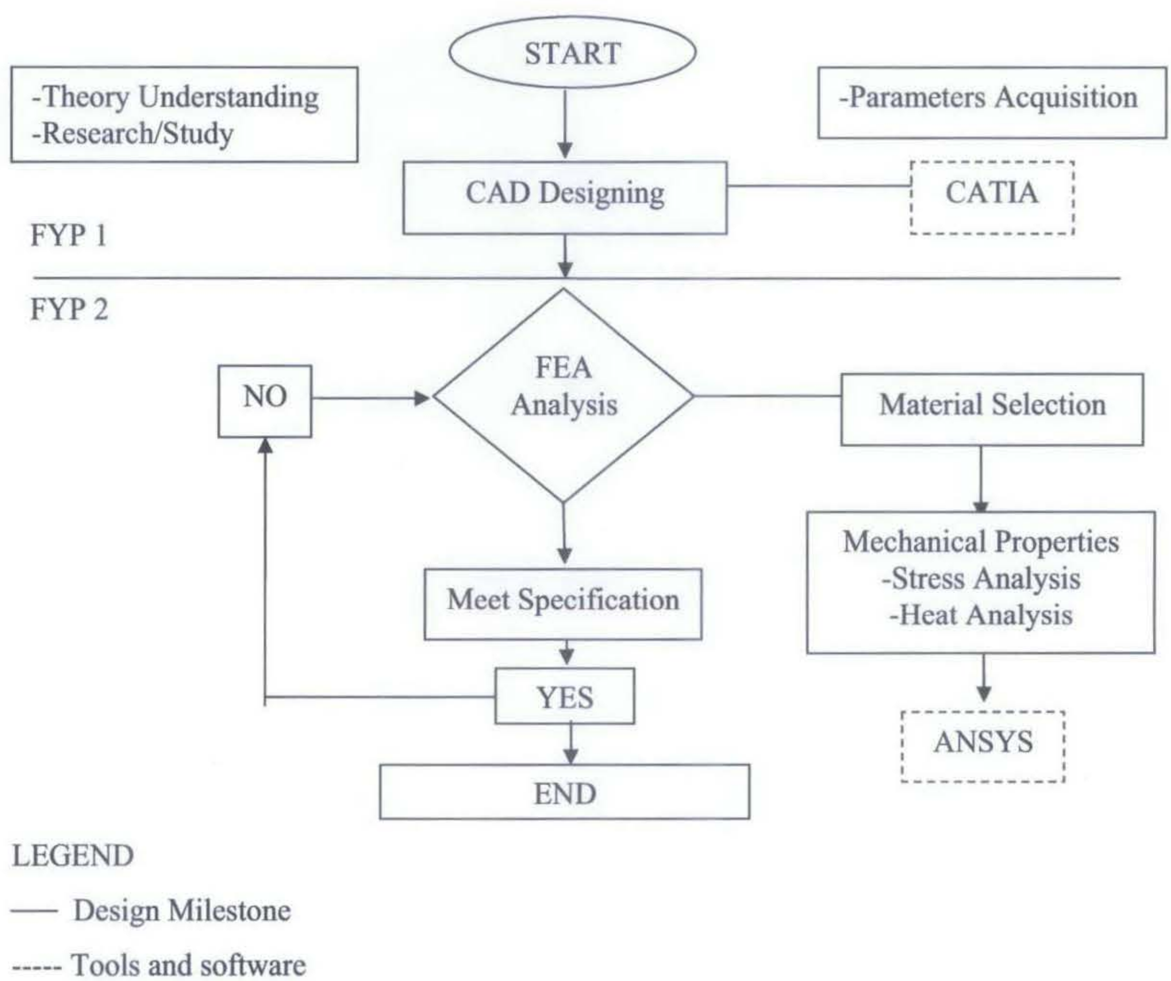


Figure 3.1: Process Flow

3.2 Tool Used

Several engineering software have been used in completing the first part of this project. These software's are used to perform all the required analysis of the project and its functions are as described.

3.2.1 Microsoft Excel 2003

This spreadsheet application provides some features of calculation, graphing tools and pivot tables which allow insertion of mathematical formulas and equation. In this project, the author used this software to calculate the braking parameters and adhesion utilization.

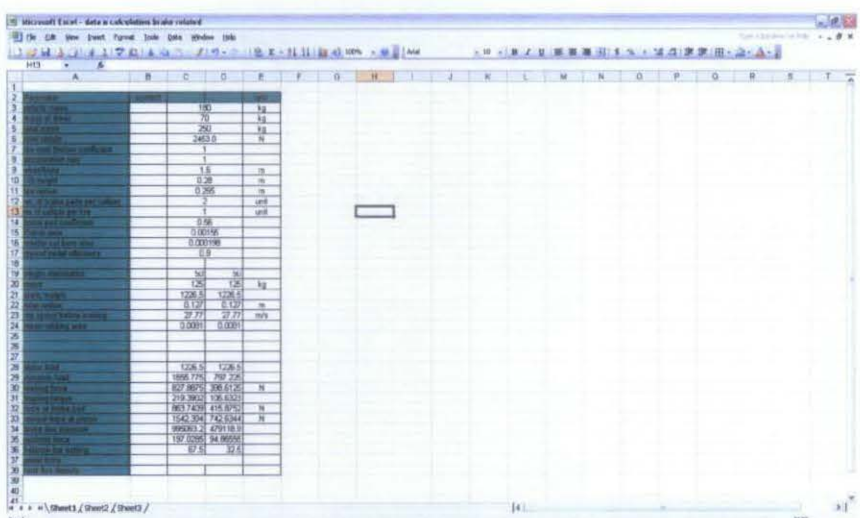


Figure 3.2: Microsoft Excel Iteration Calculation

3.2.2 CATIA V5R14

CATIA (Computer Aided Three dimensional Interactive Application) is a multi-platform CAD/CAM/CAE software which is written in the C++ programming language. It supports multiple stages of product development which range from conceptualization, through design (CAD) and manufacturing (CAM), until analysis (CAE). In this project, it is used to design the brake components solid modeling.

