SIMULATION TEST OF DISC BRAKE FUNCTIONALITY USING COMPUTER AIDED ENGINEERING SOFTWARE

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A report submitted in partial fulfilment of the requirements
for the award of the degree of
Bachelor of Mechanical Engineering with Automotive Engineering

Faculty of Mechanical Engineering
UNIVERSITI MALAYSIA PAHANG

NOVEMBER 2008

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We hereby declare that we have checked this project and in our opinion this project is satisfactory in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering with Automotive/Manufacturing*

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I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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DEDICATION

To my beloved mother and father

Mrs. Zuyah Binti Ismail

Mr. Abd. Halim Bin Hanapi

ACKNOWLEDGEMENTS

I am grateful and would like to express my sincere gratitude to my supervisor Mr. Rashidi Bin Maarof for his germinal ideas, invaluable guidance, continueous encouragement and constant support in making this research possible. He has always impressed me with his outstanding professional conduct, his strong conviction for science, and his belief that a degree program is only a start of a life-long learning experience. I appreciate his consistent support from the first day I accepted this project until these concluding moments. I am truly grateful for his progressive vision about my training in science, his tolerance of my naïve mistakes, and his commitment to my future career. I also sincerely thanks for the time spent proofreading and correcting my many mistakes.

I acknowledge my sincere indebtedness and gratitude to my parents for their love, dream and sacrifice throughout my life. I cannot find the appropriate words that could properly describe my appreciation for their devotion, support and faith in my ability to attain my goals. Special thanks should be given to my committee members. I would like to acknowledge their comments and suggestions, which was crucial for the successful completion of this study.

ABSTRACT

This thesis deals with simulation test of disc brake functionality by using computer aided engineering software. The objective of this thesis is to investigate and analyze the stress distribution of disc brake during operation using CAE software. The thesis describes the finite element analysis techniques to predict the failure region on the brake disc and to identify the critical locations of the components. The disc brake implemented on the front axle of Proton Wira 1998 model with gray cast iron materials were studied in this thesis which commonly used in industry. Despite all the stresses experience by the disc doesn’t damage the disc due to high tensile strength but the disc may fail under fatigue loading. It is important to determine the critical area of concentrated stress, so appropriate modification can be made. The structural three-dimensional solid modelling of brake disc was developed using the computer-aided drawing software. The strategy of validation of finite element model was developed. The finite element analysis was then performed using ALGOR-Fempro. The finite element model of the components was analyzed using the static stress with linear material model approaches. Finally, the stress distribution obtain from the result of analysis are employed as input for the failure region. From the results, it is observed that the analysis using Fempro can predict the failure region under fatigue loading. The acquired results tell the failure region occurred at the outer radius for both side of the brake disc due to concentrated maximum stress in these regions. Concentrated stress at these regions may promote conning effect. By moving the contact area of the brake pads and brake disc inside and away from the edge, maximum stress at the outer radius of the disc can be reduced or prevented. The stress analysis results are significant to improve the component design at the early developing stage. The results can also significantly reduce the cost and time to market, and improve product reliability and customer confidence.

ABSTRAK

Tesis ini membentangkan simulasi penyelidikan terhadap brek cakera menggunakan perisian kejuruteraan bantuan komputer. Objektif tesis ini adalah untuk mengkaji serakan tekanan terhadap brek cakera semasa operasi menggunakan perisian kejuruteraan bantuan komputer. Tesis ini menerangkan teknik kajian unsur terhingga untuk menjangka kawasan cakera brek yang akan mengalami kerosakan dan untuk mengenalpasti lokasi-lokasi kritikal pada cakera brek. Cakera brek yang terdapat pada tayar hadapan kereta Proton wira model 1998 dengan bahan yang digunakan adalah besi kelabu acuan dikaji dalam tesis ini kerana ia biasa digunakan dalam industri automotif. Walaupun semua tekanan yang dialami oleh cakera brek tidak akan merosakkan, namun kerosakan akan berlaku jika daya lesu dikenakan. Jadi sangat penting untuk menentukan dimana kawasan kritikal yang ditumpu oleh tekanan supaya ubahsuai yang sesuai dapat dilakukan. Permodelan struktur pejal tiga-dimensi bagi cakera brek dibangunkan dengan perisian lukisan bantuan komputer. Strategi pengesahan model unsur terhingga dibangunkan. Analisis unsur terhingga dijalankan meggunakan Fempro yang terdapat dalam perisian ALGOR. Model unsur terhingga tersebut dikaji meggunakan pendekatan tekanan pegun dengan model bahan linear. Akhir sekali, serakan tekanan yang didapati daripada analisa kajian menggunakan Fempro boleh digunakan untuk menjangka kawasan yang akan mengalami kerosakan sekiranya tekanan lesu dilaksanakan. Keputusan yang diperoleh memberitahu kawasan yang akan mengalami kerosakan adalah pada jejari luar cakera brek pada kedua-dua bahagian permukaan cakera brek disebabkan oleh tekanan maksima yang tertumpu pada kawasan tersebut. Tekanan maksima pada kawasan tersebut boleh menyebabkan kesan kon terjadi. Dengan mengalihkan kawasan sentuhan pad brek dengan cakera brek daripada hujung cakera brek, tekanan maksima pada kawasan ini dapat dikurangkan atau dielakkan. Keputusan penilaian distribusi tekanan amat bermakna bagi memperbaiki reka bentuk komponen diawal tahap pembangunan. Keputusan juga berupaya menurunkan kos dan masa ke pasaran, memperbaiki kepercayaan produk dan keyakinan pelanggan.

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LIST OF SYMBOLS

E	-	Energy
m	-	mass
v	-	velocity
σ	-	stress
F	-	Force
A	-	Area
J_2	-	second deviatoric stress invariant
σ_v	-	von Mises stress
σ_y	-	Yield strength
I_1	-	first stress invariant
Rp	-	pedal lever ratio
Fb	-	booster assist force
Am	-	area of master cylinder
Aw	-	area of the front caliper piston
μ	-	coefficient of friction of lining
r	-	effective radius of the caliper
R	-	loaded radius of the tire
P	-	Pressure

LIST OF ABBREVIATIONS

CAE	-	Computer Aided Engineering
FEA	-	Finite Element Analysis
CAD	-	Computer Aided Design
FYP	-	Final Year Project
2D	-	Two Dimensional
3D	-	Three Dimensional
ASTM	-	American Society for Testing and Materials
UTS	-	Ultimate Tensile Strength

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Of all the systems that make car, the brake system might just be the most important. Its function determined the safety of the driver, passenger and also pedestrian. In the olden days it was also one of the simplest. Over the years as improvements have been made, the system that has evolved isn't so simple anymore. Brake system work as hard or harder than any other part of the car, however much energy it takes to get the car up a hill, it takes at least as much energy to stop it at the bottom. In general, there are three main functions of a brake system, to maintain a vehicle’s speed when driving downhill, to reduce a vehicle’s speed when necessary and to hold a vehicle when in parking [1]. When the brakes were applied, the pads or shoes that press against the brake drum or rotor convert kinetic energy into thermal energy via friction. The cooling of the brakes dissipates the heat and the vehicle slows down. This is all to do with The First Law of Thermodynamics, sometimes known as the law of conservation of energy. This law states that energy cannot be created nor destroyed; it can only be converted from one form to another. In the case of brakes, it is converted from kinetic energy to thermal energy.

Typically, there are two types of brake that were implemented in today’s car, drum brake and disc brake. Disc brake is widely used because its design is far superior to that of drum brakes. Disc brakes use a slim disc and small caliper to halt wheel movement. Within the caliper are two brake pads, one on each side of the disc, that clamp together when the brake pedal is pressed. Fluid is used to transfer the movement of the brake pedal into the movement of the brake pads. The disc used in disc brakes is fully exposed to outside air. This exposure works to constantly cool the disc, greatly reducing its tendency to overheat or cause fading. The pad and disc would wear gradually when in used [8]. It need to be replaced when the pad reach its limits or disc have problem like warped and thermal crack that leads to reduction of braking efficiency. Friction between the contact area of pad and disc during braking process cause wear as the pad degraded gradually. Uniform pad and disc stress distribution is essential to ensure uniform pad wear and prolong the lifespan for both pad and disc.

Uniform pad and disc wear and brake temperature, and more even friction coefficient could only be achieved when pressure distributions between the pads and disc are uniform [3]. Uneven pressure distribution on contact area on disc and brake pad can be predicted through simulation analysis. Unevenness of the pressure distribution causes uneven wear and consequently shortens the life of disc rotor [3]. This might lead to more frequent tapered wear disc replacement. The dynamic contact pressure distribution in a disc brake system remains impossible to measure through experimental methods. This makes numerical analysis using the finite element method an indispensable alternative tool to its prediction. Simulation analysis is used to predict the failure of the disc rotor and help design improvement on the production of disc rotor. This project present the systematic clarification of the stress analysis of disc brake by analyzes in computer aided engineering (CAE) software. CAE or more specifically finite element analysis (FEA) will analyzed the stress distribution on the disc rotor during operation and prediction of failure regions can be made.

1.2 PROBLEM STATEMENT

The disc brake is a device for slowing or stopping the rotation of a wheel of vehicles. 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 and cause the wheel to slow or stop [11]. By the First Law of Thermodynamics, when brake pedal is pressed, the brakes on vehicle heat up, slowing it down. But if the brakes were used rapidly, the discs and brake pads will stay hot and get no chance to cool off. The brake cannot absorb much more heat because the brake components are already so hot. The braking efficiency is reduced. This malfunction of the brake system is called brake fade. In every brake pad there is the friction material which is held together with some sort of resin. Once brake pad starts to get too hot, the resin holding the pad material together starts to vaporize (forming gas). That gas can't stay between the pad and the disc, so it forms a thin layer between the brake pad and rotor trying to escape. The pads lose contact with the disc, thus reducing the amount of friction [11]. Other than brake fade, disc rotor also undergo cracking, coning, thermal judder, brake shudder, high disc thickness variation and high level of lateral runout (Appendix 1) because of poor design, inappropriate materials and uneven stress distribution during braking.

The usage of the brake may promote wear to disc and brake pad. Uniform disc and pad wear, brake temperature, and more even friction coefficient could only be achieved when pressure distributions between the pads and disc are uniform. In addition, unevenness of the pressure distribution causes uneven stress distribution that can lead to uneven wear and consequently shortens the life of disc and pad. The design of the disc is important to determine the rate of cooling and uniform wear of disc and brake pad and thus affecting braking efficiency.

This project will focus on the simulation analysis of disc on typical disc brake during operation when forces and moments generate from braking is applied during the static. The stress distribution of disc from simulation result can be analyzed.

1.3 OBJECTIVES

Investigate and analyze the stress distribution of disc brake during operation using CAE software.

1.4 SCOPES

Use CAE software to determine finite element stress of disc on general/common disc brake used in automotive industry (Wira model year 1998).

1.5 FLOW CHART

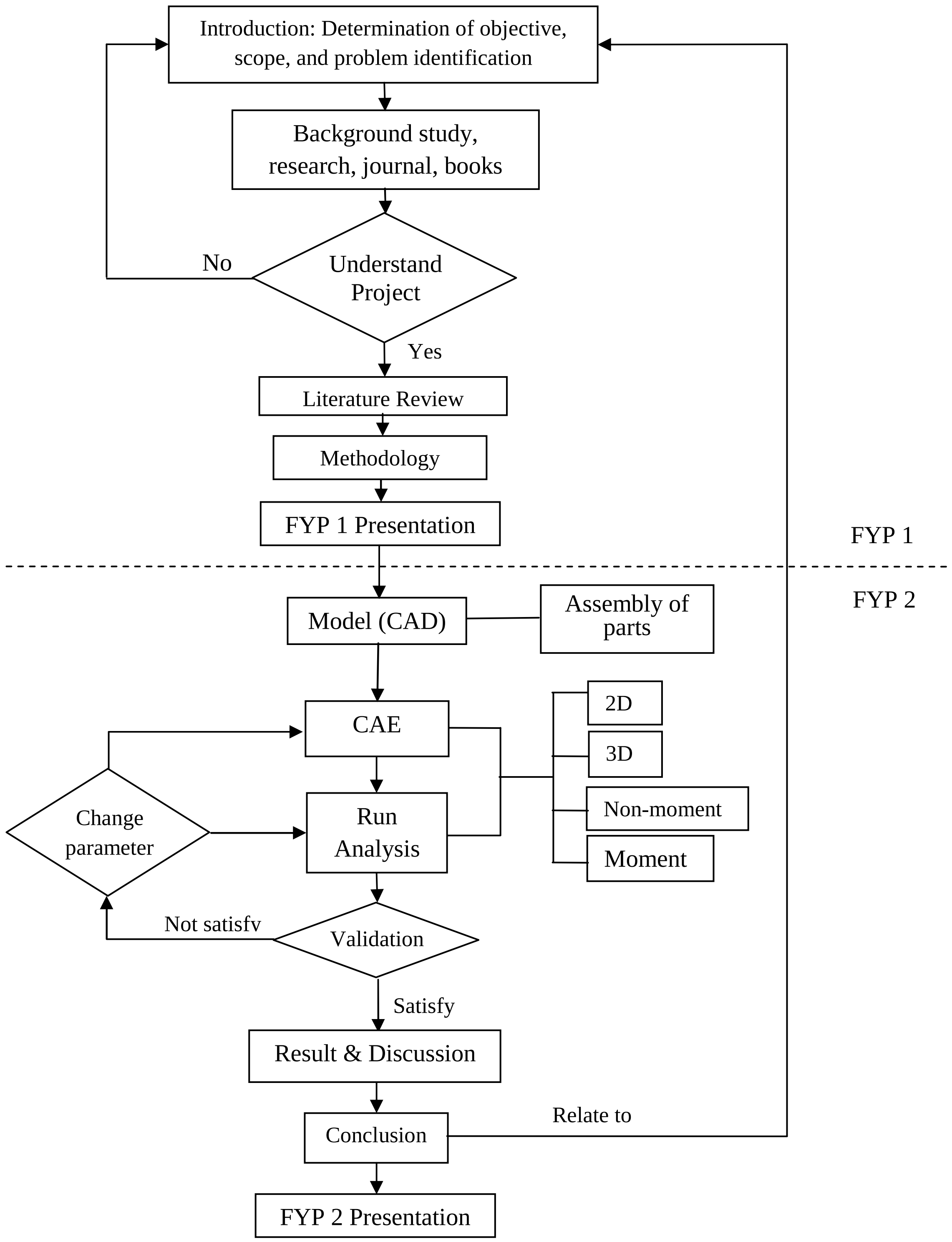


Figure 1.1: Project's flow chart

1.6 GANTT CHART

Table 1.2: Gantt chart for final year project 1

	TASK	SEMESTER 2 2007/2008															
		WEEK															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Background Studies																
2	Project understanding																
3	Work planning																
5	Problem identification																
4	Chapter 1																
6	Chapter 2																
7	Parameters & Material Properties determination																
8	Chapter 3: Forming of Research Methodology																
9	Result Expectation																
10	Project Proposal Preparation																
11	Project Proposal Approval & Submission																
12	Presentation 1 Preparation																
13	Project Presentation 1																

Table 1.3: Gantt chart for final year project 2

	TASK	SEMESTER 1 2008/2009															
		WEEK															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	Background Studies																
2	Introduction to CAD & CAE																
3	Disc and other part modeling																
5	Analysis																
4	Chapter 4: Result & Discussion																
6	Chapter 5: Conclusion																
7	Final Report preparation																
8	Presentation 2 preparation																
9	Project Presentation 2																
10	Final Report approval & submission																

CHAPTER 2

LITERATURE REVIEW

2.1 BRAKE SYSTEM

A brake is a device for slowing or stopping the motion of a machine or vehicle, or alternatively a device to restrain it from starting to move again. Brakes of some description are fitted to most wheeled vehicles, including automobiles of all kinds, trucks, trains, motorcycles, and bicycles. Baggage carts and shopping carts may have them for use on a moving ramp. Some airplanes are fitted with wheel brakes on the undercarriage. Some aircraft also feature air brakes designed to slow them down in flight. Friction brakes on cars store the heat in the rotating part (drum brake or disc brake) during the brake application and release it to the air gradually [12]. The kinetic energy lost by the moving part is usually translated to heat by friction. Alternatively, in regenerative braking, much of the energy is recovered and stored in a flywheel, capacitor or turned into alternating current by an alternator, then rectified and stored in a battery for later use.

