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DESIGN SELECTION OF FLOATING BRAKE CALLIPER MAGNESIUM HYBRID COMPOSITES

CHIA SIEW TING

Report submitted in partial fulfillment of the requirements
for the award of the degree of
Bachelor of Engineering (Hons.) in Manufacturing Engineering

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June 2016

EXAMINER APPROVAL DOCUMENT

We certify that the thesis entitled “DESIGN SELECTION OF FLOATING BRAKE CALLIPER MAGNESIUM HYBRID COMPOSITES” is written by CHIA SIEW TING. We have examined the final copy of this project and in our opinion; it is fully adequate in terms of scope and quality for the award B. Eng. (Hons.) of Manufacturing Engineering. We are here with recommend that it be accepted in fulfilment of the requirement for the B. Eng. (Hons.) of Manufacturing Engineering.

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ABSTRACT

This thesis deals with material selection and design selection of high performance floating brake calliper. The main function of brake system is to decelerate or stop a car. Disc brake system consist of brake rotor, brake pads and brake calliper. Most of the commercial vehicles use brake calliper made of Gray cast iron which possess heavy weight results in high fuel consumption. Another major problem is calliper being deflection during clamping action, known as "bending of bridge" will results in extended pedal travel since additional braking fluid volume is required to compensate for deflections, reduce comfort, driving feelings and safety of vehicle. The demand of Metal Matrix Composites (MMC) is greatly increased in automotive industry since it having a lower density, higher strength and comparable modulus of elasticity as compared to Gray cast iron. The objective of this thesis is to study the advantages of Magnesium hybrid MMC to replace conventional brake calliper and proposed few innovative design alternatives for automotive industry. This is done by creating an original brake calliper and validate for appropriate material using Finite Element Analysis (FEA), followed by select optimum design. In design selection, Quality Function Deployment (QFD) approach was used to rank the design parameters, few alternative designs were created using CatiaV5R17 and analyzed for static structural analysis using FEA. In the end, best floating brake calliper design among those alternative designs was selected using Super Decision software. For further research, these fresh designs could be act as benchmark for further developed and tested for automotive applications.

ABSTRAK

Tesis ini berkaitan dengan pemilihan bahan dan pemilihan reka bentuk prestasi tinggi brek terapung angkup. Fungsi utama sistem brek ialah untuk memperlahan atau memberhenti kereta. Sistem brek cakera terdiri daripada rotor brek, pad brek dan brek angkup. Kebanyakan kenderaan komersial menggunakan brek angkup diperbuat daripada Besi Tuang Kelabu yang mempunyai berat yang tinggi mengakibatkan penggunaan bahan api yang tinggi. Selain itu, masalah utama adalah angkup yang pesongan semasa tindakan pengapitan, dikenali sebagai "lenturan jambatan" akan menyebabkan perjalanan pedal lanjutan akibat daripada jumlah cecair tambahan diperlukan untuk mengimbangi pesongan, mengurangkan keselesaan, memandu perasaan dan keselamatan kenderaan. Permintaan Metal Matrix Composites (MMC) semakin meningkat dalam automotif industri kerana ia mempunyai ketumpatan yang lebih rendah, kekuatan yang lebih tinggi dan modulus keanjalan setanding berbanding Besi Tuang Kelabu. Objektif projek ini adalah untuk mengkaji kelebihan Magnesium hybrid MMC untuk menggantikan angkup brek konvensional dan beberapa alternatif reka bentuk yang inovatif dicadangkan untuk industri automotif. Ini dilakukan dengan menciptakan angkup brek asal dan mengesahkan untuk bahan yang sesuai menggunakan Finite Element Analysis (FEA), diikuti oleh pemilihan reka bentuk optimum. Dalam pemilihan reka bentuk, Quality Function Deployment (QFD) telah digunakan untuk menentukan kedudukan parameter reka bentuk, beberapa reka bentuk alternatif telah dicipta dengan menggunakan CatiaV5R17 dan dianalisis untuk analisis struktur statik dengan menggunakan FEA. Akhirnya, reka bentuk brek terapung angkup terbaik dalam kalangan reka bentuk alternatif lain telah dipilih dengan menggunakan Super Decision software. Untuk kajian lanjut, reka bentuk ini boleh bertindak sebagai penanda aras untuk terus dibangunkan dan diuji untuk aplikasi automotif.

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LIST OF SYMBOLS

F	Force
P	Presure
A	Area of cylinder
D	Diameter
Π	Pi
Σ	Sum
wt%	Percentage of weight
λ	Eigen value

LIST OF ABBREVIATIONS

MMC	Metal Matrix Composite
QFD	Quality Function Deployment
HOQ	House of Quality
CATIA	Computer Aided Three-dimensional Interactive Application
ANSYS	Analysis System
FEA	Finite Element Analysis
AHP	Analytical Hierarchy Process
ASTM	American Society for Testing and Materials
YS	Yield Strength
UTS	Ultimate Tensile Strength

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Product design is an approach of creating new product has become increasingly essential to the survival of manufacturers in today's fast-changing and hypercompetitive environment as reported by (Encyclopedia of Management, 2009). A company may waste their effort, money and time of developing due to wrong design concept. Therefore, it is extremely important to make sure the design is perfect before production.

According to (Maleque and Salit, 2013), there is a direct relationship between material selection and product design. The goal to produce excellent and reliable product only can achieve while both material selection and design fulfil the requirements together. (Jayakody, 2009) has stated that the integrity of a product design can be determined only after complete a systematic material selection procedure. Otherwise, the result it is highly susceptible for failures. A successful product tend to reduce the development cost, offer competitive advantages in the marketplace and also bring profit to the company.

In today's growing automotive industry, every car manufacturers strive to invent new products or enhance existing products for efficient fuel consumption, safety and comfort. (Pishdad, 2012) has mentioned that brake calliper, being an essential part of brake system to decelerate or stop a vehicle. Brake calliper is act as a U-shaped housing that wraps around the brake rotor and is mostly made of cast iron. (Sergent et al., 2014) have highlighted that a successful brake calliper design must be light and stiff to prevent excessive deformation and extended brake pedal travel.

Metal Matric Composite (MMC) are mostly used automotive industry due to their significant improved properties including high specific strength and stiffness, temperature resistance, low thermal expansion coefficient, wear resistance and light weight which appear to offer more advantages over traditional cast iron, as has been proven (Macke et al., 2012).

According to (Encyclopedia of Management, 2009), Quality function deployment (QFD) is being used by company to transform the voice of customer into functional requirements for a product or service to satisfy the customers. QFD is a structured approach that adopt the seven management and planning tools to identify and prioritize customer's expectations quickly and effectively. The House of Quality is a basic design tool of the management method. The foundation of the house of quality is the belief that a product should be designed to reflect customer's desires and tastes. Through this framework, people facing different problems and responsibilities can discuss various design priorities.