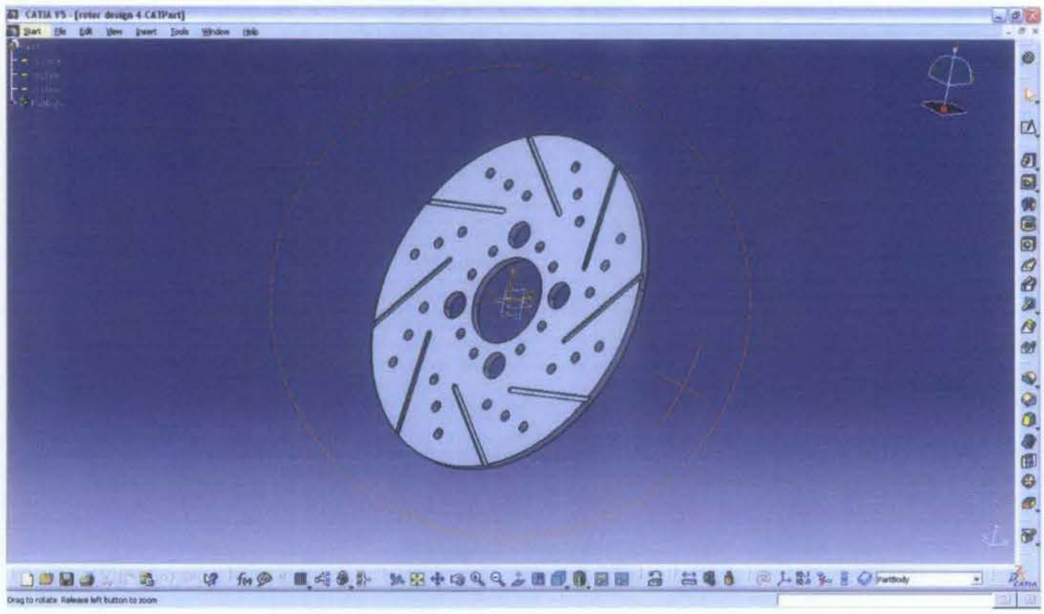


Figure 3.3: CATIA solid modeling

3.2.3 ANSYS Workbench 11.0

The ANSYS Workbench platform is an environment that offers an efficient and intuitive user interface, superior CAD integration automatic meshing and access to model parameters as well as to the functionality available within the ANSYS Mechanical products. It provides high-end desktop environment for all ANSYS technologies from static linear analysis to nonlinear rigid/flexible dynamics, from steady state thermal analysis to coupled thermo-mechanical transient studies. In this project, this software is used to make an FEA analysis on the rotor disc designed.

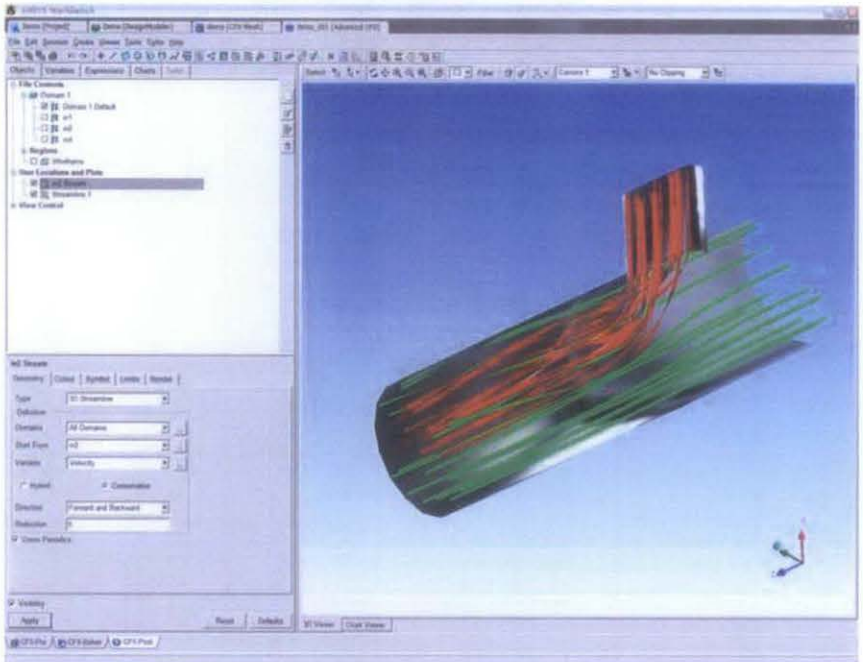


Figure 3.4: ANSYS Workbench FEA

3.3 Verification on Previous Calculation

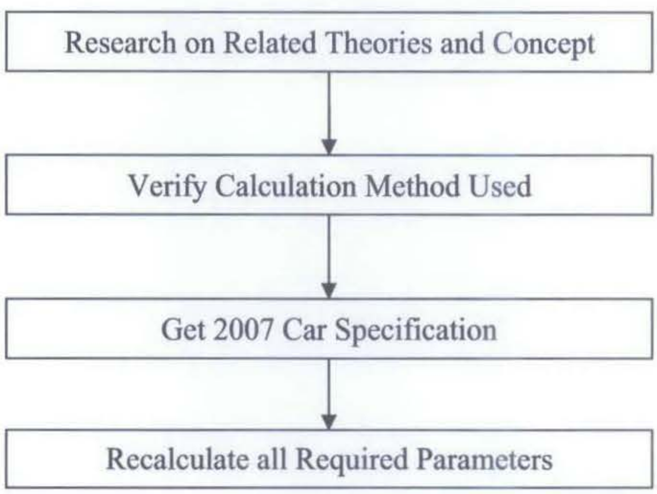


Figure 3.5: Process Flow on Calculation Verification

By referring to Figure 3.1 above, the verification process on previous calculation calculated based on the guideline above.

3.3.1 Research on Related Theories and Concept

Research on theories and concept that related to brake design and safety. All information is gathered from the net, published automotive journal and references text. Besides, a weekly meeting with respective automotive supervisor also done in order to polished the understanding on project's requirement.

3.3.2 Verify Calculation Method Used

The calculation method is verified using theories and concept found during the 1st stage.

3.3.3 Get 2007 Car Specification

The 2007 FSAE car specification is gathered from other respective departments of the team such as drive train, chassis and suspension. This is to ensure the updated design parameters is taken into consideration for the calculation purposes.

3.3.4 Recalculate all Required Parameters

Using all the applicable and related formulas, parameters are recalculated using Microsoft Excel by inserting the related formulas.