Kinetic energy increases with the square of the velocity ($E = (mv^2)/2$). This means that if the speed of a vehicle doubles, it has four times as much energy. The brakes must therefore dissipate four times as much energy to stop it and consequently the braking distance is four times as long. When the brake pedal is depressed, the vehicle’s braking system transmits the force from your foot to its brakes through a fluid. Since the actual brakes require a much greater force than the leg could apply with, vehicle must also multiply the force of foot. It does this in two ways; mechanical advantage (leverage) and hydraulic force multiplication. The brakes transmit the force to the tires using friction, and the tires transmit that force to the road using friction also [8].

The modern automotive brake system has been refined for over 100 years and has become extremely dependable and efficient. The typical brake system consists of **disk brakes** in front and either **disk** or **drum brakes** in the rear connected by a system of **tubes and hoses** that link the brake at each wheel to the **master cylinder.** Other systems that are connected with the brake system include the **parking brakes, power brake** booster and the **anti-lock** system. When the brake pedal is pressed, it pushed against a plunger in the master cylinder which forces hydraulic oil (**brake fluid**) through a series of tubes and hoses to the braking unit at each wheel. Since hydraulic fluid (or any fluid for that matter) cannot be compressed, pushing fluid through a pipe is just like pushing a steel bar through a pipe. Unlike a steel bar, however, fluid can be directed through many twists and turns on its way to its destination, arriving with the exact same motion and pressure that it started with. It is very important that the fluid is pure liquid and that there is no air bubbles in it. Air can compress which causes sponginess to the pedal and severely reduced braking efficiency. If air is suspected, then the system must be bled to remove the air. There are "bleeder screws" at each wheel cylinder and caliper for this purpose.

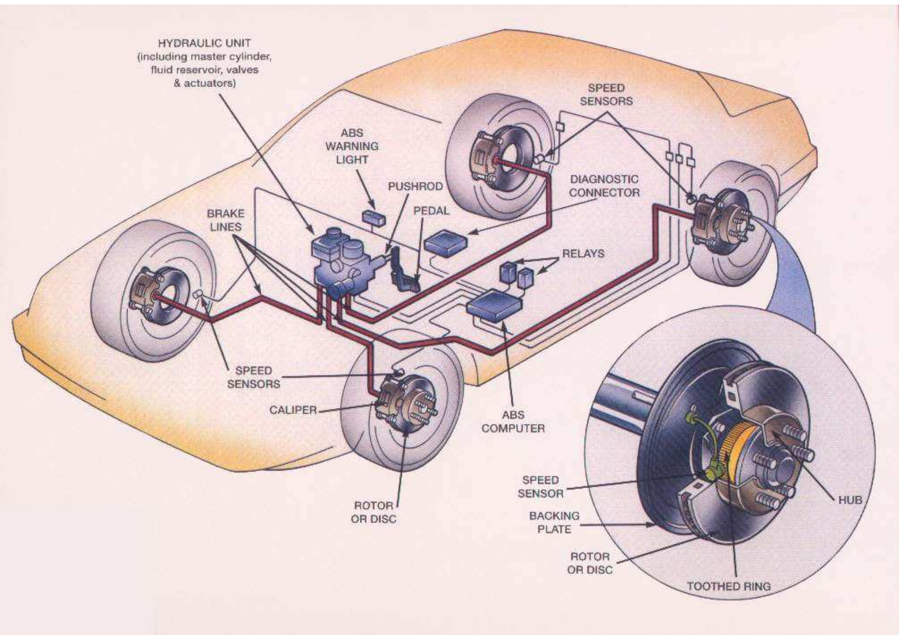


Figure 2.1: Modern automotive brakes system

2.2 DISC BRAKE

Disk brakes are used to stop everything from cars to locomotives and jumbo jets. Disk brakes wear longer, are less affected by water, are self adjusting, self cleaning, less prone to grabbing or pulling and stop better than any other system around. On a **disk brake**, the fluid from the master cylinder is forced into a caliper where it presses against a piston. The piston, in-turn, squeezes two brake pads against the disk (**rotor**) which is attached to the wheel, forcing it to slow down or stop. This process is similar to a bicycle brake where two rubber pads rub against the wheel rim creating friction. A disc brake assembly consists of a disc (rotates with the wheel), caliper assembly (attached to the steering knuckle), and friction material (disc pads) mounted to the caliper assembly [12].

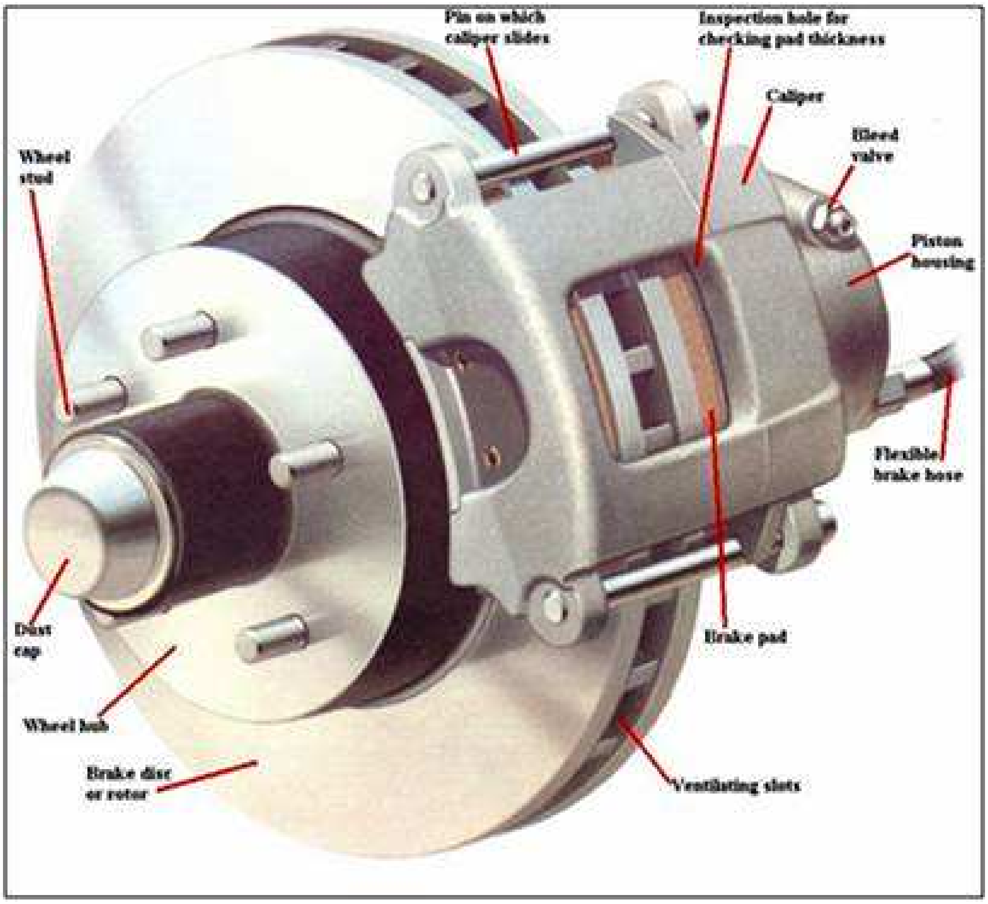


Figure 2.2: Disc brake

2.2.1 Brake Disc

Generally, the disc made of gray cast iron, and is either solid or ventilated. The ventilated type disc 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 disc has spiral fins which creates more air flow and better cooling. Spiral finned disc are directional and are mounted on a specific side of the vehicle. The solid type disc is found on the rear of four wheel disc brake systems and on the front of earlier model vehicles. A third style disc can be either the ventilated or solid type which incorporates a brake drum for an internal parking brake assembly. The disk is made of iron with highly machined surfaces where the brake pads contact it. Just as the brake pads wear out over time, the disc also undergoes some wear, usually in the form of ridges and groves where the brake pad rubs against it. This wear pattern exactly matches the wear pattern of the pads as they seat themselves to the disc.

The design of the disc varies somewhat. Some are simply solid cast iron, but others are hollowed out with fins joining together the disc's two contact surfaces (usually included as part of a casting process). This "ventilated" disc design helps to dissipate the generated heat and is commonly used on the more-heavily-loaded front discs [13]. Many higher performance brakes have holes drilled through them. This is known as cross-drilling and was originally done in the 1960s on racing cars. Brake pads will outgas and under use may create boundary layer of gas between the pad and the disc hurting braking performance. Cross-drilling was created to provide the gas someplace to escape. Although modern brake pads seldom suffer from outgassing problems, water residue may build up after a vehicle passes through a puddle and impede braking performance. For this reason, and for heat dissipation purposes, Cross Drilling is still used on some braking components, but is not favored for racing or other hard use as the holes are a source of stress cracks under severe conditions.

Discs may also be slotted, where shallow channels are machined into the disc to aid in removing dust and gas. Slotting is the preferred method in most racing environments to remove gas, water, and de-glaze brake pads. Some discs are both drilled and slotted. Slotted discs are generally not used on standard vehicles because they quickly wear down brake pads; however, this removal of material is beneficial to race vehicles since it keeps the pads soft and avoids vitrification of their surfaces. On the road, drilled or slotted discs still have a positive effect in wet conditions because the holes or slots prevent a film of water building up between the disc and the pads. Cross drilled discs will eventually crack at the holes due to metal fatigue. Cross-drilled brakes that are manufactured poorly or subjected to high stresses will crack much sooner and more severely.

2.2.2 Disc Material

Brake disc are commonly manufactured out of a material called grey iron due to its superior heat handling and damping (vibration absorption) character. The SAE (Society of Automotive Engineers) maintains a specification for the manufacture of grey iron for various applications. This specification dictates the correct range of hardness, chemical composition, tensile strength, and other properties that are necessary for the intended use. For normal car and light truck applications, the SAE specification is J431 G3000 (superseded to G10) which has a Brinell hardness of 187-241, and a minimum tensile strength of 30,000 psi (206,844kPa) with pearlitic microstructure [1].

A casting meets both physical property and chemical composition requirement can still fail pre-maturely in brake applications due to its inferior microstructure. Microstructure is the most important criteria dictating the rotor performance under extreme heat. Microstructure as it implies is the matrix of the cast iron which is visible only under microscope (100X). Microstructure analysis involves graphite distribution and matrix structure of the cast iron. A standard rotor cast iron should have the following graphite formation: (per ASTM A-247 classification).

2.3 RELATED RESEARCHES

Journals from various researches were use as references and guardian to perform the analysis. The parameter, properties, and findings from these journals can be use as standardization of the analysis (benchmarking).

Table 2.1: Summarization of Researches

Research	Illumination
Prediction Of Disc Brake Contact Pressure Distributions By Finite Element Analysis. [3]	• Analysis of the contact pressure distributions at the disc/pad interfaces using a detailed 3-dimensional finite element model of a real car disc brake. • Investigates different levels in modeling a disc brake and simulating contact pressure distributions. • Four levels in modeling and simulation of contact pressure distributions were carried out. • When the disc is at rest, the pressure distribution is symmetric about the geometric centre line of the pad. • When the disc slides, the pressure distributions are no longer symmetric and the highest pressure occurs at the leading side of the pads.
Modeling And Simulation Of Disc Brake Contact Analysis And Squeal. [4]	• Predicting disc brake squeal by means of the complex eigenvalue method. • Studies the disc brake squeal using a detailed 3-dimensional finite element (FE) model of a real disc brake. • Studies the influence of contact pressure distributions on the squeal occurrence as a result of structural modifications. • Partial connection and stiffer disc can eliminate unstable frequencies below 8000Hz, which are dominant in the baseline model. • Shifting the pressure towards the trailing edge alone is insufficient to suppress unstable frequencies.
Disc Brake Simulation And Analysis. [14]	• Simulate the operation of a disc brake typically found on a car. • The use of c++ program to solve the differential equations associated with it. • The coulomb material, with static friction larger than dynamic, sticks to the disc initially as the brake pad support deforms elastically. When the friction force is overcome, the displacement of the pad decreases rapidly until the pad sticks again and oscillations are produced. • The coulomb material could possibly cause violent

	oscillations to occur under certain circumstances, and put a lot of stress on the brake pad support, leading to brake failure.
Wear Resistance Of Cast Irons Used In Brake Disc Rotors.	• Study and comparison of wear resistance of three different types of gray cast iron used in brake disc rotors, (gray iron grade 250, high-carbon gray iron and titanium alloyed gray iron). • The wear tests were carried out in a pin-on-disc wear-testing machine. • The wear was measured by weighing discs and pads before and after the test. • The results showed that compact graphite iron reached higher maximum temperatures and friction forces as well as greater mass losses than the three gray irons at any pressure applied.
Wear Simulation and Its Effect on Contact Pressure Distribution and Squeal of a Disc Brake. [5]	• Wear over time at the pads interface is simulated using a modified wear rate formula. • The detailed 3-dimensional finite element model of a real disc brake is developed and validated through appropriate analyses. • Investigates squeal generation in the braking applications using complex eigenvalue analysis that is available in a commercial software package. • Predicted results are compared to the squeal events observed in the experiments. • The results show that the contact area increases as wear progresses. • Rhee’s wear formula can be used in the finite element analysis in order to examine wear of the friction material and in turn to predict squeal generation.
Contact Analysis for Drum Brakes and disc Brakes using ADINA. [6]	• Drum and disc-brakes are modeled with finite elements using ADINA-IN. • The correct calculation of contact is essential for the design of friction brakes. • The sparse solver implemented in ADINA Version 7.1 reduces job duration time of large models. • Higher contact pressure at the outer radius of the disc. • This analysis is the basis for dynamic calculations of friction-induced vibrations.
Thermal Cracking in Disc Brakes. [7]	• Disc failure is a consequence of low cycle thermo-mechanical fatigue. • An analysis of the vehicle dynamics was used to find a heat flux equation related to braking forces. • Heat flux equation was then used in finite element analysis

	to determine the temperature profile in the brake. • A simplified shrink fit analysis was used to estimate the stresses that arise during hard braking. • Plastic deformation occurs due to the large thermal strain associated with high-g braking.