1.2 PROBLEM STATEMENT

The current problem of existing brake callipers are made from cast iron which possess heavy weight result in high fuel consumption as has been highlighted by (Pishdad, 2012). As (Sergent et al., 2013) carried out their study, deflection during clamping action is the major problem of a brake calliper, thus will influence the comfortableness of a driver to press brake pedal since more additional braking fluids volume required to compensate the deflection and also safety of the vehicle. Therefore, a successful floating brake calliper design should be light weight, high stiffness and strength to prevent deflection.

1.3 OBJECTIVE OF THE RESEARCH

The primary goal of this project is to select the best design of a Metal Matrix Composite (MMC) brake calliper design. The following are the objectives that have to meet in this research:

i. To compare selected MMC material with conventional brake calliper.
ii. To define and rank the design parameters of brake calliper.
iii. To propose few alternative designs of floating brake calliper and analyse the performance of brake calliper designs based on design parameters.
iv. To evaluate and rank the best brake calliper design based on product performance.

1.4 SIGNIFICANT OF THE RESEARCH

This research emphasize on both material selection and design selection in floating brake caliper design. The significances of this research are:

i. Better understanding of the function of automotive floating brake calliper.
ii. Define the desired design parameters of brake callipers.
iii. Comparison of the performance of proposed conceptual designs of brake calliper based on important design selection parameters.
iv. Select the best design of brake calliper concept among design alternatives.

1.5 SCOPE OF THE RESEARCH

Some software and method will be applied in this research to achieve the goal. The following are the scopes of this this research:

i. Validation of appropriate material for the use of brake caliper using FEA.
ii. Apply Quality Function Deployment (QFD) to rank the design parameters based on product performance.
iii. Modelling few designs of brake calliper using CatiaV5R17 software.
iv. Analyze the product performance of each brake calliper designs using ANSYS software.
v. Evaluate, rank and select best brake calliper design by using Super Decision software.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter, the author was intended to review the journal that related to the project. The keywords like material selection, design selection, Metal Matrix Composite (MMC), floating brake calliper design considerations, Quality Function Deployment (QFD), Finite Element Analysis (FEA), Analytical Hierarchy Process (AHP) are to be reviewed and discussed in order to achieve the objectives of the project.

2.2 BRAKE SYSTEM

(Grayen, 2014) has stated that the main function of brake system is to decelerate or stop a car. There are two types of brake assemblies which are disc brakes and disc drum. **Figure 2.1** presents an illustration of a brake system. Graven also said that disc brake system consist of brake disc or brake rotor, brake pads and brake callipers. An illustration of a disc brake assemblies is shown in **Figure 2.2**.

(Automotive Basics, 2012) has showed the working of braking system in car. When brake pedal is pressed, the brake fluid flows from the master cylinder to the floating brake calliper. The hydraulic pressure act on the piston inside the brake calliper, pushing the brake pads inside against the revolving rotors. When brake pads contact with rotor, friction force generated which tends to reduce the speed and stop ultimately.

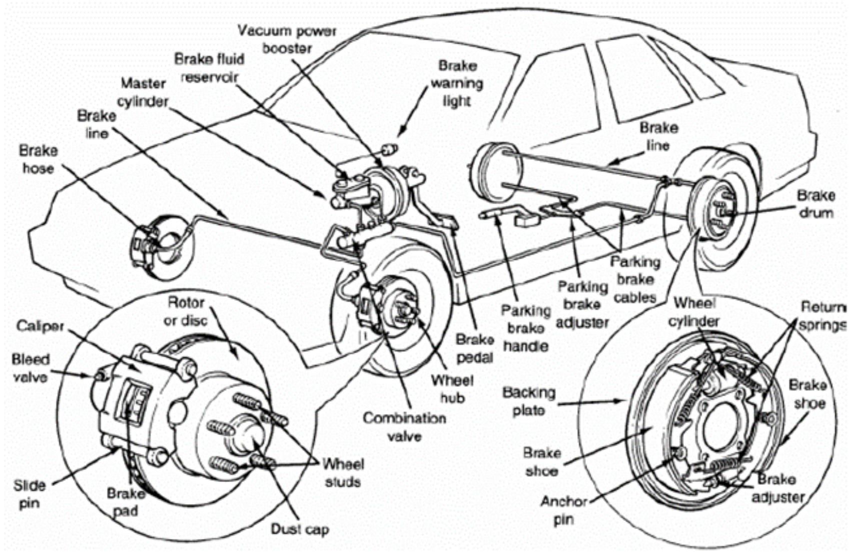


Figure 2.1: An illustration of a brake system

Source: Wagh (2005)

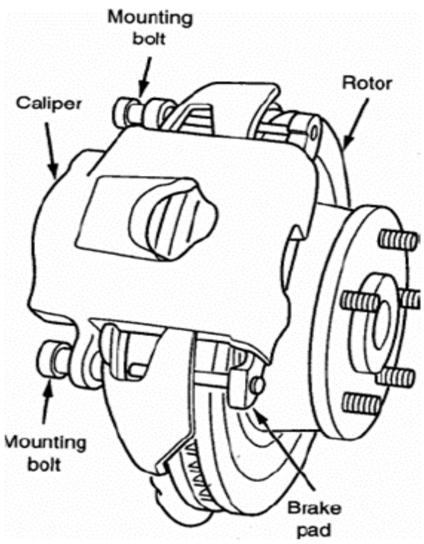
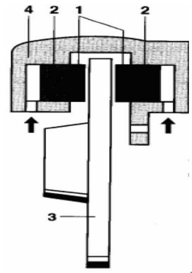


Figure 2.2: An illustration of a disc brake assemblies

Source: Wagh (2005)

2.2.1 Brake Calliper

Brake calliper is classified as fixed calliper and floating calliper. Fixed brake calliper has multiple pistons which is in pair and located on both sides of brake rotor. Calliper body is fixed to the mountings. During braking, hydraulic pressure forces both pistons inwards, pushing the pads against the revolving brake disc, as reported by (Phad et al., 2015). **Figure 2.3** presents an illustration of a fixed brake calliper.

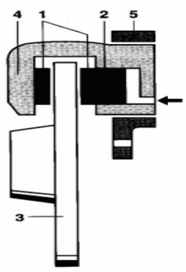


1 Brake pads, 2 Piston, 3 Brake disc, 4 Fixed calliper.

Figure 2.3: An illustration of a fixed brake calliper

Source: Wagh (2005)

Floating brake calliper has one or more pistons and only located on the inboard side of the calliper. Calliper body is mounted on a pin to give cylindrical support and allow to move linearly. During braking, hydraulic pressure forces the piston inwards, pushing the pads against the revolving brake disc. The calliper create a reaction force cause the calliper slide over the pin leading to clamp action on rotor, as mentioned by (Phad et al., 2015). **Figure 2.4** presents an illustration of a floating brake calliper.