3.4 Analysis on New Rotor Design

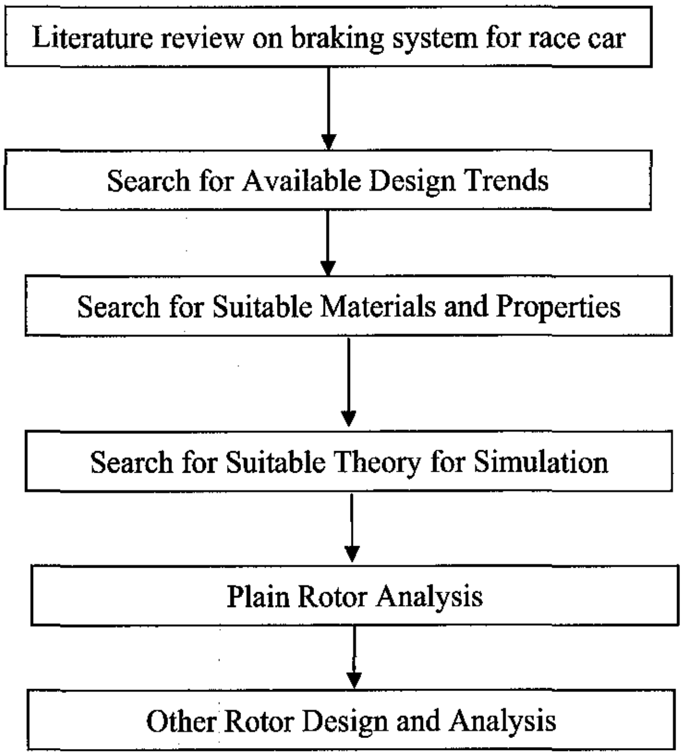


Figure 3.6: Project Process Flow on Rotor Design and Analysis

As stated before, the design and analysis of a new rotor is the focal point for this project. Most of the project critical stages occurred in this section. The design and analysis of a new rotor is done through 6 steps as shown in Figure 3.2 above.

3.4.1 Literature review on braking system for race car

Search for suitable braking system design process with focusing in rotor design and development. The literature review is required in order to master the concept of designing

3.4.2 Search for Available Design Trends

Study current design trends to get the idea on what the rotor would be looks like.

3.4.3 Search for Suitable Materials and Properties

Seek out for material properties of the proposed materials to be used to fabricate the rotor. These include comparison study on properties of available material as well as the higher grade materials.

3.4.4 Search for Suitable Theory and Method for Simulation

Method on analyzing the rotor is explored from other university's research papers and by exploring the particular FEA software, where in this project is the ANSYS Workbench

3.4.5 Plain Rotor Analysis

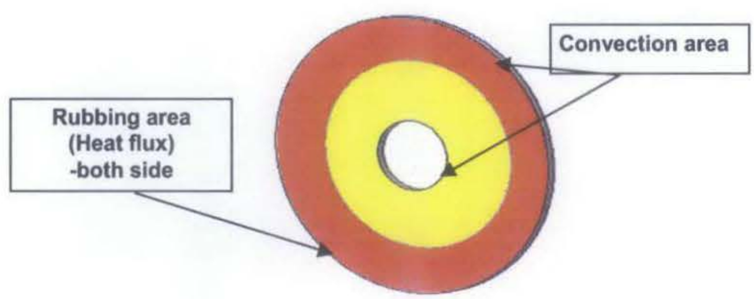


Figure 3.7: Basic Geometry Modeling for Plain Rotor Analysis

Rotor analysis is done by constructing a simple rotor model which consisted of pad rubbing area (red area) and convection area (yellow area). The main interest of the analysis is to study on the temperature rise and thermal stress of the rotor during its operation condition. The pad-rotor reaction is simulated by inserting an amount of heat flux density input, calculated from equation in section 2.2.4. Below is the assumptions made for the plain rotor analysis:

- Transient process applied to the whole simulation where the braking process is defined as applying heat flux for 2.83 seconds and convection took place consecutively until 10 seconds. (Refer to Figure 3.4 below)

Figure 3.8: Analysis time line

- No convection occurs on the surface where the heat flux being applied
- The time interval used; 2.83s, is the maximum braking time when the car decelerates from 100 km/h to 0 km/h at constant 1g deceleration rate.
- Heat flux density value Q'_b, is calculated as 1.524 E6 Watts/m^2
- Amount of heat flux being applied to the rotor surface is constant throughout the braking period.
- Heat conduction to other braking components is negligible.
- Effect of air flow to convection is negligible.
- Initial temperature was predefined at 20 (Temperature will change according to the ambient conditions)

3.4.6 Other Rotor Design and Analysis

A new rotor for SAE car is expected to comprise of heat dissipation capabilities, which as stated in theory, will be able to prevent or at least minimizing the effect of the brake fade phenomenon to occur. Thus the design stage is done based on a pre described guideline which to create enough convection area by implementing cross drilled and grooved design.

To summarize the process, below are the method used for the design stages:

- Four set of geometry model is developed using Workbench including plain rotor
- The analysis is performed using plane rotor analysis method
- Maximum temperature, maximum thermal stress and maximum deformation values is taken and compared.

CHAPTER 4

RESULT AND DISCUSSION

4.1 New Calculation Result

For new calculation result, there are few changes in terms of braking parameters in Table 4.2 since the main specification of the car is being changed drastically.

Table 4.1: 2008 FSAE Car Specifications

Parameters	Value		Unit
Vehicle mass	180.00		kg
Mass of driver	70.00		kg
Total mass	250.00		kg
Total Weight	2452.50		N
Tyre Ground C.O.F (mue)	1.00		
Deceleration Rate	1.00		g
Deceleration due to Gravity	1.00		g
1g	9.81		m/s2
z	1.00		
Wheelbase	1.60		m
CG height	0.28		m
Tire Radius	0.265		m
No. of Brake pads/caliper	2.00		
No. of caliper/tire	1.00		
Brake pad C.O.F	0.56		
	Value		
	Front	Rear	
Weight Distribution	0.45	0.55	%
Mass	112.50	137.50	kg
Static Weight	1103.63	1348.88	N
Rotor Radius	0.229	0.229	m
Top Speed Before Braking	27.77	27.77	m/s
Mean rubbing Area	0.0081	0.0081	m2

The main adjustment on specification stated as follows:

- **Reduction in total mass**

  The total mass of the car is reduced from 320 kg to 250 kg due to the change in design of chassis where the previous car used space frame while the 2008 car uses a monocoque body.

- **Reduction in wheel base length**

  The car size is targeted to be smaller compare to last year. The reduction of wheel base from 1.65m to 1.60m will assist in fulfilling the objective to have a smaller race car.