2.4 INTRODUCTION TO STRESS

Stress is a measure of the average amount of force (F) exerted per unit area (A). It is a measure of the intensity of the total internal forces acting within a body across imaginary internal surfaces, as a reaction to external applied forces and body forces. It was introduced into the theory of elasticity by Cauchy around 1822. Stress is a concept that is based on the concept of continuum. In general, stress is expressed as

$$\sigma = \frac{F}{A}$$

where $\boldsymbol{\sigma}$ is the average stress, also called engineering or nominal stress and $\boldsymbol{F}$ is the force acting over the area $\boldsymbol{A}$. The SI unit for stress is the pascal (symbol Pa), which is a shorthand name for one newton (Force) per square metre (Unit Area). The unit for stress is the same as that of pressure, which is also a measure of Force per unit area. Engineering quantities are usually measured in megapascals (MPa) or gigapascals (GPa).

2.4.1 Von Mises stress yield criterion

The von Mises yield criterion suggests that the yielding of materials begins when the second deviatoric stress invariant J_2 reaches a critical value k. For this reason, it is sometimes called the J_2-*plasticity* or J_2 flow theory. It is part of a plasticity theory that applies best to ductile materials, such as metals. Prior to yield, material response is assumed to be elastic.

In material science and engineering the von Mises yield criterion can be also formulated in terms of the **von Mises stress**, σ_v , a scalar stress value that can be computed from the stress tensor. In this case, a material is said to start yielding when its von Mises stress reaches a critical value known as the yield strength, σ_y. The von Mises stress is used to predict yielding of materials under any loading condition from results of simple uniaxial tensile tests. The von Mises stress satisfies the property that two stress states with equal distortion energy have equal von Mises stress. Because the von Mises yield criterion is independent of the first stress invariant, I_1, it is applicable for the analysis of plastic deformation for ductile materials such as metals, as the onset of yield for these materials does not depend on the hydrostatic component of the stress tensor.

2.5 DISC BRAKE MECHANISM

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 cause the outside pad to contact the disc. Braking force is generated by friction between the disc pads and as they are squeezed against the disc rotor. Since disc brake do not use friction between the lining and rotor to increase braking power as drum brakes do, they are less likely to cause a pull. The friction surface is constantly exposed to the air, ensuring good heat dissipation, minimizing brake fade. It also allows for self-cleaning as dust and water are throw off, reducing friction differences.

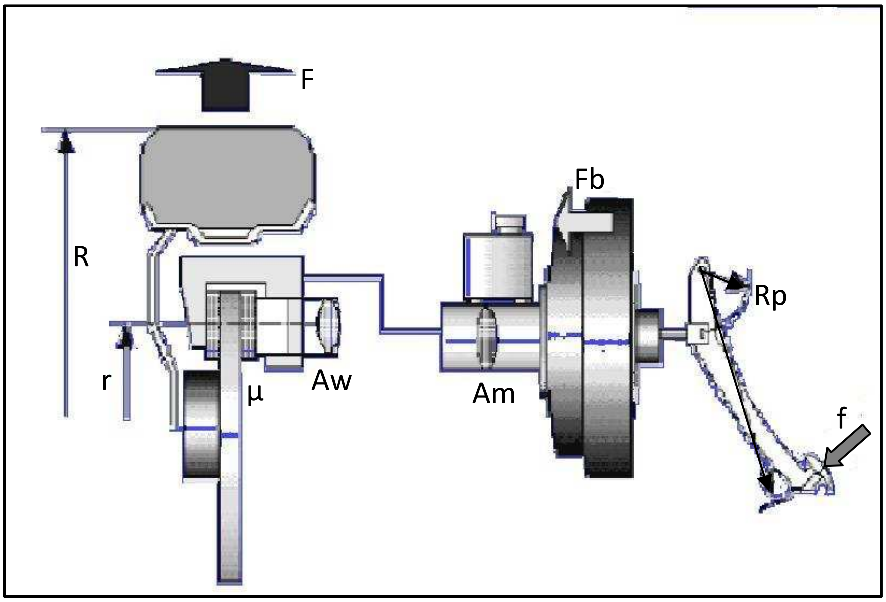


Figure 2.3: Force path from the driver’s foot to the tire road interface

Symbol	Description
f	force applied by driver's foot
Rp	pedal lever ratio
Fb	booster assist force
Am	area of master cylinder
Aw	area of the front caliper piston
μ	coefficient of friction of lining
r	effective radius of the caliper
R	loaded radius of the tire

Braking force, $F \propto \frac{r}{R} \times 2 \times \mu \times \frac{Aw}{Am} \times (Rp \times f + Fb)$

Source: Introduction to Brake System, SAE Brake Colloquium, P. Gritt, DaimlerChrysler, 2002

Hydraulic pressure transferred from driver's foot is applied to piston (A) and thus presses the inner pad against the disc rotor. At the same time, an equal hydraulic pressure (reaction force B) acts on the bottom of the cylinder. This causes the caliper to move to the right, and presses the outer pad located opposite the piston against the disc rotor.

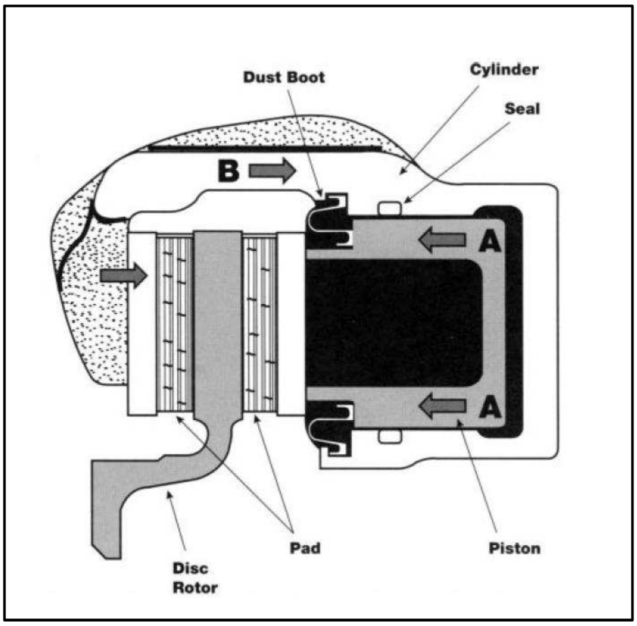


Figure 2.4: Piston and brake pad mechanism

The effort or force exerted on the brake pedal combined with the output of the booster and the diameter of the master cylinder pistons determines the pressure in a hydraulic brake system. The smaller the master cylinder bore diameter is, the higher the pressure will be for a given force on the brake pedal. However, a smaller diameter master cylinder will require more travel of the piston to displace the same amount of fluid as a large piston. The larger the diameter of the wheel cylinder or caliper piston is, the higher the force will be pushing on the brake shoes. It can sometimes be very difficult to get accurate information about the caliper effective radius and/or the tire loaded radius.

2.6 SOFTWARE

Software is the core element in this project because all the modeling and analysis were performed virtually by computer. The software that was involved in the modeling and analysis were CAD and CAE.

2.6.1 Computer Aided Design (CAD)

Computer-aided design is the use of computer technology to aid in the design and especially the drafting (technical drawing and engineering drawing) of a part or product, including entire buildings. It is both a visual (or drawing) and symbol-based method of communication whose conventions are particular to a specific technical field. Drafting can be done in two dimensions ("2D") and three dimensions ("3D").Drafting is the integral communication of technical or engineering drawings and is the industrial arts sub-discipline that underlies all involved technical endeavors. In representing complex, three-dimensional objects in two-dimensional drawings, these objects have traditionally been represented by three projected views at right angles. **SolidWorks** is one of the common CAD tools and widely use in industry. This tool was used to model disc brake rotor and brake pad. The models and then imported to CAE tools for analysis.

2.6.2 Computer Aided Engineering (CAE)

Computer-aided engineering is the use of information technology for supporting engineers in tasks such as analysis, simulation, design, manufacture, planning, diagnosis and repair. Software tools that have been developed for providing support to these activities are considered CAE tools. CAE tools are being used, for example, to analyze the robustness and performance of components and assemblies. It encompasses simulation, validation and optimization of products and manufacturing tools. In the future, CAE systems will be major providers of information to help support design teams in decision making. CAE tools are very widely used in the automotive industry. In fact, their use has enabled the automakers to reduce product development cost and time while improving safety, comfort, and durability of the vehicles they produce. The predictive capability of CAE tools has progressed to the point where much of the design verification is now done using computer simulations rather than physical prototype testing. ALGOR is the CAE tool that was used in this project. Models from CAD is imported to this tools for failure analysis.

2.7 INTRODUCTION TO SOLIDWORKS

SolidWorks is a 3D mechanical CAD program that runs on Microsoft Windows and was developed by SolidWorks Corporation - now a subsidiary of Dassault Systèmes, S. A. (Suresnes, France). Building a model in SolidWorks usually starts with a 2D sketch (although 3D sketches are available for power users). The sketch consists of geometry such as points, lines, arcs, conics, and splines. Dimensions are added to the sketch to define the size and location of the geometry. Relations are used to define attributes such as tangency, parallelism, perpendicularity, and concentricity. The parametric nature of SolidWorks means that the dimensions and relations drive the geometry, not the other way around. The dimensions in the sketch can be controlled independently, or by relationships to other parameters inside or outside of the sketch.

SolidWorks pioneered the ability of a user to roll back through the history of the part in order to make changes, add additional features, or change to sequence in which operations are performed. Later feature-based solid modeling softwares also copied this idea.

In an assembly, the analog to sketch relations are mates. Just as sketch relations define conditions such as tangency, parallelism, and concentricity with respect to sketch geometry, assembly mates define equivalent relations with respect to the individual parts or components, allowing the easy construction of assemblies. SolidWorks also includes additional advanced mating features such as gear and cam follower mates, which allow modeled gear assemblies to accurately reproduce the rotational movement of an actual gear train. Drawings can be created either from parts or assemblies. Views are automatically generated from the solid model, and notes, dimensions and tolerances can then be easily added to the drawing as needed. The drawing module includes most paper sizes and standards (ANSI, ISO, DIN, GOST, JIS, BSI and GB). It is currently one of the most popular products in the 3D mechanical CAD market.

2.8 INTRODUCTION TO ALGOR

ALGOR is a general-purpose multiphysics finite element analysis software package developed by ALGOR Incorporated for use on the Microsoft Windows and Linux computer operating systems. It is distributed in a number of different core packages to cater to specifics applications, such as mechanical event simulation and computational fluid dynamics. ALGOR is used by many scientists and engineers worldwide. It has found application in aerospace, and it has received many favorable reviews. Algor typically used for bending; stress–strain, mechanical contact, thermal (conduction, convection, radiation), fluid dynamics, and coupled and uncoupled multiphysics

CHAPTER 3

METHODOLOGY

3.1 ANALYSIS METHOD

Stress analysis of contact area between brake disc and brake pads during operation is the focus of the analysis. The disc that will be modeled is solid type disc found on front axle of Proton's car (Wira 1.5L, 1998 model). Disc Brake on Proton Wira was chosen because this passenger car was widely used and common vehicle in Malaysia and cruising on the road for almost 20 years. The disc brake is modeled in SolidWorks. The dimension of the part is exactly the same with the actual dimension referred to ACDelco Disc Rotors Catalogue: Issue 2 (General Motor's Delphi Corporation). Analyses were done with Algor-Fempro by considering the operation of disc brake in static conditions.

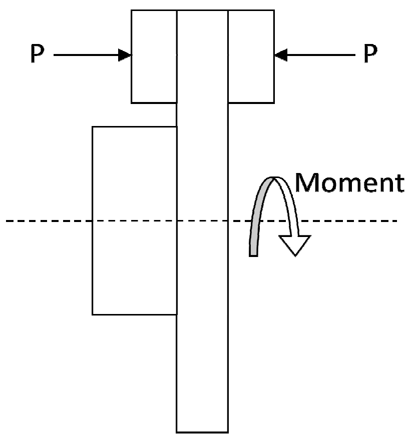


Figure 3.1: Free body diagram of disc with moment at the center of the disc and applied pressure from the brake pads

3.2 WORKS FLOW

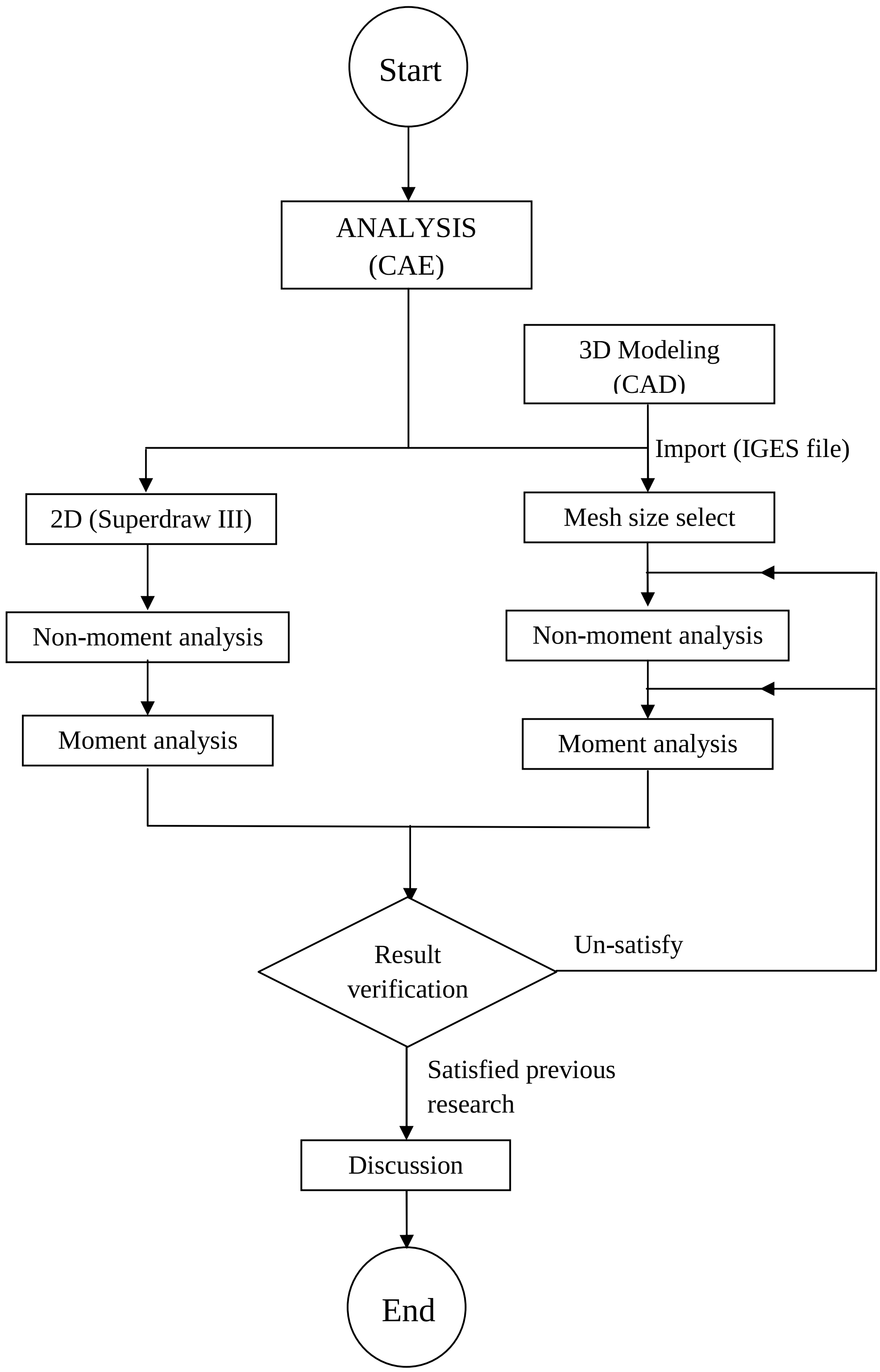


Figure 3.2: Works flow of modeling and analysis

3.3 MODEL

The model consists of solid type disc. The shape and properties of the disc rotor was taken from the actual disc brake implemented in the proton Wira. Dimension of disc rotor was referred to ACDelco's Disc Rotors catalogue, Issue number 2. ACDelco is the manufacturer of disc brake implemented in Wira generation's model. In that catalogue, dimensions and the shape of disc rotor were provided. All the parts were done three-dimensionally in Solidworks version 2008. The fundamental shape of the solid type disc rotor was sketch in the Solidworks. The sketch (Figure 3.3) then was sweep 360^o. The finish 3-Dimensional model was shown in Figure 3.4. The model then was assembled with the brake pad and save as IGES format in order to be opened in Algor-Fempro.