1 Brake pads, 2 Piston, 3 Brake disc, 4 Floating calliper, 5 Support.

Figure 2.4: An illustration of a floating brake calliper

Source: Wagh (2005)

2.2.2 Design consideration of brake calliper

(Phad et al., 2015) have mentioned that applied clamping force results in frictional force and generates heat may be transferred to the calliper body through the brake pads. Single piston is preferable due to light weight, less leakage points and also perform the least uneven pad wear as compared to more pistons.

(Ballo et al., 2015) have stated that minimizing the mass and maximizing the stiffness should be primary design considerations. High structural stiffness could prevent uneven wear of brake pads and large deformations of brake calliper results in short pedal travel, improving comfort, driving feelings and safety.

(Sergent et al., 2013) have highlighted the defection problem of calliper. **Figure 2.5** presents an illustration of disc and calliper assemblies. During braking, brake calliper being deflect due to the hydraulic pressure acting on the piston and calliper housing, which is also known as "bending of bridge". **Figure 2.6** presents an illustration of calliper "opening up". This problem will results in extended pedal travel since additional fluid volume is required to compensate for deflections.

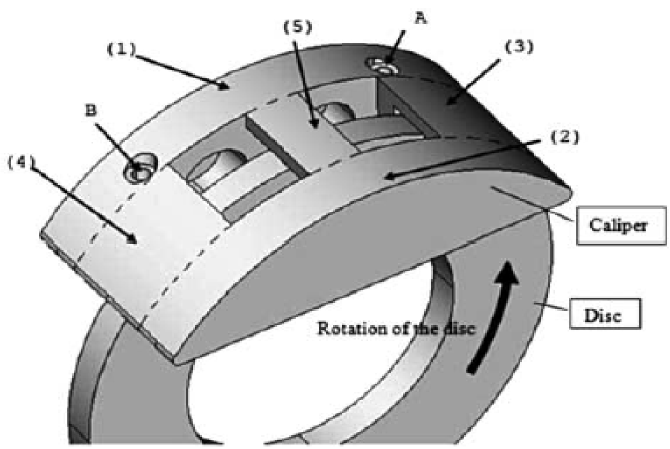


Figure 2.5: An illustration of disc and calliper assemblies

Source: Sergent et al. (2013)

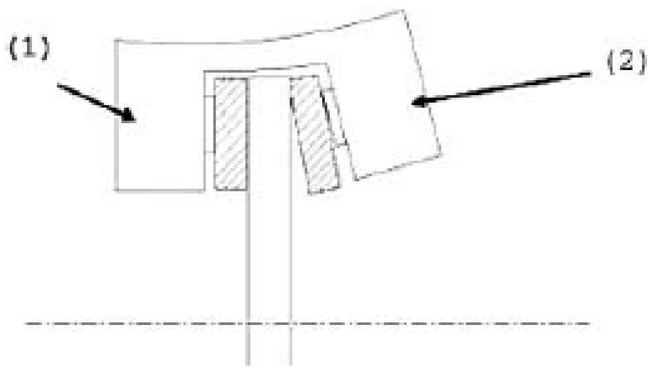


Figure 2.6: An illustration of calliper “opening up”

Source: Sergent et al. (2013)

(Sergent et al., 2013) have investigated the individual and combined features on bridge of brake calliper. He mentioned that bridge design features are the most important in maintaining structural stiffness. Combination of two single features gives the most stiffness improvement. **Figure 2.7** presents an illustration of calliper designs.

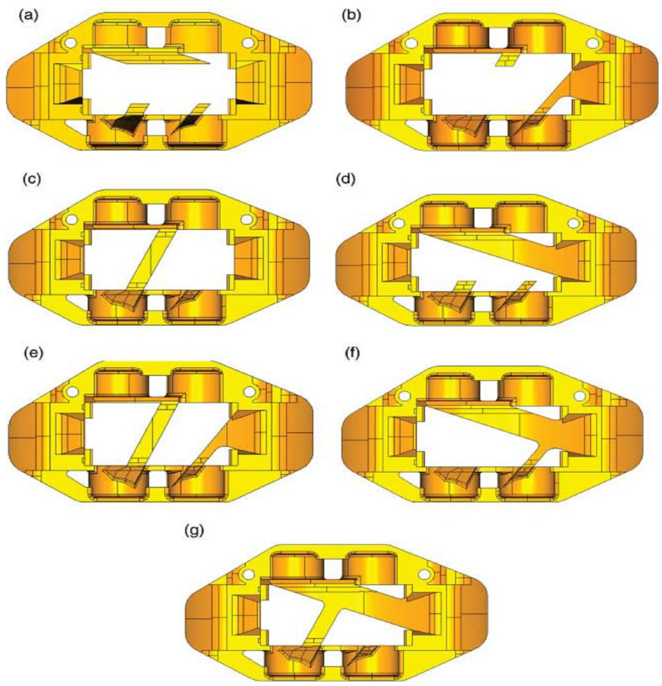


Figure 2.7: An illustration of calliper designs

Source: Sergent et al. (2013)

(Rajaram and Sudharsan, 2005) has demonstrated the optimization of calliper housing by changing certain parameters of original model. They have applied redesign strategies as follow: enlarge the ventilation hole size, parameter "E"; increase the slot thickness, parameter "D"; reduce the bridge thickness, parameter "C", reduce the cylinder outer diameter, parameter "A"; convert bridge fillet to chamfer, parameter "B"; increase the size of the rib near fix hole, parameter "G"; fillet stress concentrated corners, parameter "R". The results revealed that the modified calliper housing reduce the weight almost 20% to the original calliper housing and acceptable under real condition. **Figure 2.8** presents an illustration of designs parameter for calliper housing.

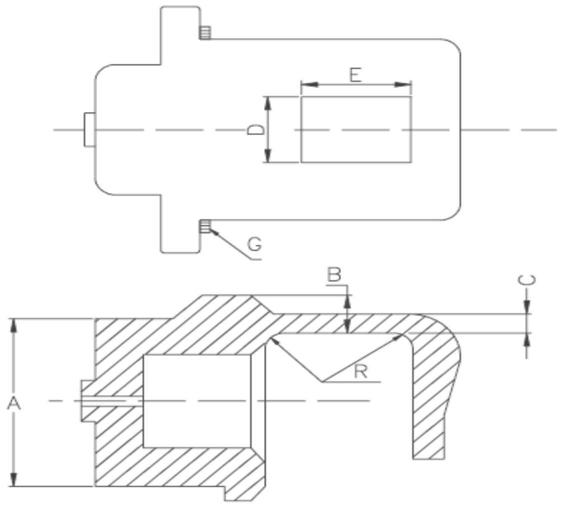


Figure 2.8: An illustration of designs parameter for calliper housing

Source: Rajaram and Sudharsan (2005)

(Stahl and Giese, 2004) have expressed their view that flexural strength can be enhanced by ribs structure on floating brake calliper design whilst weight reduced simultaneously. They described that bifurcation of middle bridge arm 34, for a floating calliper with two actual cylinder 16, 18. The extended fork branches 34a, 34b car inclined at an angle α to the symmetry A, desired range between 3° and 15°. Supporting fingers 26, 28, 30 were aligned and perpendicular to bridge arm 32, 34, 36 respectively to stabilize overall brake system. **Figure 2.9** presents an illustration of perspective view of floating brake calliper. **Figure 2.10** presents an illustration of plan view of floating brake calliper.