Table 4.2: Data on Braking System of 2008 FSAE Car

Section	Specification Parameters		Calculated Parameters	Front	Rear	Un
Tires	Radius (m)	0.265	Weight Transfer	1103.63	1348.88	N
			Braking Force (BF)	1103.63	1348.88	N
			BF / Tire	551.81	674.44	N
			Torque / Tire	146.23	178.73	N
Rotor	Radius (m)	0.229	Heat Flux Applied / Rotor	15323.83	18729.20	J/
			Heat Flux Applied/ Pad	7661.92	9364.60	J/
			Heat Flux Density	945915.63	1156123.38	J/s.
			BF / Rotor	1151.42	1407.30	N
			BF / Pad	575.71	703.65	N
Caliper	Bore (m)	0.044	Normal Force/Caliper	2056.11	2513.03	N
	Area (m2)	0.002	Normal Force/Piston	1028.05	1256.51	N
Hydraulic Brake Line Press			Pressure	662494.46	809718.46	P
Master Cylinder	Bore (m)	0.018	Pushrod Load	164.4885	201.0423	N
	Area (m2)	0.000				
Brake Pedal	Pedal Ratio	3.290	Pedal Force	62.4956	76.3839	N
	Pedal Efficiency	0.800				
Foot	Max Force (N)	445	Total Pedal Force	138.88		N
			Total Pedal force	14.16		k
			% from Driver Capabiliy	31.21		%
Balance Bar			Balance Bar Setting	0.4500	0.5500	
			Brake Force Distribution	45.00	55.00	%

4.2 Adhesion Utilization Result

Adhesion utilization analysis is used to determine how good the brake system will behave in real condition. This ability is described as a condition to have the front wheel lock first during braking which is favorable rather than rear wheel lock first. This is mainly because, according to vehicle dynamics, if the rear wheel lock first, the car would spin and become under control. For a passenger car, adhesion utilization at the front axle must be always greater than rear axle between deceleration at 0.15-0.30g and 0.45-0.80g. In order to achieve this condition, an adjustment between brake force between front and rear is configured using a device called balance bar. This device is capable in putting the right bias which leads to correct requirement of the adhesion utilization.

Table 4.3: Required parameter for adhesion utilization calculation

Notation	Parameters	Value		Unit
		Front (F)	Rear (R)	
BB	Brake Balance	0.57	0.43	
a	Deceleration	1		g
Fz(i)	Static Axle Load	0.45	0.55	N
W	Vehicle Weight	1.00		N
Fz(i)/W	Ratio	0.45	0.55	
h	CG height	0.280		m
L	Wheelbase	1.600		m
h/L	Ratio	0.1750		
Pt	Treshold Pressure	60000		Pa
Pt	Treshold Pressure	0.06		Mpa
R	Rolling Radius	0.265	0.265	m
r(eff)	Effective Radius	0.1016	0.1016	m
mue	Brake Pad C.O.F	0.56		
A	Piston Area	0.001551792		m2
BB	Balance Bar setting	55	45	%
BB	Balance Bar setting	0.55	0.45	

Table 4.4: Adhesion Utilization Calculation Spreadsheet

Pedal Force	Total Brake Line pressure (Mpa)	Total Brake Force (N)	Brake Force		Deceleration	Dynamic Load (N)		Adhesion Utilization	
			T1(N)	T2(N)	z	N1	N2	f1	f2
0	0	-79.9614	-43.9788	-35.9826	-0.0233	1535.1190	1898.3810	-0.0286	-0.0190
20	212,258.06	202.9129	111.6021	91.3108	0.0591	1570.3396	1863.1604	0.0711	0.0490
40	424,516.13	485.7871	267.1829	218.6042	0.1415	1605.5603	1827.9397	0.1664	0.1196
60	636,774.19	768.6614	422.7638	345.8976	0.2239	1640.7809	1792.7191	0.2577	0.1929
80	849,032.26	1051.5357	578.3446	473.1911	0.3063	1676.0015	1757.4985	0.3451	0.2692
100	1,061,290.32	1334.4100	733.9255	600.4845	0.3886	1711.2221	1722.2779	0.4289	0.3487
120	1,273,548.39	1617.2843	889.5063	727.7779	0.4710	1746.4427	1687.0573	0.5093	0.4314
140	1,485,806.45	1900.1585	1045.0872	855.0713	0.5534	1781.6634	1651.8366	0.5866	0.5176
160	1,698,064.52	2183.0328	1200.6681	982.3648	0.6358	1816.8840	1616.6160	0.6608	0.6077
180	1,910,322.58	2465.9071	1356.2489	1109.6582	0.7182	1852.1046	1581.3954	0.7323	0.7017
200	2,122,580.65	2748.7814	1511.8298	1236.9516	0.8006	1887.3252	1546.1748	0.8010	0.8000
220	2,334,838.71	3031.6557	1667.4106	1364.2451	0.8830	1922.5459	1510.9541	0.8673	0.9029
240	2,547,096.77	3314.5300	1822.9915	1491.5385	0.9654	1957.7665	1475.7335	0.9312	1.0107
260	2,759,354.84	3597.4042	1978.5723	1618.8319	1.0477	1992.9871	1440.5129	0.9928	1.1238
280	2,971,612.90	3880.2785	2134.1532	1746.1253	1.1301	2028.2077	1405.2923	1.0522	1.2425
300	3,183,870.97	4163.1528	2289.7340	1873.4188	1.2125	2063.4283	1370.0717	1.1097	1.3674
320	3,396,129.03	4446.0271	2445.3149	2000.7122	1.2949	2098.6490	1334.8510	1.1652	1.4988
340	3,608,387.10	4728.9014	2600.8958	2128.0056	1.3773	2133.8696	1299.6304	1.2189	1.6374
360	3,820,645.16	5011.7756	2756.4766	2255.2990	1.4597	2169.0902	1264.4098	1.2708	1.7837
380	4,032,903.23	5294.6499	2912.0575	2382.5925	1.5421	2204.3108	1229.1892	1.3211	1.9383

After several tries, the bias 55% at the front axle and 45% at the rear axle gave the correct condition for the car to have front wheel lock at deceleration lower than 0.80 g. (refer to table 4.3.) this is proven by the graph plotted in Figure 4.1 where the front adhesion (f1) is always on the top of rear adhesion (f2) from zero deceleration up to 0.8 g.