Table 3.1: Dimensions of disc

Properties	**Dimension**
Thickness, mm	18
Center Hole Diameter, mm	64
Height, mm	45
Number Bolt Hole	4
Outer diameter, mm	235

Source: ACDelco Disc Rotors Catalogue: Issue 2

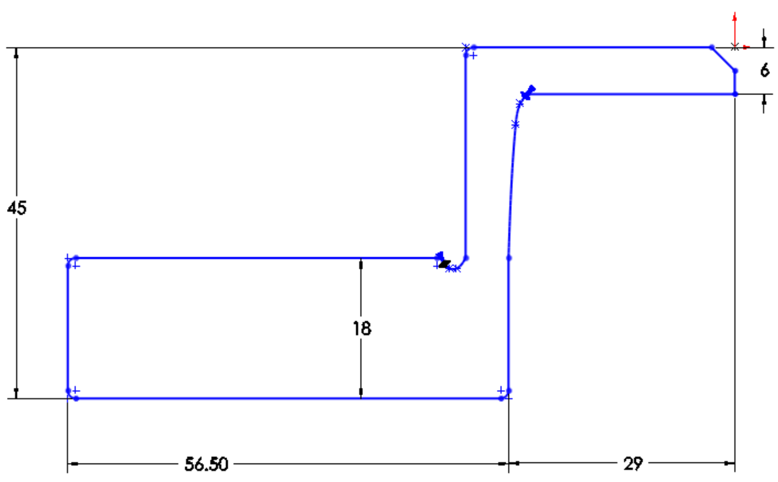


Figure 3.3: Sketch of fundamental shape of disc (all units in millimeters)

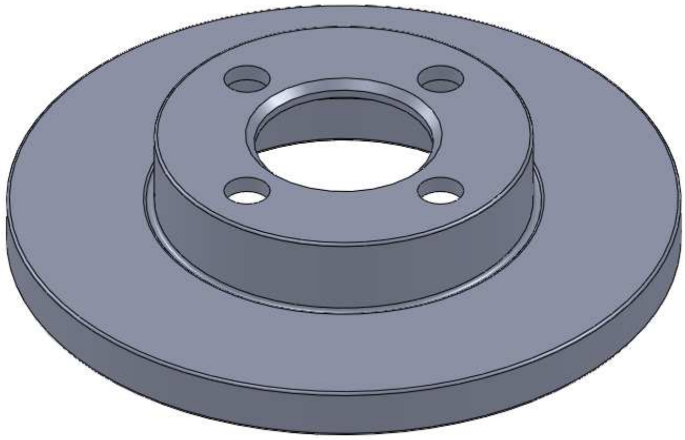


Figure 3.4: SolidWorks design of disc

3.4 ANALYSIS

Algor Fempro version 16 was used for finite element analysis of the disc brake. Analysis was divided into 2-Dimensional (2D) analysis and 3-Dimensional (3D) analysis as stated in Figure 3.2. 2D analysis was done to examine the stress distribution through the cross section of the disc while 3D analysis was done to examine the stress distribution on the surface of the disc. 2D model was locally drawn in Algor Fempro by using Superdraw III method. 3D model was imported from CAD tool (SolidWorks). IGES (format of the assembly model from SolidWorks) was imported to Algor Fempro for analysis. Analysis type is static stress with linear material model.

The constraints were applied depending on the analysis condition whether non-moment or moment. Non-moment analyses represent the operation of disc brake with no load applied to the disc; only pressures of 2 to 4MPa from brake pads are applied. 2 to 4 MPa is the range of braking pressure under normal condition. For moment analysis, moment of 5Nm is applied simultaneous with the applied pressure of 2 to 4 Mpa from the brake pad. Analysis results will be verified with the existing journal (A R A Bakar, **Prediction of Disc Brake Contact Pressure Distributions**

by Finite Element Analysis, Jurnal Teknologi, UTM, 2005) by applying 8MPa pressure and 5Nm moment for non-moment and moment analysis.

Selected mesh size will be applied and was explained below. Pin joint is created to represent the shaft at bottom of wheel hub. The moment and constraint for disc were applied at the center of the pin joint. Material for disc rotor is high carbon, grey iron composition (SAE J431 Grade G10 (G3000), ASTM A48M Class 30). Source: Introduction to Gray Cast Iron Brake Rotor Metallurgy, Mark Ihm, TRW Automotive, SAE.

Table 3.2: Parameter of analysis

Parameter	
Pressure	2 – 4 MPa 8MPa (verification of result)
Coefficient of friction	0.6
Moment	5 Nm
Material	Disc: Iron, gray cast class 30 Pad: Dupon Kevlar Aramid fibre Pin joint: Steel, ASTM A36
Analysis type	Static Stress with Linear Material Model

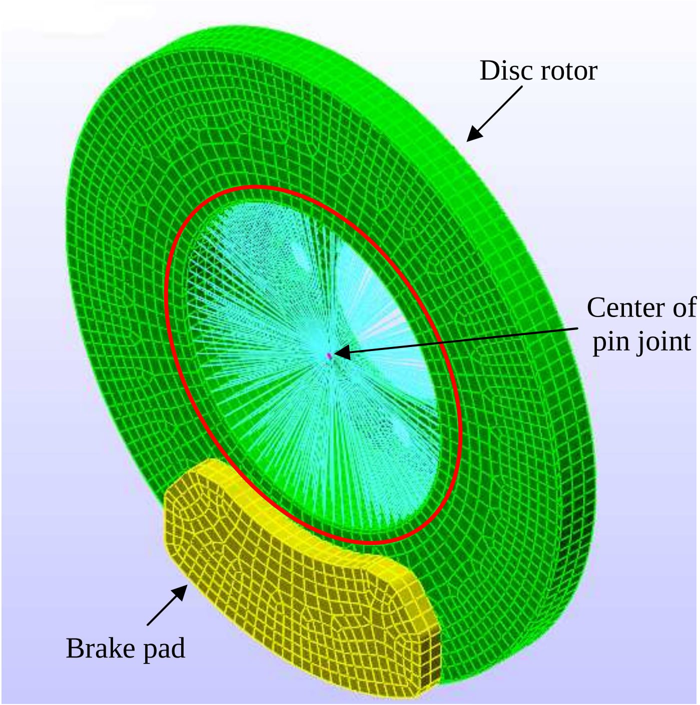


Figure 3.5: Pin Joint location at the assembly (red circle)

3.4.1 Mesh Size Analysis

A pre-analysis must be done to select the mesh size suitable and reliable for the analysis. Mesh size of 30% to 100% solid are applied to the imported IGES assembly in Algor-Fempro on the ‘model mesh setting’ stage. Pressure of 2MPa is applied to the model on each of the meshing levels. Fixed constraint is applied to the disc rotor while on the pads; all translation and rotation are fixed except translation of y-axis (same as static analysis). The distributed stress of the results will be examined to find the best mesh size to further the analysis. The best mesh size will be determined base on the uniform stress distribution and maximum stress occurred.

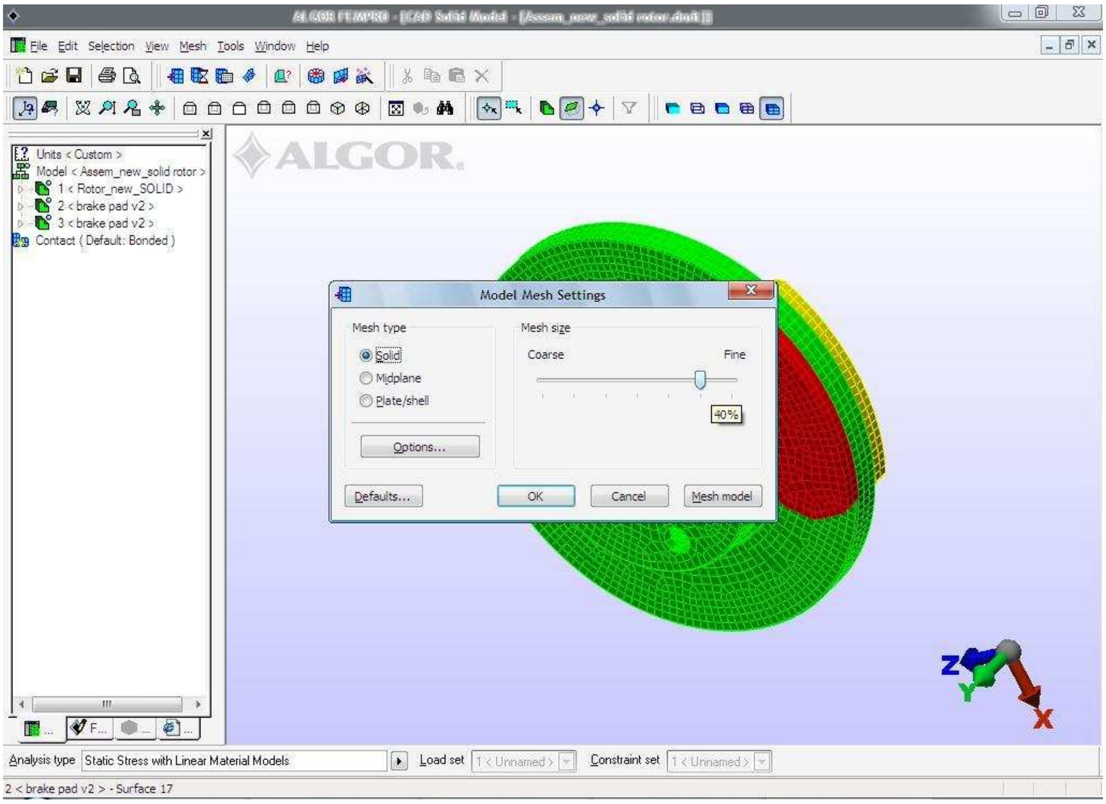


Figure 3.6: Model mesh size is set to 40%

3.4.2 2D Analysis

The purpose of 2-Dimensional analysis is to examine the stress distribution of the cross sectional area of the disc. All analyses are considering the car in static condition on a flat surface; only clamping pressure from the brake pads are applied. For 2D non-moment analysis, no loads from weight of the car or engine torque are applied to the disc. The moment of 5Nm is applied to the disc due to engine torque for moment analysis represent by the angular force (x-axis direction) applied at the tip of the disc (see Figure 3.8). Fixed constraint are applied to disc hub and z-axis direction pressures of 2 to 4 MPa were applied to the disc rotor through both of the brake pads (brake pads were crimpled the disc symmetrically). The stress distribution is examined and analyzed.

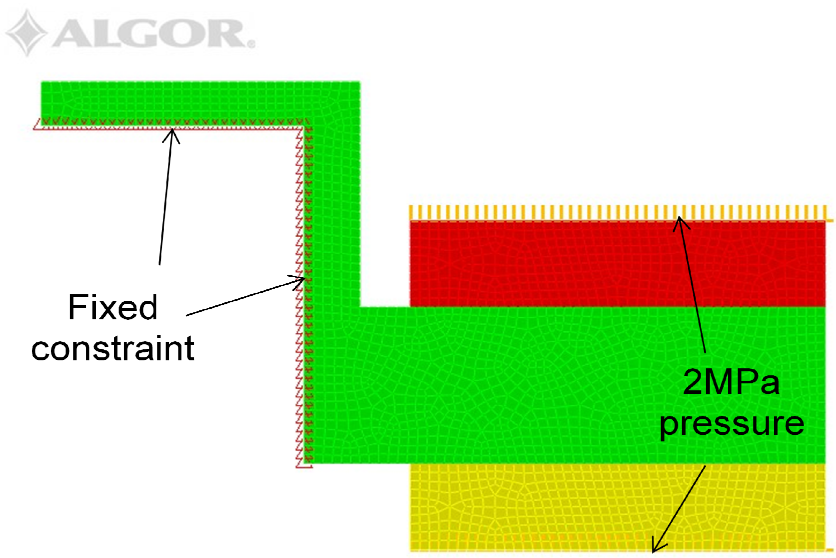


Figure 3.7: Pressure and constraint of 2D non-moment analysis

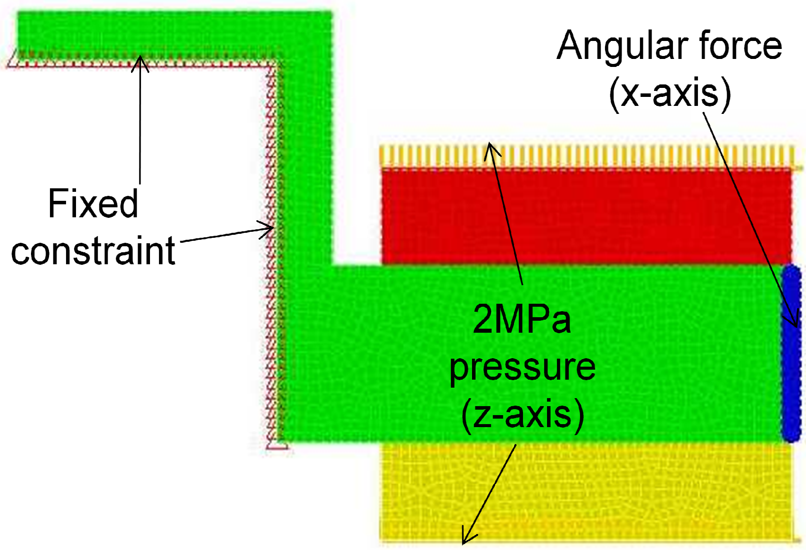


Figure 3.8: Pressure, force and constraint of 2D moment analysis

3.4.3 3D Analysis

Stress distribution on surfaces of disc can be analyzed with 3-Dimensional analysis. The surfaces of disc are the contact area between disc and brake pad where the stress is generating in this region. The analysis divided into 3D non-moment and 3D moment. For 3D non-moment analysis, fix constraint was applied at the center of the pin joint (Figure 3.4) while the pressure of 2 to 4 MPa are applied at the brake pads. For 3D moment analysis, moment of 5Nm is applied at the center of the pin joint simultaneous with the applied pressure of 2 to 4 MPa at the brake pads. The contact between brake pads and disc is set to surface contact with friction of 0.6. The result of stress distribution is examined and analyzed.