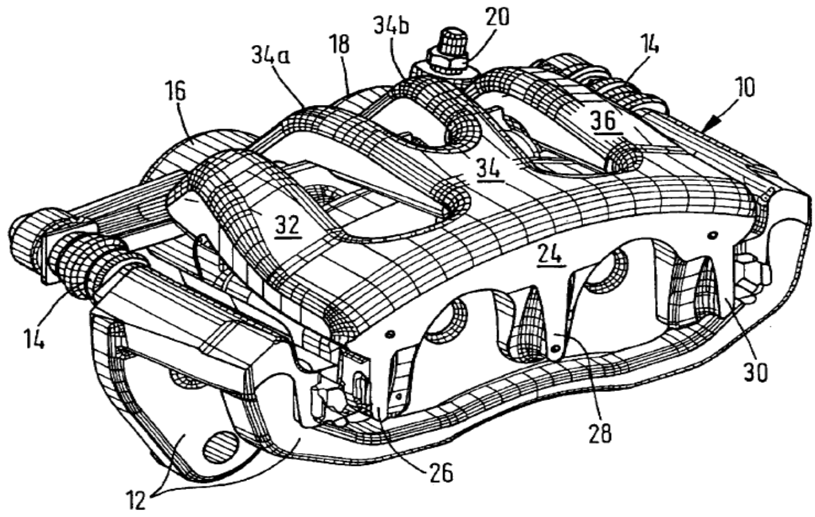


Figure 2.9: An illustration of perspective view of floating brake calliper.

Source: Stahl and Giese (2004)

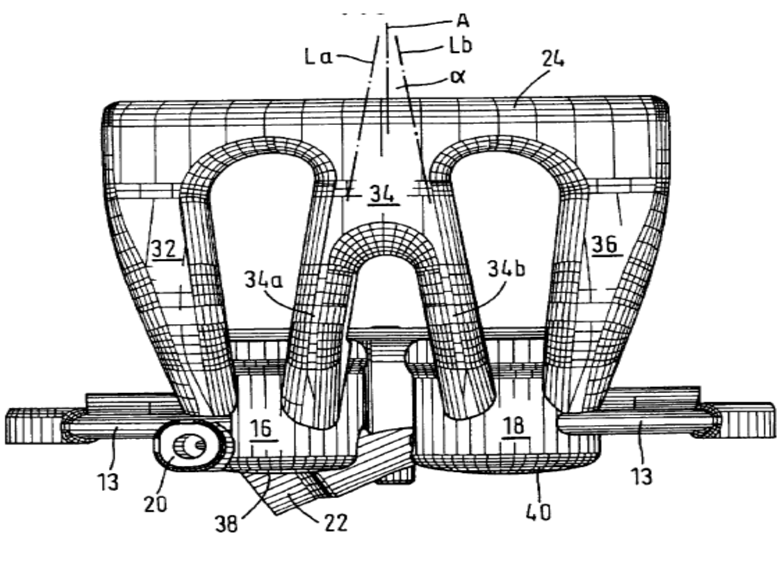


Figure 2.10: An illustration of plan view of floating brake calliper

Source: Stahl and Giese (2004)

Table 2.1 has listed the summary on brake system in this study.

Table 2.1: Review table on brake system

Author	Title of Paper	Contribution
Grayen (2014)	Disc brakes and drum brakes explained.	Brake system is to decelerate or stop a car. Disc brake system consist of brake disc or brake rotor, brake pads and brake callipers.
Phad et al., (2015)	Design and Analysis of a Brake Calliper	Floating brake calliper has one or more pistons and only located on the inboard side of the calliper. Calliper body is mounted on a pin to give cylindrical support and allow to move linearly along its axis. Hydraulic pressure forces the piston inwards, pushing the pads against the revolving brake disc. The calliper create a reaction force cause the calliper slide over the pin leading to clamp action on rotor.
Sergent et al., (2013)	Design optimization of an opposed piston brake calliper	Brake calliper being deflect due to the hydraulic pressure acting on the piston and calliper housing, known as “bending of bridge”. Bridge design features are the most important in maintaining structural stiffness. Combination of two single features gives the most stiffness improvement.
Stahl and Giese (2004)	Floating calliper for a disc brake	Flexural strength can be enhanced by ribs structure on floating brake calliper design whilst weight reduced simultaneously.

2.3 METAL MATRIX COMPOSITES (MMC)

(Groover, 2010) has highlighted that there are main three types of composite materials which are Polymer Matrix Composites (PMC), Metal Matrix Composites (MMC), and Ceramic Matrix Composites (CMC). MMC are commonly used in automotive industry due to their excellent properties.

(Chawla, 2012; Macke et al. 2012, and Jayalakshmi and Gupta, 2015) have highlighted that Metal Matrix Composites (MMC) consist of a metal or an alloy as the continuous matrix and reinforcement materials is embedded and dispersed into metal matrix to enhance the properties and convert to become composite.

(Suresh, 2013) has reported that Metal Matrix Composites (MMC) are widely used in advanced automotive, aerospace and electronics applications due to their excellent specific physical, mechanical, and thermal properties that such as low density, high specific strength, high specific stiffness, high thermal conductivity, good fatigue response, low thermal expansion, good wear resistance and good abrasion.

2.3.1 Metal Matrix materials

As (Jayalakshmi and Gupta, 2015) carried out their study, matrix is the continuous phase and its properties are enhanced by addition of suitable reinforcement. The function of the matrix is to support the reinforcement in certain position. The metallic matrix is very sensitive to any changes in its microstructure by the incorporation of reinforcement would affect the overall properties of the composite.

2.3.1.1 Magnesium alloy as matrix material

(Kumar et al., 2015) have highlighted that the usage of magnesium alloys has considerably increased in automotive sector. They have mentioned that the potential of magnesium alloy as substitution to aluminium alloys and iron alloys. They expressed their view that Mg-Al-Zn alloys are widely used in many applications due to its both high strength and ductility. **Table 2.2** are listed the ASTM code for magnesium's alloying elements. For example, AZ31 Mg alloy contain aluminium (Al) and zinc (Zn) in 3% and 1% respectively. **Table 2.3** listed types of magnesium alloys and their properties. **Figure 2.11** presents an illustration of future directions of Magnesium alloy development for automotive applications.