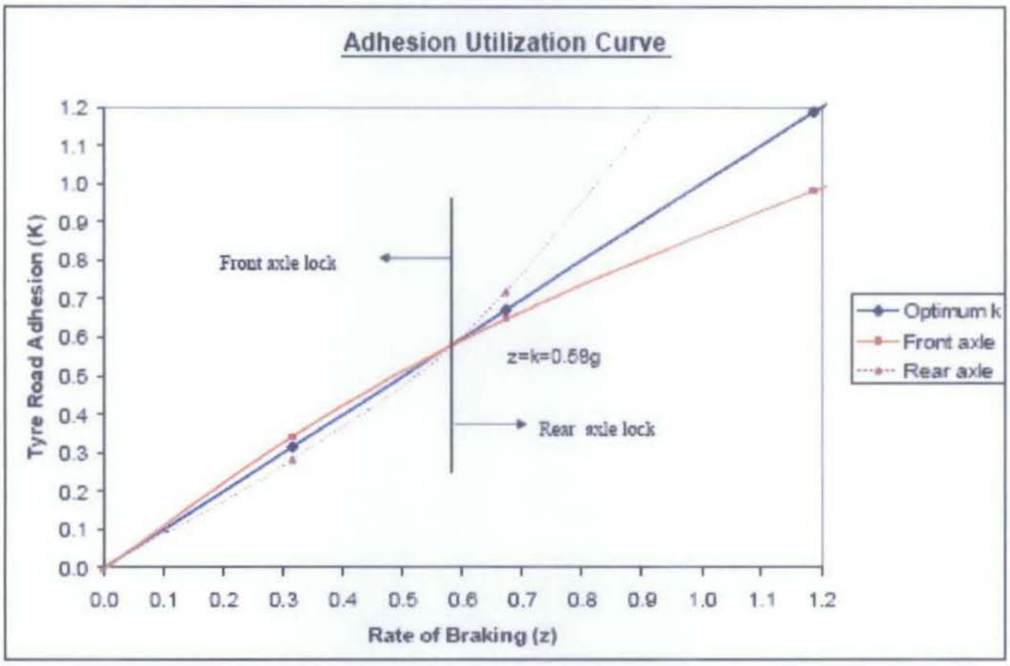


Figure 4.1: Adhesion utilization Graph

4.3 Braking Deceleration Performance

The developed system is targeted to have a braking deceleration performance as stated in the table below. The important data here is the time of deceleration of the car from the top speed, 100 km/h, which is only 2.83 seconds. This deceleration time is calculated based from constant 1g, straight line deceleration. In achieving the performance, the driver must constantly apply the braking force in 2.83 seconds.

Table 4.5: Braking Deceleration Performance

Speed (km/h)	100	90	80	70	60
Speed (m/s)	27.78	25.00	22.22	19.44	16.67
Time taken to decelerate (s)	2.83	2.55	2.27	1.98	1.70

Speed (km/h)	50	40	30	20	10
Speed (m/s)	13.89	11.11	8.33	5.56	2.78
Time taken to decelerate (s)	1.42	1.13	0.85	0.57	0.28

However this calculation is too theoretical and very subjective to be achieved in the real racing condition. This is due to several factors that kept varying throughout the operating condition system. For an example, a road condition can affect the properties of the tire-ground contact as the road conditions varies with due to a lot of factors. a driver is also a factor as a driver is likely impossible to apply a constant 1g braking force since it depends on the dynamic behavior of the car.

Thus, the table above is best put as a benchmark for the system to be tuned to, which is possible by understanding the braking dynamic principle.

4.4 Braking Components Characteristics and Specifications

After getting the correct brake bias which is 55:45 from modification of adhesion utilization, the next step is to determine all the braking components that suit the braking specifications and parameters. Below are the details of the components that have been chosen by the author.

4.4.1 Pedal Box

The pedal cluster is adjustable with two reach settings to accommodate different driver heights. The pedal ratio is designed for 3.5:1. But this designed will be done by author's project member that in-charge with the driver interface.

4.4.2 Brake Balance Bar

Balance bar is for fine-tuning the bias in the pits or, with the addition of the adjusting cable, by the driver during competition. Author decided to use Tilton brand that constructed from aircraft certified 41-40 steel, and heat treated. The clevises are 2024 T-3 aluminum. The pivot sleeve will be brazed or welded to the brake pedal and it be designed for 2 1/2 inch master cylinder spacing. This component is choosing to fit it with the push rod of the master cylinder above and due to spacing between the master cylinders.

4.4.3 Master Cylinder

For the master cylinders, author decided to use the master cylinders for front and rear with the bore size of 0.70 inch (15.88 mm). Both sides are using the same bore size because to get the balance bar setting value for the front and rear. As a result, the hydraulic ratio is same for the front and rear (1:1). This master cylinder also will be purchase. Its brand is Tilton 75 series with the volume of the reservoir is 4 oz. This reservoir is made from plastic that wills less the weight of the master cylinder that located at the front side. From author's survey of availability the component in the Malaysia market, most of the design is combination of two bore size in one master cylinder and it specific to passenger car but not for the racing car. Therefore, author decided to find this kind of shape and material of master cylinder that available in online/outside of Malaysia.

4.4.4 Tube and Hoses

Tube and hoses are made of steel. The lines will be attached to the chassis by plastic band to make the circuit go to the rear side without interrupt the engine and drive train system at the rear side.

4.4.5 Calipers and Brake Pads.

In this design, author decided to use the same piston size of the caliper that used for the front and rear. The caliper has 2 pistons that opposing with the size 1.75 inch (44.45 mm). The brand of the product is Wilwood Billet Dynalite Single caliper. With the mount center is 3.25 inch (82.6mm) to fit it with the up-right size and suspension size. Because of the rotor is the floating type, then the caliper will be fixed-caliper. More specific on dimension of the product can be seen in the Appendix B that shows all components design and the price of the components.

Wilwood's Billet Dynalite Single utilizes close tolerance design and manufacturing techniques which results in the most rigid, lightweight and attractive caliper in the evolution of the Dynalite Single Series. The Billet Dynalite Single is perfect for compact high performance braking as required in Open Wheel, Drag, Modified, Kart, Motorcycle and Off Road applications. The two piston caliper is rigid, lightweight (1.4 pounds) and holds a .49" thick, 1.1 cubic inch brake pad. Internal fluid passage and multiple bleed fittings permit right or left, front or rear mounting options, with either 3.25" or 3.75" lug spacing, and will fit .25" to .38" thick rotors, with diameters from 6.00" to 13.00" High temperature square piston seals control piston retraction while the stainless steel deep cup pistons reduce heat transfer from the pad to the brake fluid.

For the brake pads, the Wilwood Company's has suggested the shape and its material. For the calculation performance, author has chosen to use the pad coefficient of friction, $\mu = 0.56$ and the material is compound B.

4.4.6 Rotor

For the front and rear rotor, author decided to use the 9 inch (228.6 mm) of diameter with the thickness of 0.25 inch (6.35mm), which it is the minimum value of thickness to fits it with the caliper. The maximum thickness is 0.38 inch (9.65mm). As objective to design the rotor, the author decided to make it in solid shape where it simple likes the rotor that used in motorcycle.

The material that selected for this rotor is cast iron. The material been selected because of it availability it in the market instead of using aluminum alloy or metal-matrix composites (MMC).

The rotor is expected to comprise of heat dissipation capabilities will be able to prevent or at least minimizing the effect of the brake fade phenomenon to occur. Thus the design stage is done based on a pre described guideline which to create enough convection area by implementing cross drilled and grooved design.