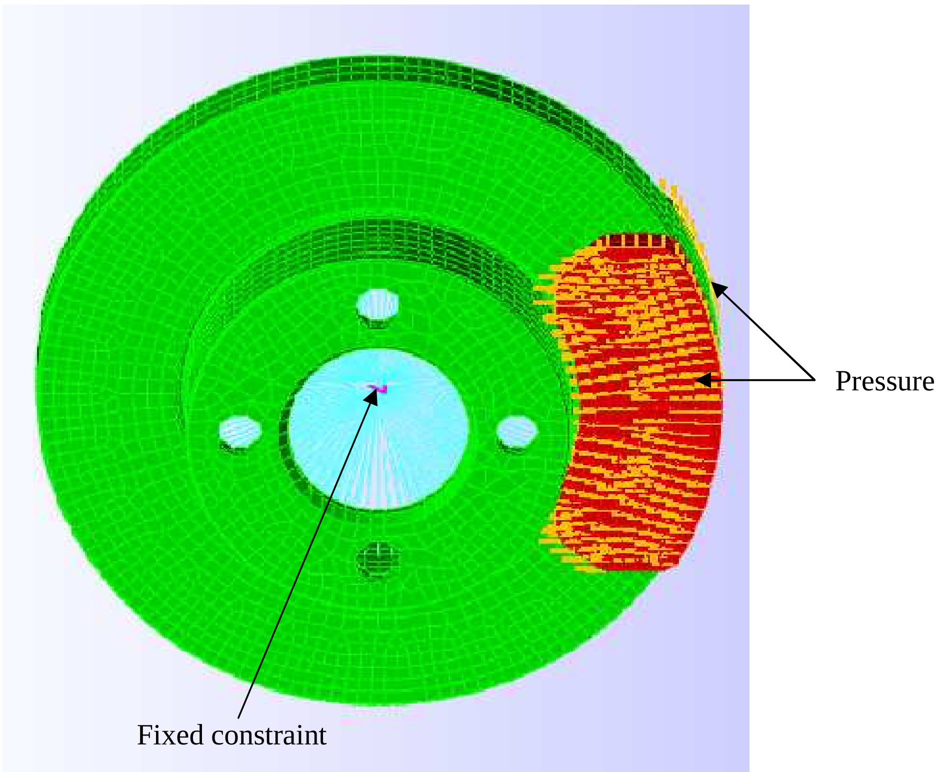


Figure 3.9: Constraints and pressures applied on 3D non-moment analysis

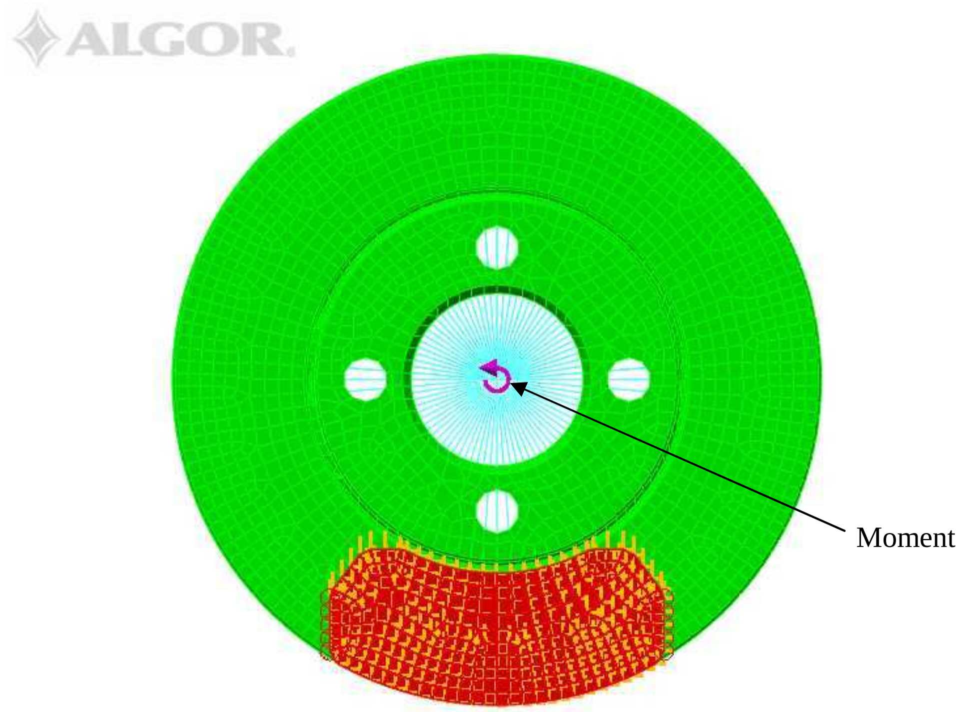


Figure 3.10: Moment and pressures applied on 3D moment analysis

3.5 RESULTS VERIFICATION

Verification of the result can be done by comparing the certain results to the existing research. The journal Prediction of Disc Brake Contact Pressure Distribution by Finite Element Analysis by Mr. Abd Rahim Abu Bakar [3] has been used as benchmark to validate the obtain results. For verification, 8MPa pressures are applied to the 3D non-moment analysis and 3D moment analysis. The percentage difference will be calculated between acquired data and data from previous research. For 2D analysis, the region of concentrated stress will be compared to the previous research.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 RESULTS

The applied pressure on the brake pads is in MPa and the resultant stress taken from analysis is in N/mm^2 units. MPa (Mega Pascal) used for pressure is equal to N/mm^2 (Newton over millimeters square) which is the unit of von Mises stress (1 MPa = 1 N/mm^2). Color gradient start with red and continue with orange, yellow, and green until dark blue on top left of the analysis result show the stress location. Red spot is the highest von Mises stress location. The dark blue shows the location of near zero stress.

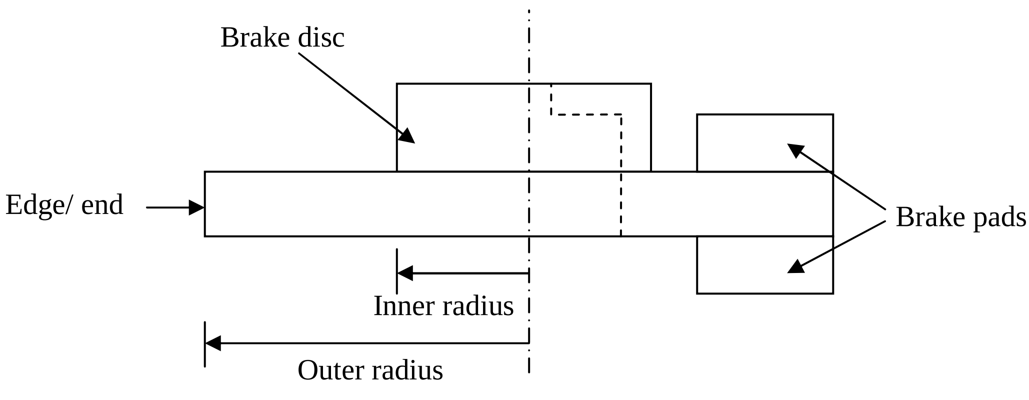


Figure 4.1: Cross section of the disc/ pads and the terms that will be used in analysis

4.1.1 Mesh Size Result

The results of varying mesh size from 30% to 100% are as followed. The pressures of 2 MPa were applied to the brake pads.

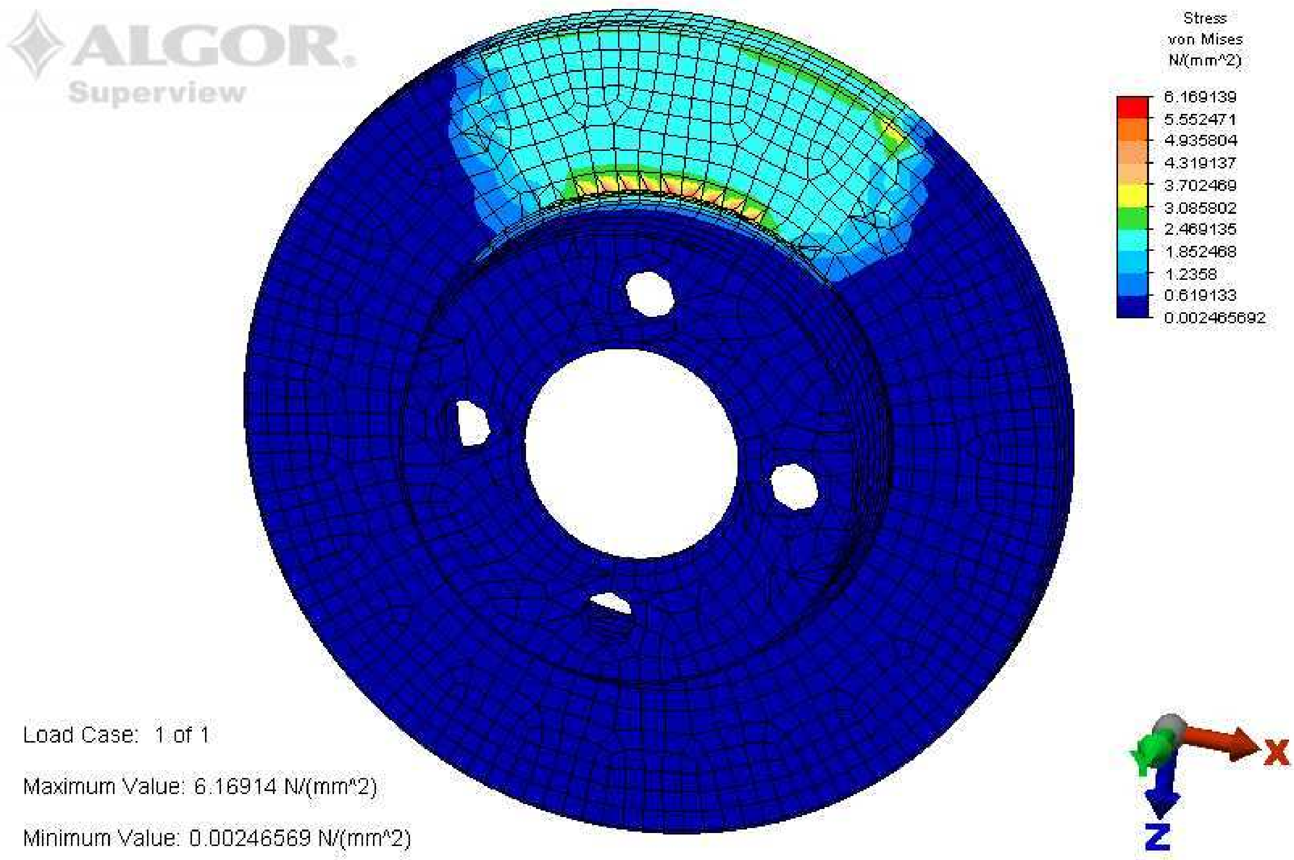


Figure 4.2: Stress distribution of 50% mesh level

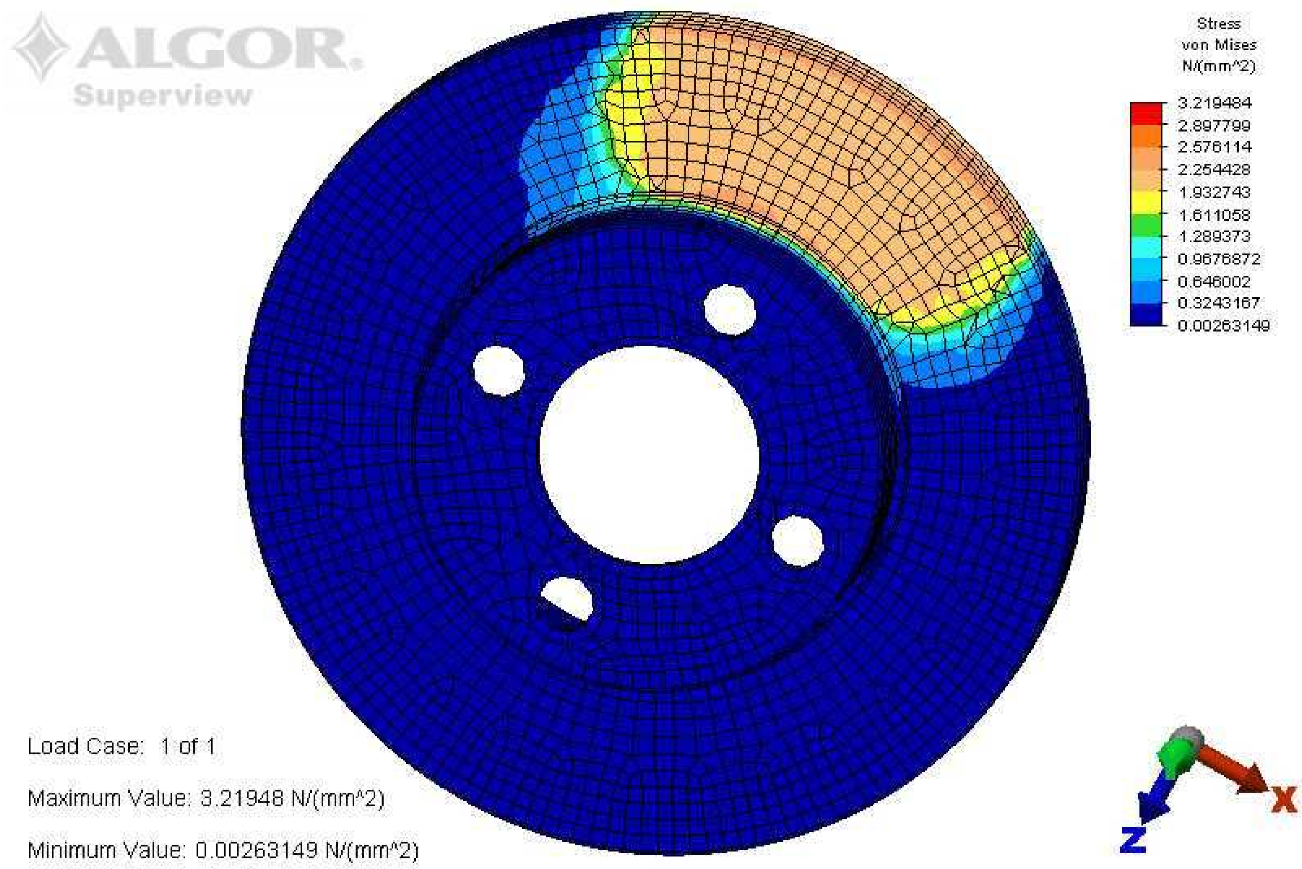
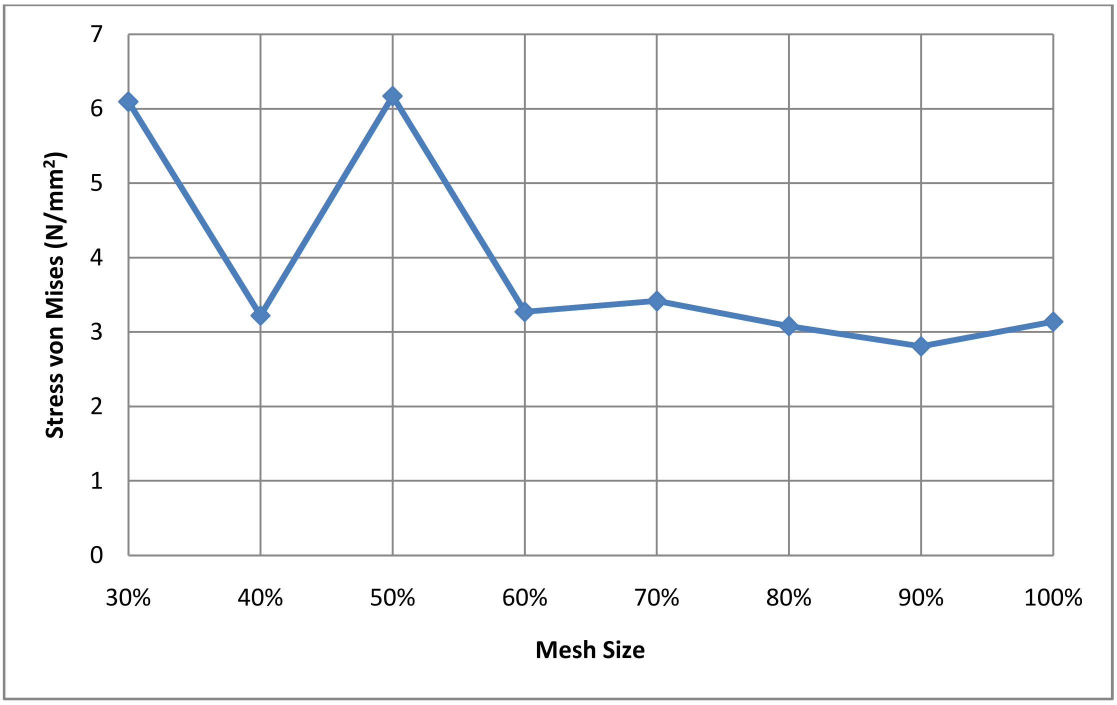