Table 2.2: An ASTM code for magnesium's alloying elements

Letter	Alloying Element	Letter	Alloying Element
A	Aluminium	L	Lithium
B	Bismuth	M	Maganese
C	Copper	N	Nickel
D	Cadnium	P	Lead
E	Rare Earths	Q	Silver
F	Iron	R	Chromium
H	Thorium	S	Silicon

Source: Kumar et.al (2015)

Table 2.3: Magnesium alloys and their properties

Material	Density (g/cm^3)	UTS (Mpa)	YTS (Mpa)	Fatigue Strength (Mpa)	Hardnes s (BHN)	Coefficien t Thermal Expansio n (µm/m-C)	Thermal Conduct ivity (W/mK)
AZ91	1.81	230	150	97	63	26	72
AM60	1.79	241	131	80	65	26	62
AM50	1.77	228	124	75	60	26	65
AZ31	1.77	260	200	90	49	26	96
ZE41	1.84	205	140	63	62	26	113
EZ33	1.80	200	140	40	50	26.4	100
ZE63	1.87	295	190	79	75	27	109
ZC63	1.87	240	125	93	60	26	122

Source: Kumar et.al (2015)

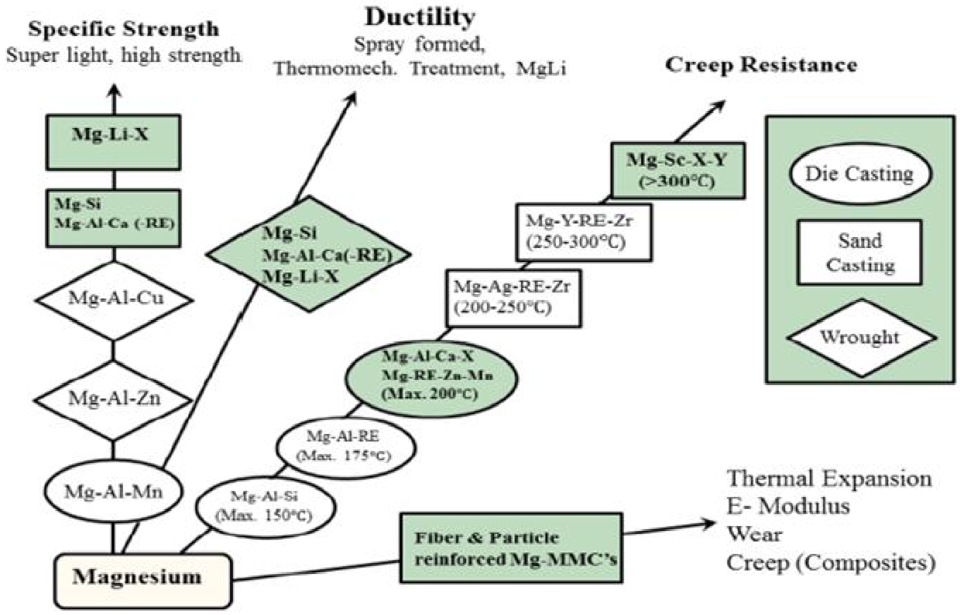


Figure 2.11: An illustration of future directions of magnesium alloy development for automotive applications

Source: Kumar et.al (2015)

(Bettles and Barnett, 2012) have stated that magnesium alloy is the lightest structural metal, it possess same physical and mechanical properties with aluminium alloys and has a density less than one-third of aluminium alloys and one-fourth of ferrous alloys such as cast iron and mild steel. AZ80 and AZ31 offer comparable tensile strength to aluminium extrusion alloy 6061, has shown in **Table 2.4**. Magnesium alloy could be reinforced with reinforcement materials to improve other properties such as elastic modulus.

(Musfirah and Jaharah, 2012) have highlighted that magnesium alloys exhibit greater specific strength as compared to steels and aluminium alloys. Magnesium alloys possess superior physical properties and excellent mechanical properties. For example, high specific strength, good cast ability and machinability. Although magnesium alloys are certainly expensive than aluminium alloys. But, in terms of manufacturing, magnesium alloys are more cost effective due to their better machinability properties. **Table 2.5** listed common magnesium alloys and their applications.

Table 2.4: Comparison of mechanical properties of various automotive materials

Material	Cast Mg		Wrought Mg		Cast Al		Wrought Al		Cast Iron	Steel	
Alloy/grade	**AZ91**	**AM50**	**AZ80**	**AZ31**	**380**	**A356**	**6061**	**5182**	**Class 40**	**Mild Steel Grade 4**	**AHSS**
Process/product	Die cast	Die cast	Extrusion	Sheet	Die cast	P/M cast	Extrusion	Sheet	Sand cast	Sheet	Sheet
Density (g/cm3)	1.81	1.77	1.8	1.77	2.68	2.76	2.7	2.7	7.15	7.8	7.8
Elastic Modulus (GPa)	45	45	45	45	71	72	69	70	100	210	210
Yield Strength (Mpa)	160	125	275	220	159	186	275	235	N/A	180	340
Ultimate Tensile Strength (Mpa)	240	210	380	290	324	262	310	310	293	320	600
Elongation (%)	3	10	7	15	3	5	12	20	0	45	23
Fatigue strength (Mpa)	85	85	180	120	138	90	95	120	128	125	228

Source: Bettles and Barnett (2012)

Table 2.5: Common magnesium alloys and their applications

Alloy designation	Alloying additives	Uses	Basic properties and applications
AZ91	9.0%Al, 0.7%Zn, 0.13%Mn	General casting alloy	Good castability, good mechanical properties
AM60	6.0%Al, 0.15%Mn	High pressure die-casting alloy	Greater toughness and ductility than AZ91, slightly lower strength. Often preferred for automotive structural applications
AM50	Mg-Al system	General casting alloy	Good strength, ductility, energy absorption properties
AE44	Mg-Al-rare earth system	General casting alloy	Better creep behaviour and castability than AE42
AE42	Mg-4 Al2 atomic percent	General casting alloy	Low castability, good creep behaviour
AS41	4.2%Al, 1.0%Si	General casting alloy	Better creep resistance than AZ91 at elevated temperatures
ZE41	4.2%Zn, 1.2%RE, 0.7%Zr	Specialist casting alloy	Rare earth addition improves creep strength at elevated temperatures. Pressure tight.
AZ31	3.0%Al, 1.0%Zn, 0.2%Mn	Wrought magnesium products	Good extrusion alloy
AM20	Mg-Al System	Casting alloy	High ductility, toughness, poop die-castability
AI62	Mg-Al-Sr System	High pressure die-casting	Good thermal and mechanical strength, superior castability, corrosion resistance and creep behaviour

Source: Musfirah and Jaharah (2012)

2.3.2 Reinforcement materials

(Jayalakshmi and Gupta, 2015) have mentioned that the reinforcement is classified as continuous and discontinuous. MMC with discontinuous reinforcements includes particles, whiskers or short fibres have isotropic properties. While continuous reinforcement uses monofilament wires or fibres are dispersed into the matrix in a certain direction, results in anisotropic structure.