Below are the author's designs for the rotors:

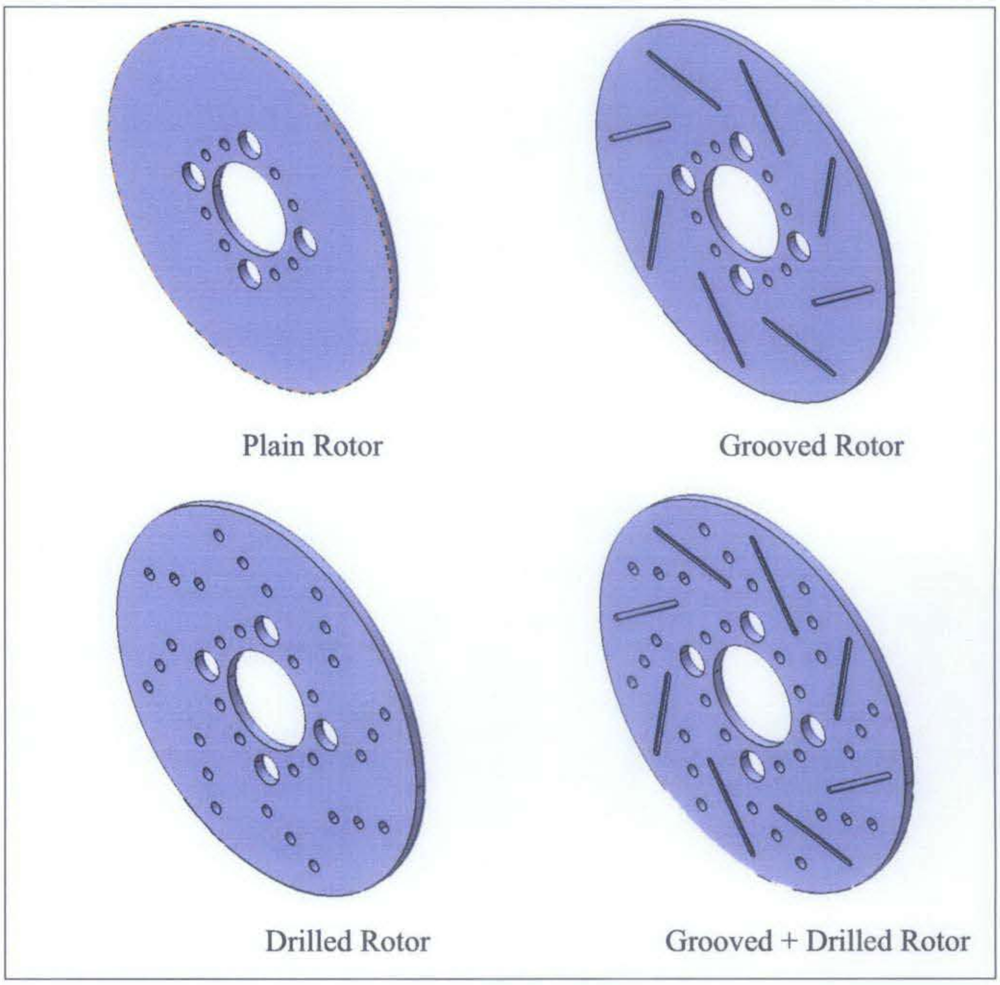


Figure 4.2: Four Different Geometry Model for Rotor Design

Dual ventilated rotors are not practical for the UTP Formula SAE Team as they are hard to be fabricated in-house and costly to outsource the fabrication. Due to this factor, the author did not make any design for the dual ventilated rotors.

4.5 Thermal Analysis

There are 2 stages in performing the suitable thermal analysis in designing a new rotor. Two main parameters that are determined from all three analyses are the maximum thermal stress and maximum deformation.

4.5.1 Plain Rotor Analysis

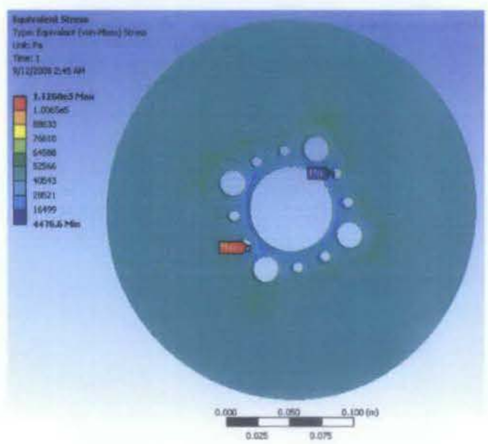


Figure 4.3: Thermal Stress (Von Misses) Result

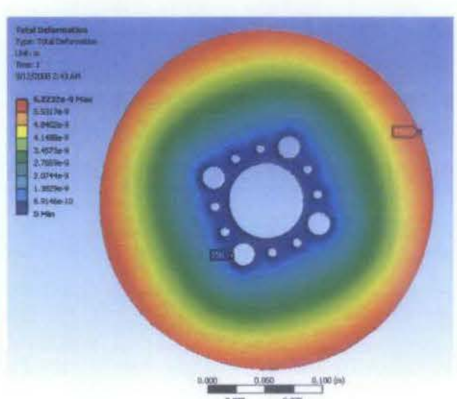


Figure 4.4: Deformation Result

Plain rotor analysis showed a result as shown in Figure 4.3 and 4.4. The result is stated as follows:

i. Max Stress (Von misses) : 0.1127 MPa
ii. Maximum Deformation : 6.2232e-009 m

4.5.2 Other Design Analysis

3 other designs; cross-drilled, slotted and cross-drilled + slotted rotors; are based on the concept of maximizing the heat dissipation capability as well as the weight reduction of the rotor.