Figure 4.3: Stress distribution of 40% mesh level

Table 4.1: Maximum von Mises stress of mesh level 30% to 100%

Mesh level	**Max von Mises stress (N/mm^2)**
30%	6.0946
40%	3.2195
50%	6.1691
60%	3.2715
70%	3.4162
80%	3.0788
90%	2.8075
100%	3.1375



Graph 4.1: Maximum von Mises stress versus mesh size graph

4.1.2 2D Analysis Result

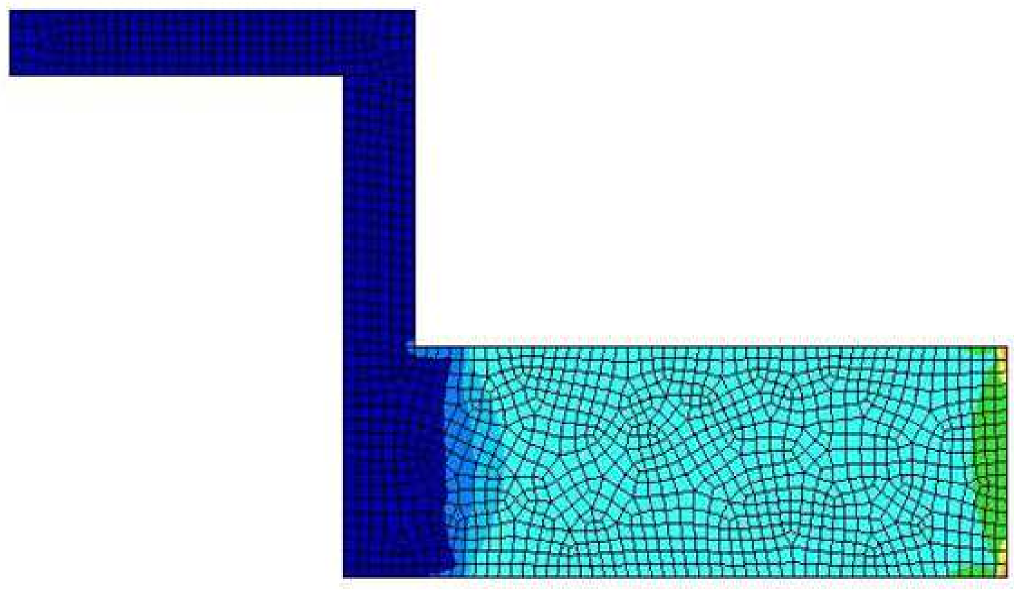


Figure 4.4: Stress distribution of 2D non-moment analysis

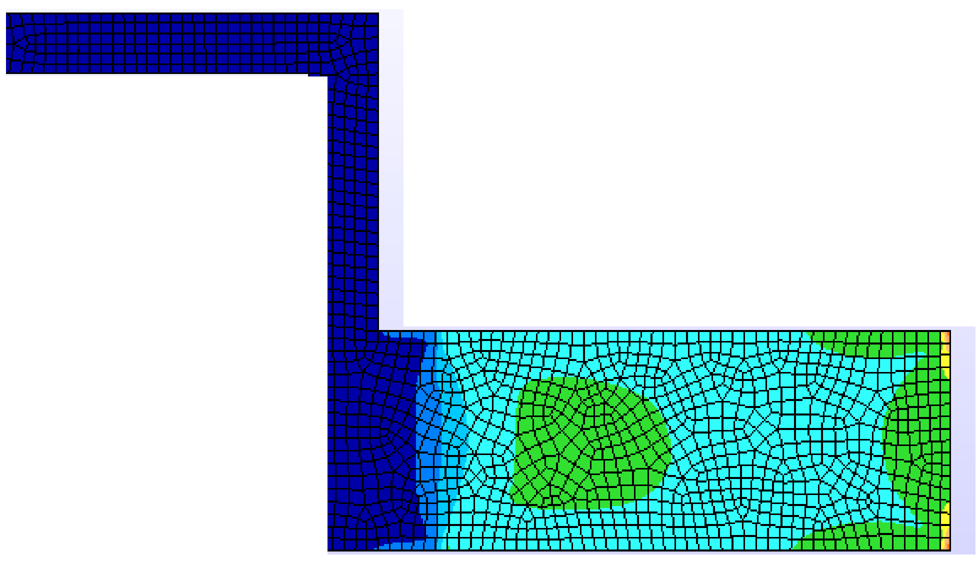


Figure 4.5: Stress distribution of 2D moment analysis

4.1.3 3D Analysis Result

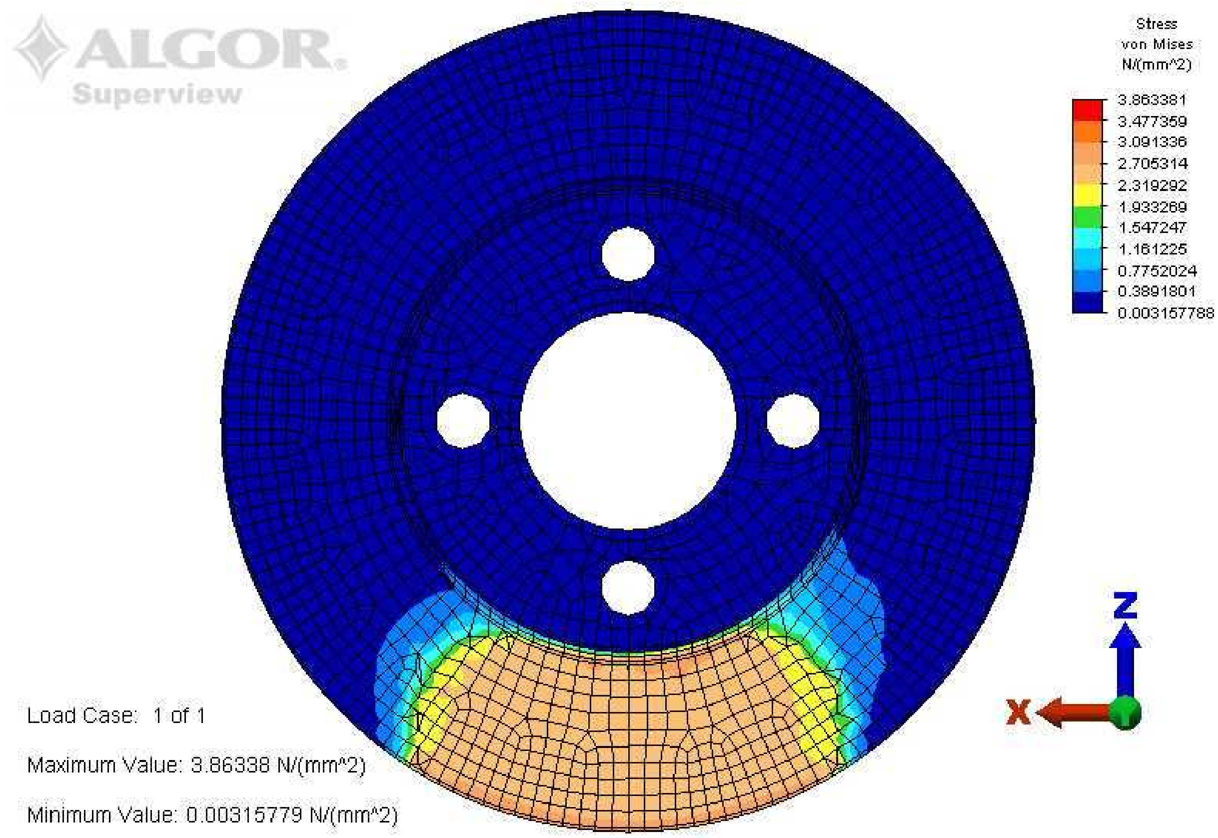
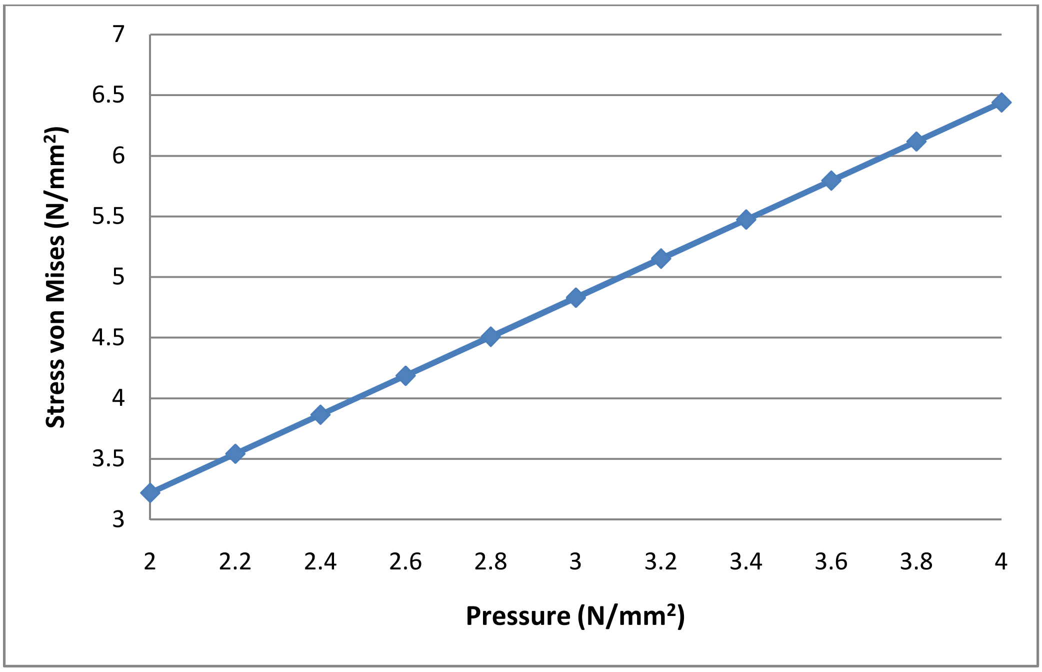


Figure 4.6: Stress distribution of 3D non-moment analysis

Table 4.2: Load versus maximum von Mises stress for 3D non-moment analysis

Pressure (MPa)	Max von Mises stress (N/mm^2)
2.0	3.2195
2.2	3.5414
2.4	3.8634
2.6	4.1853
2.8	4.5073
3.0	4.8292
3.2	5.1512
3.4	5.4731
3.6	5.7951
3.8	6.117
4.0	6.4389



Graph 4.2: Pressure versus maximum von Mises stress graph for 3D non-moment analysis