According to (Chawla, 2012), metal matrix composites is classified as particle reinforced MMC, short fibre or whisker reinforced MMC and continuous fibre sheet reinforced MMC. **Figure 2.12** presents different types of reinforcement for composites.

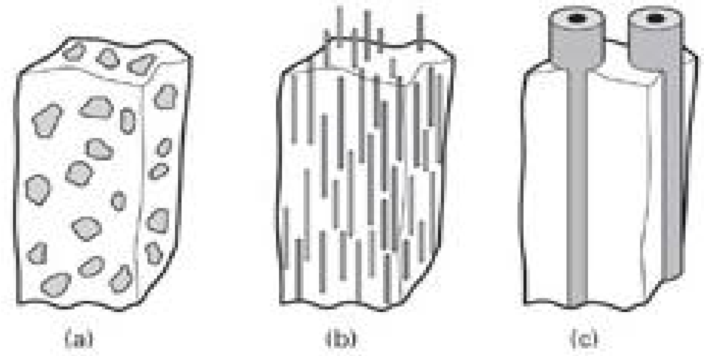


Figure 2.12: An illustration of types of reinforcement for composites (a) particle reinforcement; (b) short fibre or whisker reinforcement; (c) continuous fibre reinforcement.

Source: Chawla (2012)

(Qiang, Z., 2010; Champbell, 2012 and Zhou et al. 2013) stated that particle reinforced MMC are widely used due to their relatively isotropic properties compared to fibre reinforced composites and economic. **Table 2.6** and **Table 2.7** listed the properties of commonly used particulate reinforcements. According to (Qiang, Z., 2010), while adding two or more reinforcement materials to metal matrix, strengthening effect of these hybrid reinforcements is greater as compared to single reinforcement.

Table 2.6: Properties of commonly used ceramic particulate reinforments

Ceramic	Density (g/cm^3)	Elastic modulus (GPa)	Hardness	Compressive strength (MPa)	Thermal conductivity (W/mK)	Coefficient of thermal expansion ($10^{-4}/K$)
SiC	3.21	430	2480	2800	132	3.4
Al_2O_3	3.92	350	2000	2500	32.6	6.8
B_4C	2.52	450	2800	3000	29	5.0
TiC	4.93	345	2150	2500	20.5	7.4

Source: Champbell (2012)

Table 2.7: Properties of commonly used particulate reinforcements

Particulates	Density (g/cm^3)	Elastic modulus (GPa)	Hardness	Bending strength (MPa)	Thermal conductivity (W/mK)	Coefficient of thermal expansion ($10^{-4}/K$)
SiC	3.21	427	2700	400-500	491	4.8
Al_2O_3	-	-	-	-	-	9.0
B_4C	2.52	360-460	2600	300-500	-	5.7
TiC	4.92	345	2150	500	-	7.4
Si_3N_4	3.2	300		900	81.9	2.5-3.2
TiB_2	4.5	-	-	-	-	-
$3Al_2O_3.2SiO_2$	3.17	-	3250	1200		4.2

Source: Zhou et al. (2013)

(Casati and Vedani, 2014) have reported that addition of nano-particles reinforced Metal Matrix Composites are being studied in recent years, due to their promising properties are suitable for the used in functional and structural applications.

According to (Macke et al., 2012), advanced Metal Matrix Micro- and Nano-Composites can effectively reduce mass, improve reliability and efficiency. **Table 2.8** are listed MMC being developed for use in automotive applications.

Table 2.8: MMC being developed at university of Wisconsin-Milwaukee for use in automotive applications

Automotive Applications	**Required properties**	**Materials**
Connecting rods, brake rotors, brake callipers	High strength	Micro and Nano MMCs reinforced with SiC or Al_2O_3 particles, carbon nanotubes (CNT), carbon or Nextel fibers, and in-situ ceramics

Source: Macke et.al (2012)

2.3.2.1 Micro particles hybrid reinforcement

(Girish et al., 2015) have studied the wear behaviour of AZ91 magnesium alloy hybridized with both micro-sized Silicon Carbide (SiC) and Graphite (Gr) particle reinforcements. Graphite was enhance the hardness and strength. The results revealed that the wear resistance of the developed composites were better than unreinforced alloy.

(Hadnoorkar and Lathe, 2014) have investigated the wear properties of AZ61 magnesium alloy reinforced with Silicon Carbide (SiC) and Aluminium Oxide (Al_2O_3) particulates during sliding. SiC and Al_2O_3 particles are commonly chosen as reinforcement in Mg because of their low cost and easy availability. The results showed that AZ61 reinforced with 3% SiC&1% Al_2O_3 exhibit superior wear resistance as compared to magnesium alloy AZ61 reinforced with 1% SiC&3%Al_2O_3.

2.3.2.2 Micro-Nano particles hybrid reinforcement

(Jayakumar et al. 2012 and Indhu and Sooryaprakash, 2015) have reported that magnesium-based materials were low ductility and fracture resistance have limit widespread applications. Adding of nano-sized particulates in magnesium can solve these limitations by showing excellent combination of both ductility and strength.

(Casati and Vedani, 2014) have highlighted that Metal Matrix Nano Composites imparted good hardness mechanical strength, wear resistance, creep behaviour and damping properties as a result of optimization of the particle dispersion. Metal Matrix Nano Composites were widely used in industrial applications.

(Nguyen et al., 2012) have studied the microstructure and mechanical behaviour of magnesium alloy AZ31 hybridized with nano-sized Alumina (Al_2O_3) to improve the ductility and micro-sized Copper (Cu) particulates to enhance the microstructural characteristics, hardness and strength of AZ31 alloy which synthesized through the technique of disintegrated melt deposition. 0.2%YS, UTS and failure strain (%) to about 300MPa, 350MPa and 8.5%, respectively were achieved with addition of 2.84wt-% Al_2O_3 and 17.08wt-% Cu shown in **Table 2.9**.