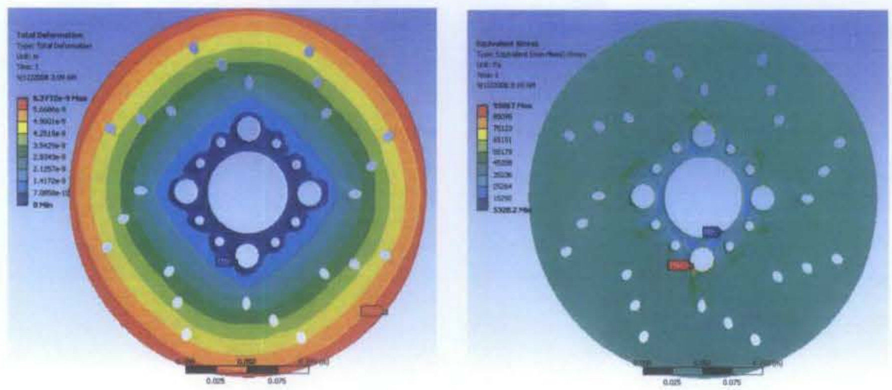


Figure 4.5: Cross-drilled Rotor Analysis Result

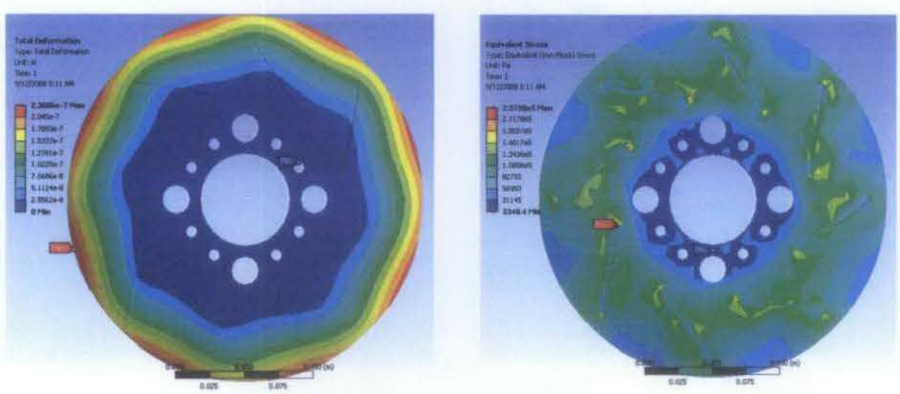


Figure 4.6: Slotted Rotor Analysis Result

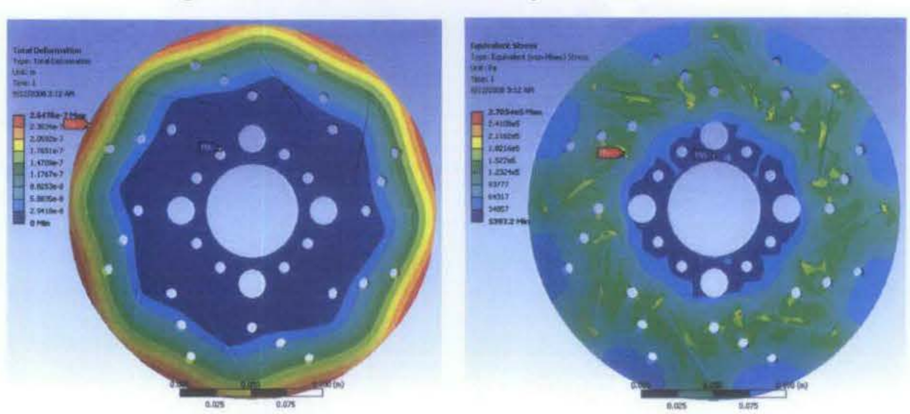


Figure 4.7: Cross-drilled + Slotted Rotor Analysis Result

The other design rotor analysis showed a result as shown in Figure 4.5 to Figure 4.7. The result is stated in Table 4.6 below:

Table 4.6 Other Rotor Design Analysis Result

	Plain rotor	Cross-drilled rotor	Slotted rotor	Cross-drilled + slotted rotor
Max Stress (Von Misses) (MPa)	0.1127	0.095067	0.23758	0.27054
Max Deformation (m)	6.2232e-009	6.3772e-009	2.3006e-007	2.6476e-007

i. Effect of air flow neglected

For a race car, the brake system is having an 'out board' configuration; meaning that as the car moves, that the brake rotor is expose to a significant air flow. This air flow effect contributes to most of the convection process for the rotor to dissipate heat energy generated during braking process. However, this effect is neglected in the assumption for this analysis. Therefore, it caused the model to experience such a big amount of heat energy and lead to generate a high value of thermal stress.

ii. Reduction in material volume

This analysis is done using modified rotor geometry where a number of material volumes are removed from the geometry used in the plain rotor analysis. Theoretically, as the volume of material reduced, the capability of a particular component to absorb energy is reduced along. Thus, that explained the thermal stress value is higher for this analysis.

4.6 Fabrication Process

The aim this section is to propose a manufacturing process involved in producing a brake disc rotor from a raw material which is a cast iron plate. The manufacturing processes that will be explained are based on the design of the cross-drilled rotor. All processes involved in producing the end product are done by utilizing manufacturing technology machines described in this section.

4.6.1 Process 1

A 20mm thick iron plate is used in manufacturing the brake disc rotor. The plate is first milled using Universal Milling Machine until the thickness is 7mm. This is to help in reducing the machining time at the EDM workstations that will be carried out.

Figure 4.8: Universal Milling Machine

4.6.2 Process 2

The second process is marking. Using an EDM Superdrill, holes are drilled to determine the coordinate for the cross-drilled hole. Each coordinate belonged to different holes for specific purpose in producing the shape of the rotor.

Figure 4.9: EDM Superdrill

4.6.3 Process 3

Using a Pedestal Drilling, the marked holes are drilled. The holes are in different diameter size using drill bits sized 6mm, 8mm and 12mm.

Figure 4.10: Pedestal Drilling

4.6.4 Process 4

EDM Wirecut is used in shaping the brake disc rotor. The marking hole that has been drilled using the EDM Superdrill is the reference to cut the plate in circular shape.

Figure 4.11: EDM Wirecut

4.6.5 Process 5

The final process is surface finishing. Universal Milling Machine is used to remove the excess 1mm from both sides of the brake disc rotor. This is to ensure that the brake disc rotor has a smooth surface finish.

CHAPTER 5

CONCLUSION & RECOMMENDATION

5.1 Conclusion

Formula SAE Braking System Project is a challenging project where, best efforts needed in journey to develop a great design to achieve the aims of the Formula SAE design competition. From the theoretical calculation, it shown that the car will stop the car at the 2.83 second with deceleration of 1 g from speed of 100km/h.

The iterations on component sizing had done in the Excel Form to achieve the target of brake balance bias setting of 55:45. Moreover, the adhesion utilization curves shown that the both axles will lock at z=k at 0.58 g and the graph approved the braking system that need the front axle will lock up first and simultaneous continue with rear.

The rotor design drawing had been done by using CATIA. After that, the thermal analysis of the rotor had been done using ANSYS Workbench.

The real performance of the braking system can be identified if the fabrication of the parts be done. Therefore the theoretical performance calculations can be comparing when it be testing for the real conditions.

5.2 Recommendation

In the journey to complete the project, author had faced a few problems. There are:

i. Product Availability in Market

In this stage, not all of products that been searching are available in the Malaysia's market. Moreover, author had difficulties in getting the catalogue from the manufactures and it affects the components selection due to search the availability of the product in the market. Also, the component budget is quite hard to be estimate because in the online it just included the price only and not the shipping cost.

ii. Redesign and recalculate

Most of the time of the project is concentrate on recalculate the braking components sizing, braking performance, and adhesion utilization and redesign the braking system design due to packaging and driver's ergonomics problem.

iii. Basic skill of using ANSYS Workbench

Analyzing the rotor using ANSYS Workbench is not very easy. Drawing in the CATIA is not easy as we see. For non-expert, the student need more time to learn and apply it to analyze the rotor. In this stage, author had taken a long time in the learning process of ANSYS Workbench.