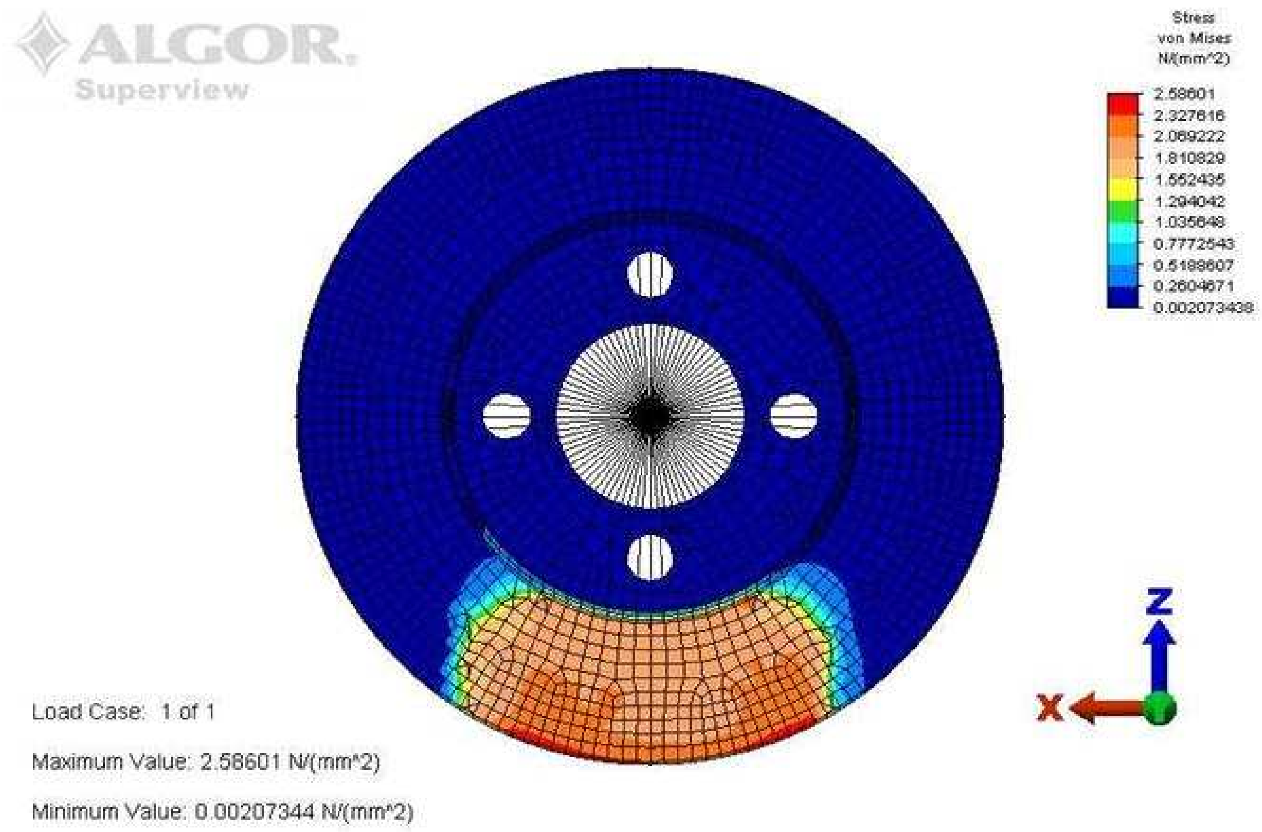
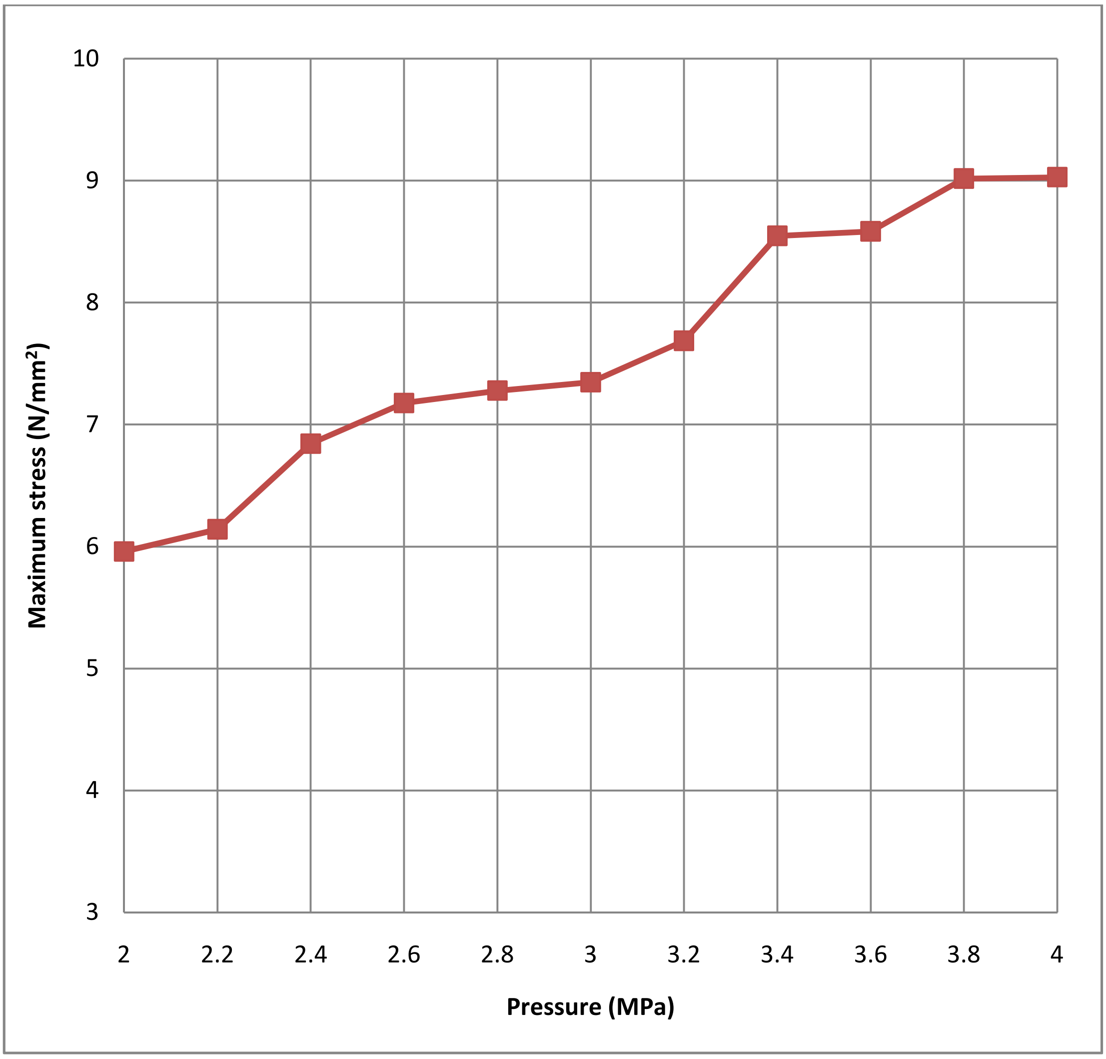


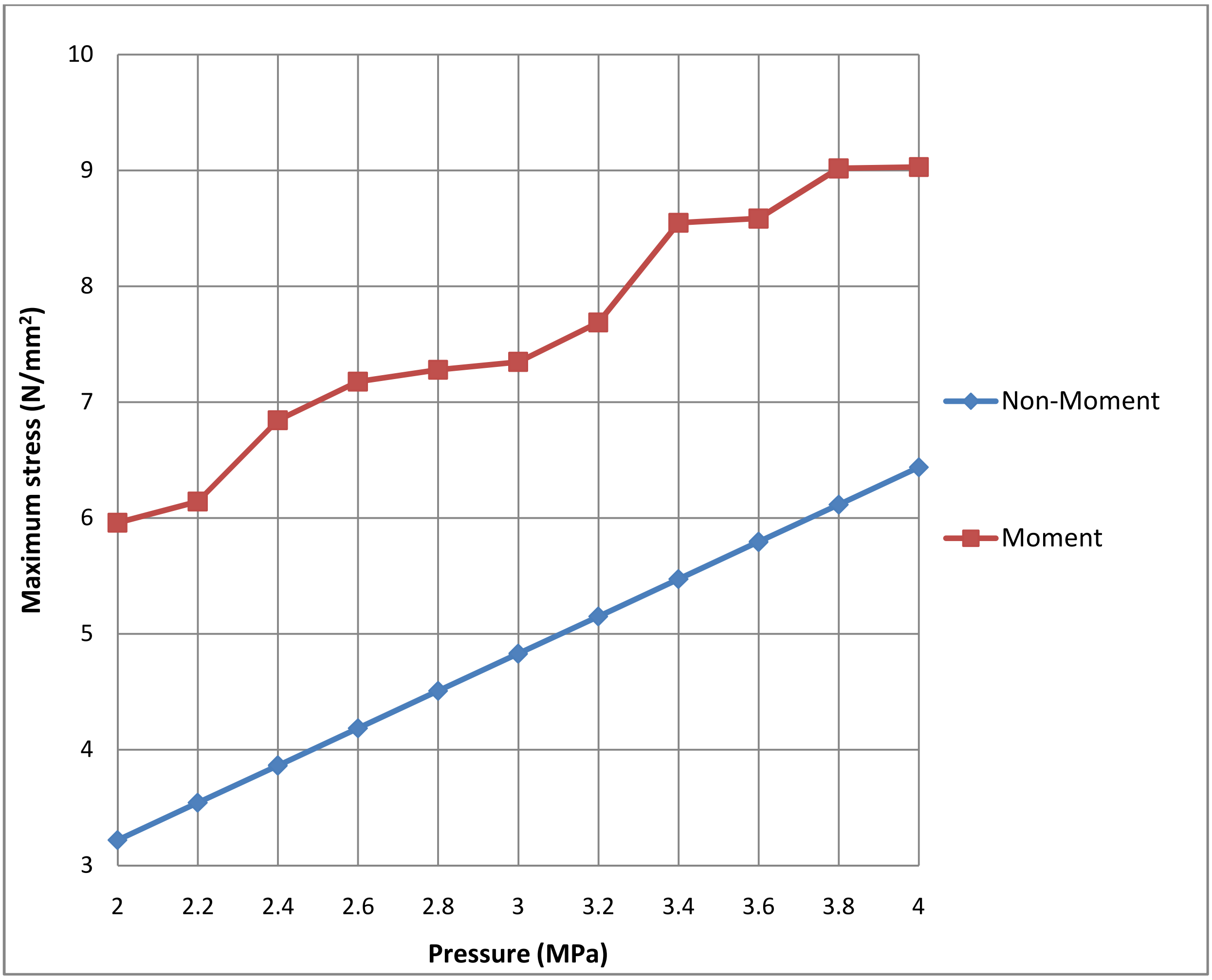
Figure 4.7: Stress distribution of 3D moment analysis

Table 4.3: Pressure versus maximum von Mises stress for 3D moment analysis

Pressure (MPa)	**Max von Mises stress (N/mm^2)**
2.0	5.9594
2.2	6.1411
2.4	6.8431
2.6	7.1763
2.8	7.2785
3.0	7.3473
3.2	7.6869
3.4	8.5474
3.6	8.5841
3.8	9.0167
4.0	9.0283



Graph 4.3: Pressure versus maximum von Mises stress graph for 3D moment analysis



Graph 4.4: Maximum von Mises stress of 3D non-moment and moment analysis versus applied pressure

4.1.4 Results verification

Table 4.4: Percentage difference of 3D non-moment analysis

	Maximum stress	Value difference	Percentage difference
Acquired data	8.5896 N/mm^2	0.9886 N/mm^2	12.97%
Journal	7.6210 N/mm^2		

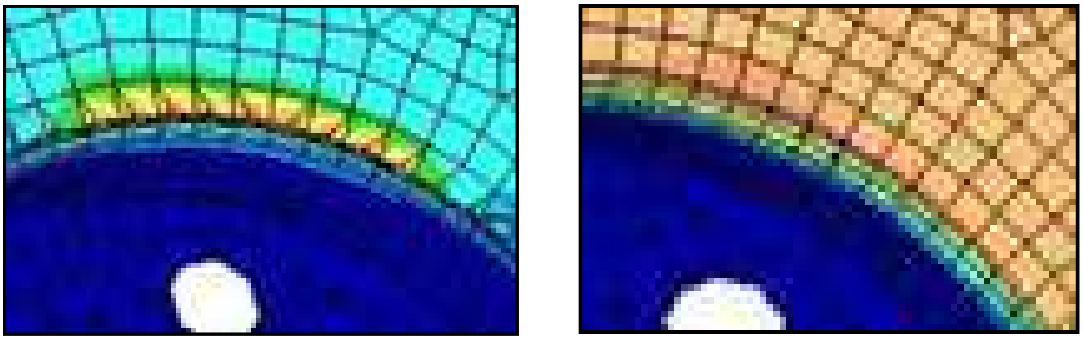
Table 4.5: Percentage difference of 3D moment analysis

	Maximum stress	Value difference	Percentage difference
Acquired data	15.2486 N/mm^2	2.3014 N/mm^2	13.11%
Journal	17.550 N/mm^2		

4.2 DISCUSSIONS

The results obtain from analysis are discuss in this section. The result divided into mesh size, 2-Dimensional non-moment and moment and 3-Dimensional non-moment and moment. The graph trend will also be discussed and appropriate modification and improvement will be done.

4.2.1 Mesh Size



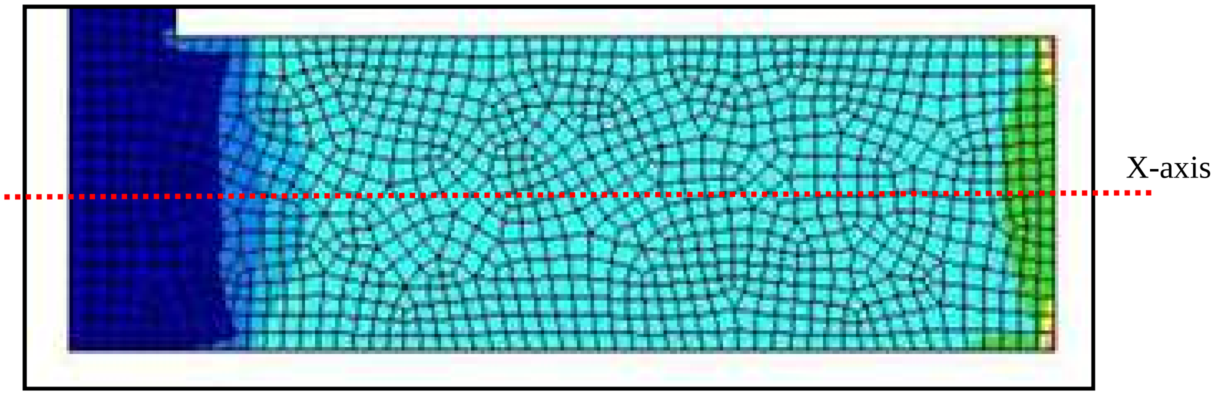
(a) (b)

Figure 4.8: Mesh sizes of (a) 50% and (b) 40%

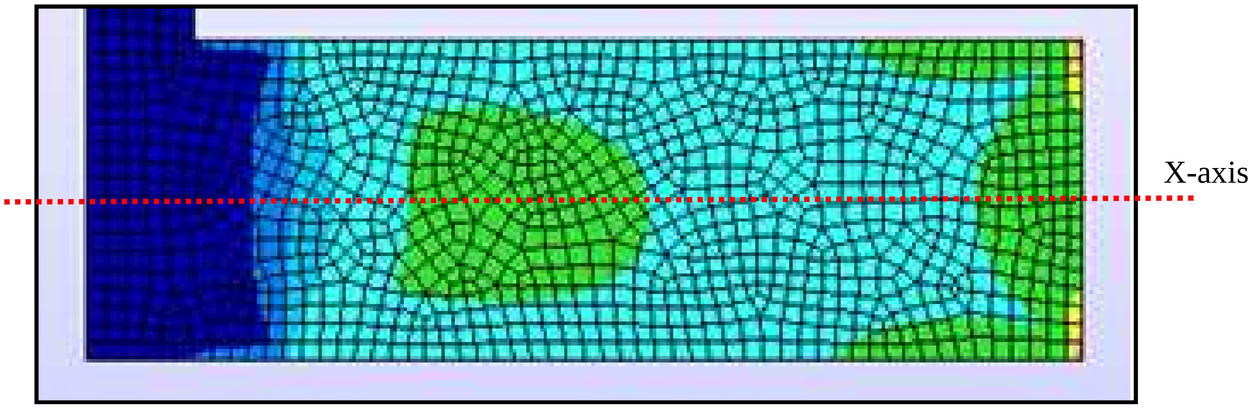
Mesh size of 40% is selected as the default mesh size. This is due to the uniformity of mesh distribution on the entire disc. From Figure 4.8 (a) the size of meshes is not even especially on the inner radius of the contact area between the disc and pads where the concentrated stress occurred. Compare with the mesh size of 40%; Figure 4.8 (b), the size of the meshes and the stress distribution are even and uniformly distribute on the contact area. The maximum stress was occurred at this area and the maximum value of 50% mesh size is double the value of the maximum stress that occurred on the 40% mesh.

The location of maximum stress is shown by red spot on the disc. These phenomenons are only occurred for 30% and 50% mesh size while the other mesh size shows maximum stress value around 3 N/mm^2. Computational time is also under consideration. Theoretically, the smaller the mesh size the result is more accurate but constraint by the computational time for analysis to run. This factor is more obvious when complex model is used with various loads and constraints are applied. The small mesh size is not practical when several analyses with differences parameter are applied to the various models. So, 40% is the best selected mesh size.