Table 2.9: Results of tensile properties of samples

Material	**Yield Strength (MPa)**	**Ultimate Tensile Strength (MPa)**	**Failure Strength (%)**
AZ31	180±4	265±7	10.9±2.4
AZ31-1.5Al_2O_3	219±4	295±8	15.0±2.3
AZ31-2Cu	238±8	298±6	4.50±0.5
AZ31-2Cu-1.5Al_2O_3	250±11	301±11	13.5±2.1
AZ31-4Cu	265±8	308±9	1.90±0.4
AZ31-4CU-1.5Al_2O_3	300±12	350±14	8.50±1.6

Source: Nguyen et al. (2012)

(Rashad et al., 2015) have investigated the effect of the hybridizing of micro-sized Alumina (Al_2O_3) and nano-sized Silicon Carbide (SiC) particulate reinforcements on the AZ31 magnesium alloy synthesized using powder metallurgy technique. They mentioned that Alumina (Al_2O_3) is used to enhance the mechanical strength, corrosion resistance and fracture strain value whilst Silicon Carbide (SiC) is used to increase the mechanical strength. AZ31 reinforced with 1.5Al_2O_3–1.0SiC exhibit the best 0.2%YS, UTS and failure strain (%) to about 230MPa, 333MPa and 4.32%, respectively among other formulations after heat treatment process shown in **Table 2.10**.

Table 2.10: Tensile properties of developed composites before and after heat treatment

Material	**Yield Strength (MPa)**	**Ultimate Tensile Strength (MPa)**	**Failure Strength (%)**
Before heat treatment			
AZ31	166±3.8	269±3.1	16.90±1.6
AZ31-1.5Al_2O_3-0.2SiC	198±4.1	293±5.0	10.58±2.0
AZ31-1.5Al_2O_3-0.5SiC	208±3.8	306±3.8	07.54±1.8
AZ31-1.5Al_2O_3-1.0SiC	230±2.5	322±2.5	04.32±1.3
After heat treatment			
AZ31	175±2.8	282±3.8	17.42±1.2
AZ31-0.2Al_2O_3-0.2SiC	174±3.0	275±5.9	16.50±1.8
AZ31-0.5Al_2O_3-0.2SiC	188±2.6	305±5.3	13.51±2.0
AZ31-1.0Al_2O_3-0.2SiC	196±5.7	311±4.8	14.75±2.1

Source: Rashad et al. (2015)

(Shen et al., 2015) have investigated AZ31 magnesium alloy reinforced with different ratios of micro-sized SiCp and nano-sized SiCp synthesized using semisolid stirring assisted ultrasonic vibration method. They concluded that M14:N1 composite which total volume fraction equal to 15% exhibit better 0.2%YS, UTS and failure strain (%) to about 300MPa, 380MPa and 3.2% as compared to other composites shown in **Figure 2.13.**

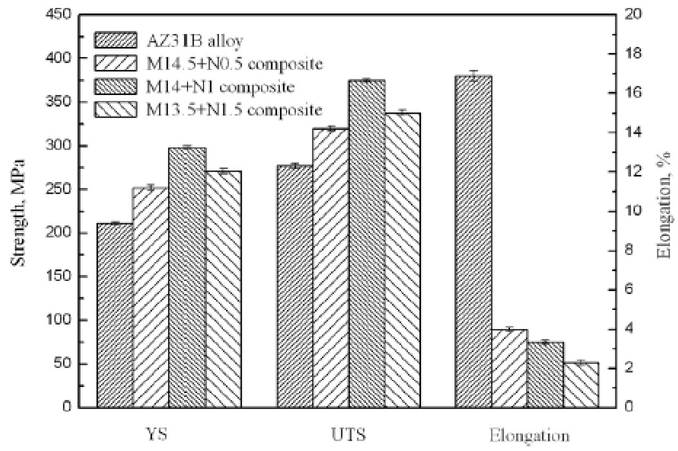


Figure 2.13: An illustration of tensile properties of AZ31 alloy and SiCp/AZ31B composites after hot extrusion

Source: Shen et al. (2015)

2.3.3 Potential of AZ31-14.0SiC$_{micro}$ 1.0SiC$_{nano}$ as brake calliper material

For material selection for brake calliper body, the material of a brake calliper body must be rigid to allow less deflection, and should be light to reduce the final weight of assembly. Therefore, the important properties considered for selection of the material must be low density, high stiffness and high strength properties. The brake calliper body subjected to high stresses, some ductility is required to prevent brittle fracture. It is hard to optimize because when ductility increase, the strength will decrease.

Magnesium alloy is selected as metal matrix because its density less than one-fourth that of ferrous alloys such as cast iron and mild steel and offers similar mechanical and physical properties as aluminium alloys with about one third mass saving. Magnesium alloys offer excellent combinations of mechanical and physical properties, such as high specific strength, high damping capacity, good cast ability and excellent electromagnetic shielding properties as compared to other alloys. Although material cost for magnesium alloys are certainly more costly than aluminium alloys, however, magnesium alloys are more cost effective in terms of manufacturing due to their better machinability properties.

Many researchers have tried to use different types with micro-sized and nano-sized of hybrid reinforcement to enhance the mechanical properties of magnesium alloy, which have been studied by (Nguyen et al. 2012; Rashad et al. 2015 and Shen et al. 2015). If we compare their studies, they were using AZ31 as metal matrix. Mg-Al-Zn alloys offer both strength and ductility at room temperatures with greater flexibility in many applications, this statement is supported by (Kumar et al., 2015).

Metal matrix reinforced with micro particles usually show improved strength, however, ductility reduced have limit widespread applications. The mechanical properties were further enhanced by adding of nano-sized particles to alloy matrix whilst ductility is still maintained. Silicon Carbide (SiC) are selected as reinforcement particulates for brake calliper body owing to their properties fulfil to the material requirements, low cost and easy availability.

Silicon Carbide (SiC) is the most common used as a reinforcement particulates due to its low density, high hardness and high thermal conductivity of magnesium based composites. Besides, it possess high modulus of elasticity as compared to other particulates reinforcement which exhibit high stiffness of the composites, as shown in **Table 2.6 and Table 2.7**.

Therefore, AZ31-14.0SiC_{micro}-1.0SiC_{nano} is selected as the material for brake calliper body. Furthermore, this composite consist the lowest volume fraction as compared to other composites, which significantly reduce the weight, hence fulfil the requirement of a brake calliper.

Table 2.11 has listed the summary on Metal Matrix Composites (MMC) in this study.