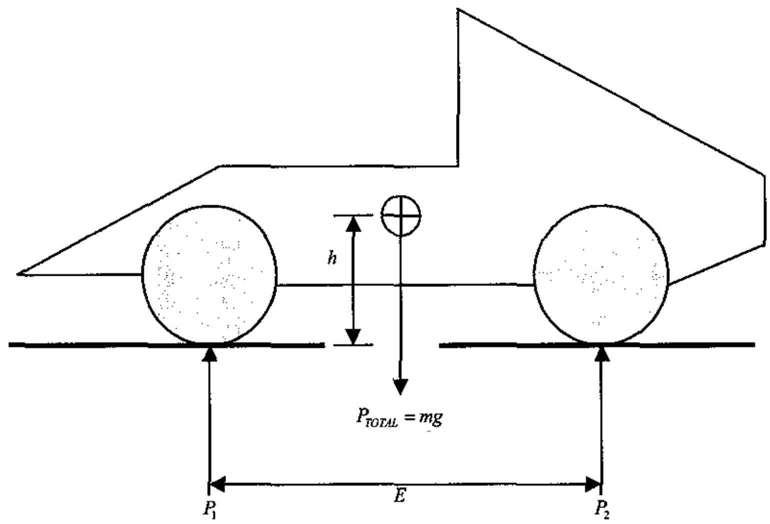
From the project experiences that author had gone through, author would like to recommend that maybe the Mechanical Engineering Department will make a relationships/links with the manufacturer to getting the specification in details, the information on the components performance and to estimating of the budget in easy instead of keeping searching the component in online. For overcoming the ANSYS Workbench problem, the author recommend that the student with project related to this software needs specific training by a trainer to reduce problem in using/learning ANSYS Workbench by her/himself. In the future improvement, the author recommends that the system need to be fabricate and be tested in comparing the theoretical with practical data.

REFERENCES

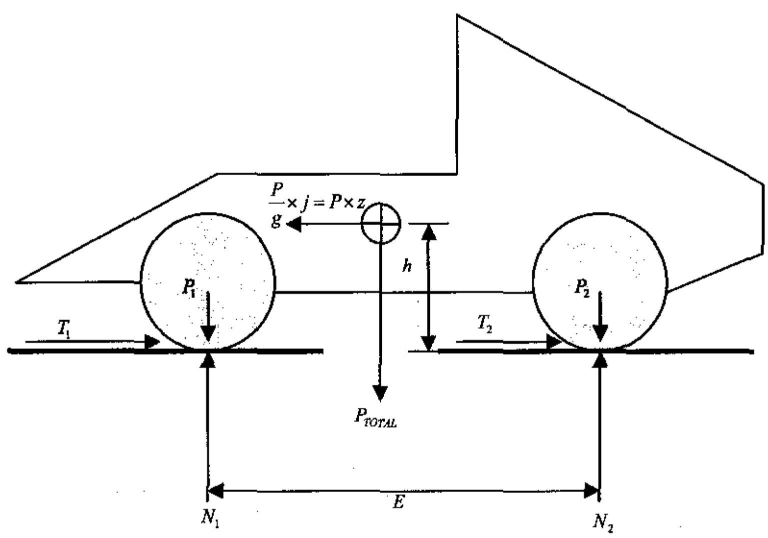
1. http://student.sae.org
2. www.wilwood.com
3. www.pegasusautoracing.com
4. www.efunda.com
5. http://www.carbibles.com/brake_bible.html
6. http://en.wikipedia.org/wiki/Disc_brake
7. F8 Brakes and Drive Train Final Report, Mech 5840 Team Project, University of Leeds, April 2004.
8. Herb Adams, Chassis Engineering, 1999.
9. J. R. Ellis, Vehicle Handling Dynamics, Page Bros. Norwich, 1994
10. Rudolf Limpert, Brake Design And Safety, 2^{nd} edition, SAE Inc. 1999
11. David Cebon, Handbook of Vehicle-Road Interaction, Swets and Zeitlanger, 1999
12. William d. Callister, Jr., Materials Science and Engineering, and Introduction, John Willey and Sons Inc, 2003.
13. Automotive System Notes, EMB 5223, University Technology of PETRONAS.
14. Yunus A. Cengel, Michael A Boles, Thermodynamics, An Engineering Approach, Mc Graw Hill, 2002.
15. Formula SAE : Braking System Design 2005
16. UTP Formula SAE Design Report 2006
17. UTP Formula SAE Design Report 2007
18. Formula SAE Rule, SAE International, 2007
19. William C. Orthwein, Clutches and Brakes, Design and Selection, Marcel Dekker Second Edition., 2004

APPENDIX A

GRAPHICAL REPRESENTATION FOR BRAKING CONCEPT



Forces Acting on Vehicle in Static Condition



Forces Acting on Vehicle in Braking Condition

APPENDIX B

FORMULA SAE REGULATIONS

As stated in Chapter 1, the preliminary design process are constrained with rules and regulations described by the organizer of the event. For braking design, there are two main section that author is focusing on which are the brake system, wheels and tires. The regulations stated as follows:

Brake system

1) The car must be equipped with braking system that acts on all four wheels and is operated by single control.
2) The system must have two independents hydraulic circuit and the need effective braking power is maintained at least two wheels.
3) Each hydraulic circuit must have its own fluid reserve, either by use of separate reservoir or by use of a dammed, OEM-style reservoir.
4) Brake by wire is prohibited.
5) Single brake acting on limited slip differential is acceptable.
6) The braking system must be protected with scatter shields from the failure of the drive train or from minor collisions.
7) Unarmored plastic brake lines are prohibited.
8) The system must be installed with Brake over Travel Switch.
9) One red brake light must be installed at the rear portion of the car; at least 15 watts or clearly visible from the rear.

Wheels and Tires

1) Wheels of the car must be 203.2 mm (8.0 inches) or more in diameter
2) Any wheel mounting system that uses a single retaining nut must incorporate a device to retain the nut and the wheel in the event that the nut loosens
3) Two types of tires needed for the car which is dry and wet tires.
4) For dry tires, it may in any size and may be slicks or treaded. For technical inspection, dry tires will be the reference
5) For wet tires, it may be in any size or type treaded or grooved tire provided that the tread paten or grooves were molded in by tire manufacturer or were cut by the tire manufacturer. Any grooves that been cut must have document proof that done in according to the rules. Minimum tread depth is 2.4mm (3/32 inch)