4.2.2 2D Analysis Result



(a)



(b)

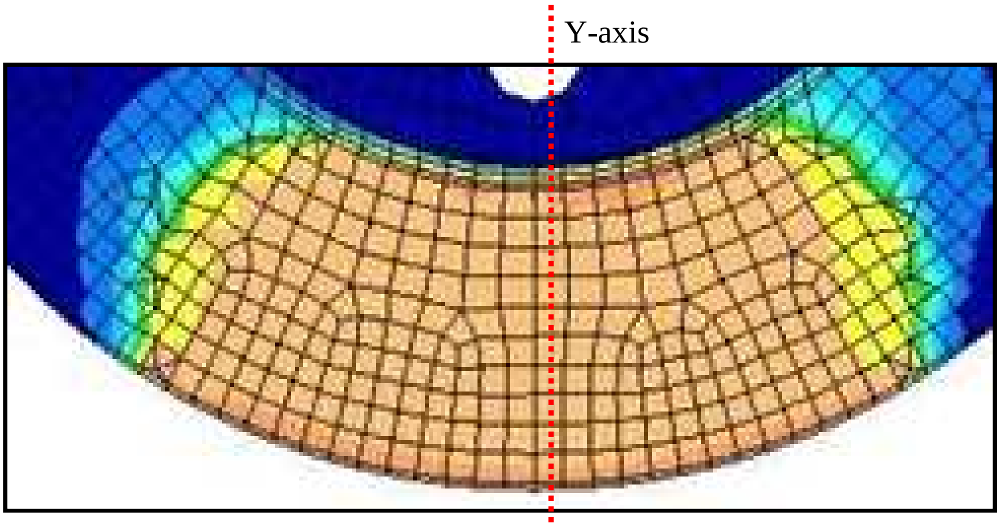
Figure 4.9: Stress distributions of 2D (a) non-moment and (b) moment analysis

The stress distribution is assumed uniform along the cross section of the disc since the disc is rotating, but distribute unevenly on the surface of the disc. Stress distribution pattern is same for all applied pressures but different magnitude. The magnitude of the von Mises stress is not shown because the value is not reasonable due to the dimensions of the disc and brake pads applied to the 2D analysis (the model type is plate with 1mm thickness). The stress distribution is symmetrically the same about X-axis. These are due to same pressures applied at the both side of the disc.

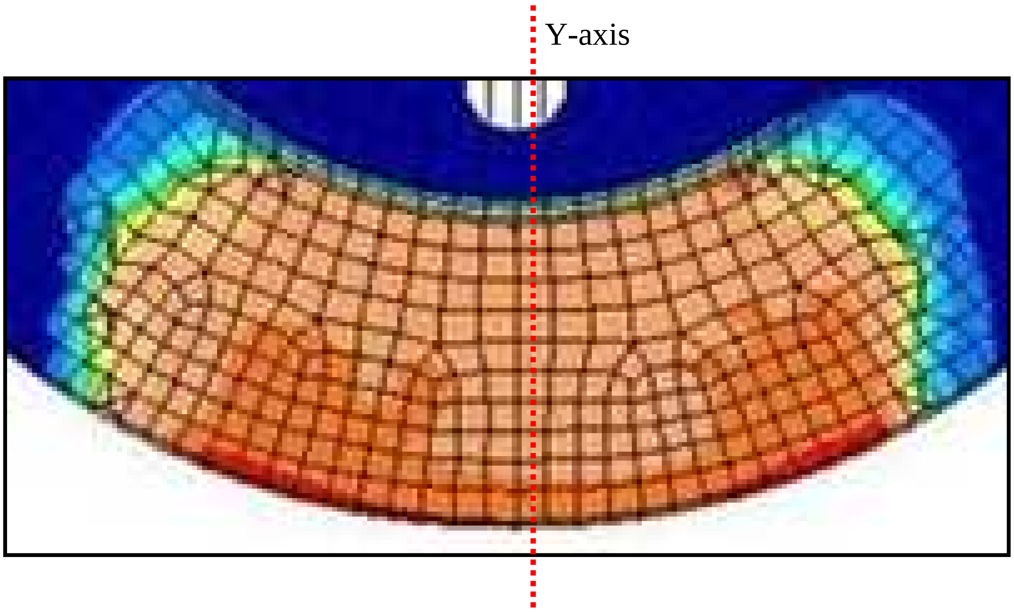
For figure 4.9 (a), the stress are distribute evenly for entire disc except the small region at the end of the disc. The highest stress occurred at both edges of the outer radius of the disc. The high stress also propagates between these edges. The maximum stress at this area is due to the location of brake pads; above and bottoms of the edges of the disc. So, when the brake pads pressed against the disc, the edges tend to deform with the shape of cone.

For figure 4.9 (b), highest stress also occurred at both edges of the outer radius of the disc with high stress propagates between these edges. But the concentrated stresses become dense at the end of the disc. Green spot can be seen at the center of the disc. The concentrated stress occurred at the end of the because of the location of brake pads and the result of applied moment. The green spot on the center of the disc is due to applied moment represent by applied forces at the end of the disc that try to bend the end towards the center of disc.

4.2.3 3D Analysis Result



(a)



(b)

Figure 4.10: Stress distributions of 3D (a) non-moment and (b) moment analysis

Figure 4.10 (a) shows the stress distribution is symmetry about Y-axis. The stress distribution is uniform at the contact area of disc and brake pads and reduces at the left and right sides of the brake pads (yellow spots). The uniform color at the contact of disc and pad show the uniformity of the hydraulic pressure applied to the brake pad.

Figure 4.10 (b) shows the concentrated stress occurred at the outer radius of the disc (orange and red spots). Right side of Y-axis is the leading edge of the pad while the left side is trailing edge. Leading edge is the location of the first contact with disc was occurred while trailing edge is last. This property explains why the concentrated stress was far from the Y-axis at leading edge but closer for trailing edge. Location of the concentrated stress is not symmetric due to the counter-clockwise direction of the applied moment. The shape of the concentrated stress is influence by the shape of the brake pad. The maximum stress (indicated by red spots) occurred at the outer edge of the disc; the area of contact between brake pads and disc.

The red and orange spots are the areas that defect will occurred. Continuous maximum stress under fatigue condition may reduce braking efficiency and damage the disc. The maximum stress distribution at the outer radius will cause conning effect and premature wear both to the disc and pads consequently shorten the lifespan. The concentrated stress can’t be avoided but can be reduced. The surface enhancement could be done at this critical area to encounter the concentrated stress.

4.2.4 Graph analysis

Graph 4.2 shows that the applied pressure is directly proportional to the maximum von Mises stress. Pressure of 2MPa that were applied to the sides of the disc producing maximum von Mises stress of 3.2195 N/mm^2 (1.2195MPa differ). 4MPa pressure was producing 6.4389 N/mm^2 maximum von Mises stress (2.4389MPa differ). The value of differences between applied pressure and maximum stress for 4MPa pressure is doubled the pressure of 2MPa. This result occurred due to the summation of stresses from the applied pressure to the brake pad 1 and 2.

Graph 4.3 shows the pressure of 2 to 4 MPa are directly proportional to the maximum von Mises stress. Even though the graph line is not straight, the maximum stress is still increase with the increase of the pressure. The trend line is due the applied moments and almost proportional with the line of non-moment analysis with approximate different magnitude of 3 N/mm^2 (Graph 4.4). The magnitude difference is affected by the applied moment and cause by the disc is attended to move but doesn't rotate. The variation of frictions between the disc and pads also contribute to the difference magnitude of the maximum von Mises stress.

The proportional graph trends will continue until the stresses reach the ultimate tensile strength (UTS) of disc. At this point, the disc will deform but would not occurred because the UTS value of disc is 210MPa while the typical applied pressure during braking are between 2 to 4 MPa.

4.2.5 Result Verification

The journal Prediction of Disc Brake Contact Pressure Distribution by Finite Element Analysis by Mr. Abd Rahim Abu Bakar [3] has been used as benchmark to validate the obtain results. The maximum von Mises stress gain from 8MPa applied pressure in the journal were compared with the obtain result. The percentage difference of 3D non-moment analysis is 12.97% while moment analysis is 13.11%.

The percentage error is acceptable within the range of 0 – 15%. The error is cause by the difference size applied to the model assembly. This project model is based on the implemented disc brake on front axle of Proton Wira (1998 model) while the dimension of comparison journal doesn't show. The assembly model used in this project contains only brake disc with 2 brake pads while the journal include full assembly of the caliper. The design and properties of the disc are same. The journal use different type of CAE software. From the verification of the result, the project result is trustworthy.

4.3 MODIFICATION AND IMPROVEMENT

The maximum stress is concentrated at the edge of the disc because the brake pads touched the disc at these points. The maximum stress can be prevented if the location of the contact area is changed. The locations of the brake pads can be move a little inside. The contact between brake pads and the edge of the disc can be removed. This modification will slightly reduce the braking force since the angular forces are reduced with the reduction of the radius of pads. The change in the size of pads is needed to allow this modification.

The change in size for pad requires modification to the design of the caliper assembly in order for the new pads to fit in. This analysis is important in the early development stage in manufacturing the disc.

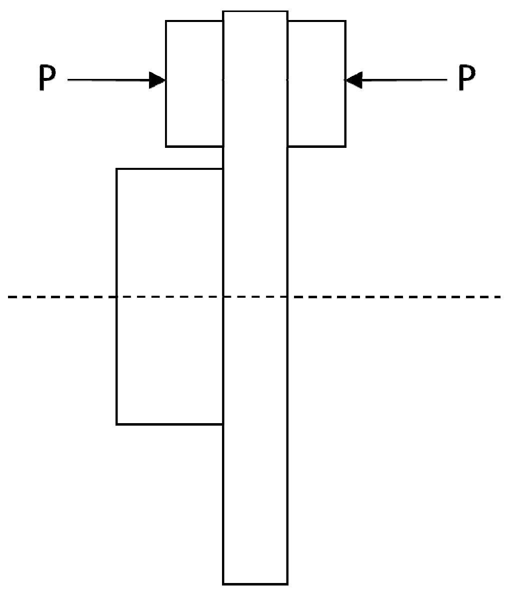


Figure 4.11: Modification on the location of brake pads at the disc

4.4 PROBLEMS AND ERRORS

A lot of assumptions have been made like surface of disc is considered perfect with no damage during manufactured but in real life, this perfection is impossible. There were other parameters that were affecting the stress distribution on disc but cannot be applied for finite element. These parameters such as ambient temperature and dust have major effect on the distribution of the stress and yet, not considered in the finite element analysis. Both sides of pads is assume pressed the disc at the same pressure but not theoretically.

Boundary condition must be correctly placed on the assembly model for analysis in order to get the correct result. Different boundary conditions will give different result and different values. Try and error approach has been done to acquire the correct result benchmarked with the stated journal. The analysis is successful if the warning and error doesn’t occur.

CHAPTER 5

CONCLUSION

5.1 OVERALL CONCLUSIONS

Stress distribution of disc brake during operation has been analyzed and investigated in this project. Analysis is considering the condition of car during static with and without torque from the engine is applied to disc simultaneous with hydraulic pressure is clamped the brake pads to disc. The operation is in static with 5 Nm moment applied to the disc and pressure of 2 to 4 MPa applied to the brake pads that clamped the disc. From the analysis, it is determine that stress concentration exist when the moment is applied. Moment is generated by engine to move car and generated by the weight of the car itself during braking. The stress concentrated at the outer radius of the disc where the defect could occur like conning effect and scratch if fatigue loading is applied. Modification can be made to this region to sustain or at least reduce the rate of deformation of the disc.

This project studies the stress distribution on disc of disc brake during operation on static by simulate in CAE software. From the analysis, the stress is determined concentrated around the outer radius of the disc. For all the stresses experienced by the disc during simulation were not damaging the disc because the ultimate tensile strength is 210MPa while the maximum stress occurred is only 9.0283 N/mm^2. The disc will start to deform gradually if fatigue pressure is applied. This work could help design engineers to design a better disc to obtain a more uniform pressure distribution and subsequently satisfy customers' needs by making disc life longer.

5.2 RECOMMENDATION

Based on the analysis result, several recommendations can be issued to make the analysis more reliable and reduce the percentage error of the analysis. The improvement of the properties of brake disc also can be recommended.

Analysis can be done with full 3-dimentional modeling include with full caliper assembly. The result will be more accurate and less error will obtain. Another CAE tools can be used that are specially made to simulate the disc brake like Simulia ABAQUS to get more reliable results.

Maximum stress is occurred at surface of brake disc base on the maximum stress distribution occurred at this region. By increasing the surface hardness of brake disc, the critical region can sustain more stress concentration and prolong the life span.

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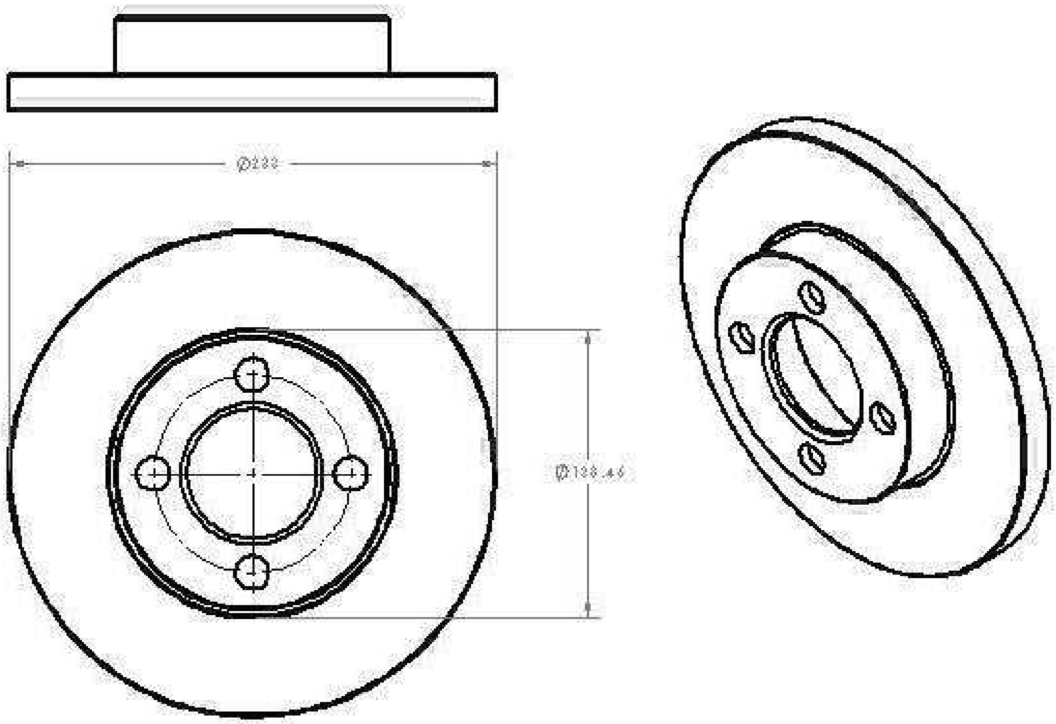
APPENDIX 1

Defect on Brake Disc

APPENDIX 2

Disc Drawing



APPENDIX 3

3 Dimensional View of Analysis