Table 2.11: Review table on Metal Matrix Composites (MMC)

Author	Title of Paper	Contribution
Jayalakshmi and Gupta (2015)	Metallic Amorphous Alloy Reinforcements in Light Metal Matrices	Metal Matrix Composites (MMC) consist of a metal or an alloy as the continuous matrix and reinforcement materials is embedded and dispersed into metal matrix to enhance the properties.
Suresh (2013)	Fundamentals of metal-matrix composites	Metal Matrix Composites (MMC) are widely used in advanced automotive, aerospace and electronics applications due to their excellent specific mechanical, physical, and thermal properties.
Kumar et.al (2015)	Magnesium and Its Alloys in Automotive Applications.	The usage of magnesium alloys has considerably increased in automotive sector. Mg-Al-Zn alloys are widely used in many applications due to its both high strength and ductility.
Bettles and Barnett (2012)	Advances in wrought magnesium alloys: Fundamentals of processing, properties and applications.	Magnesium alloy is the lightest structural metal, it possess same physical and mechanical properties and has a density less than one-third of aluminium alloys and one-fourth of ferrous alloys such as cast iron and mild steel.
Zhang Qiang (2010)	Development of Hybrid Mg-based Composites	Hybrid reinforcements have greater strengthening effect than single reinforcement.

Macke et al. (2012)	Metal matrix composites offer the automotive industry an opportunity to reduce vehicle weight, improve performance.	Metal Matrix Micro- and Nano-Composites can effectively reduce mass, improve reliability and efficiency.
Nguyen et al. (2012)	Simultaneous effect of nano-Al and micrometre Cu particulates on microstructure and mechanical properties of magnesium alloy AZ31.	Studied the mechanical behaviour of magnesium alloy AZ31 hybridized with nano-sized Alumina (Al_2O_3) and micro-sized Copper (Cu). 0.2%YS, UTS and failure strain (%) to about 300MPa, 350MPa and 8.5%, respectively were achieved with addition of 2.84wt-% Al_2O_3 and 17.08wt-% Cu.
Rashad et al. (2015)	Effect of alumina and silicon carbide hybrid reinforcements on tensile, compressive and microhardness behavior of Mg–3Al–1Zn alloy.	Investigated the effect of the hybridizing of micro-sized Alumina (Al_2O_3) and nano-sized Silicon Carbide (SiC) particulate reinforcements on the AZ31 magnesium alloy. 1.5 Al_2O_3–1.0SiC exhibit the best 0.2%YS, UTS and failure strain (%) to about 230MPa, 333MPa and 4.32%, respectively.
Shen et al. (2015)	Processing, microstructure and mechanical properties of bimodal size SiCp reinforced AZ31B magnesium matrix composites. Journal of Magnesium and Alloys	Investigated AZ31 magnesium alloy reinforced with different ratios of micro-sized SiCp and nano-sized SiCp. They concluded that M14:N1 composite which total volume fraction equal to 15% exhibit better 0.2%YS, UTS and failure strain (%) to about 300MPa, 380MPa and 3.2%.

2.4 MODELLING AND ANALYSING OF BRAKE CALLIPER DESIGN

CATIA software is used to generate 3D model. The brake calliper alternative designs are imported to ANSYS software and analysed using ANSYS software.

2.4.1 Finite Element Analysis (FEA) from Analysis System software (ANSYS)

(Phad et al., 2015) have studied analysis and optimization of brake calliper. A floating brake calliper model was created using Pro ENGINEER and analysed its performance under normal conditions neglecting the thermal effects using ANSYS 14.0. Al 7075 was used as material for brake calliper body. Mesh size of 0.84 with tetra element size of 0.6 mm was obtained. Loads were applied to the calliper body including reaction force due to fluid pressure, reaction force due to clamping force and frictional force on pads. Besides, cylindrical support is given at the mountings. Stress distribution and deformation results from static structural analysis. **Figure 2.14** presents an illustration of loads and support subjected on calliper body.

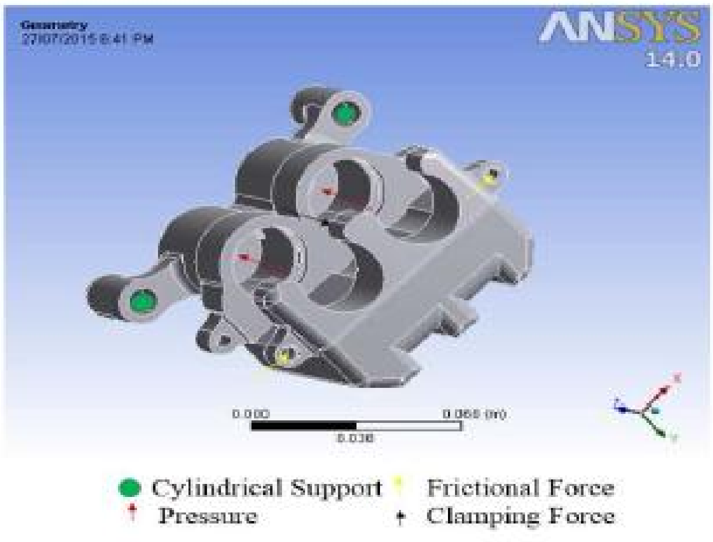


Figure 2.14: An illustration of loads and support subjected on calliper body

Source: Phad et al. (2015)

(Rajaram and Sudharsan, 2005) have analysed the deflection of calliper housing before and after redesign under different fluid pressure of 7, 15, and 30MPa using FEA. 10 noded Tetrahedron with varying mesh size was obtained. Fixed boundary condition and symmetry boundary condition were applied to the calliper body. Loads including reaction force due to fluid pressure and reaction force due to clamping force. Maximum stress, maximum deflection and housing deflection results from FEA. **Figure 2.15** presents an illustration of boundary and force applied on FEA model.

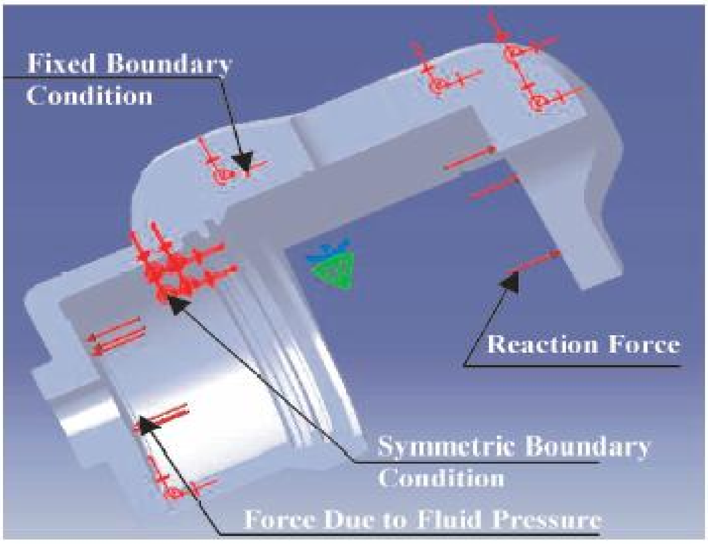


Figure 2.15: An illustration of boundary and force applied on FEA model

Source: Rajaram and Sudharsan (2005)

Table 2.12 has listed the summary on Finite Element Analysis (FEA) in this study.

Table 2.12: Review table on Finite Element Analysis (FEA)

Author	**Title of Paper**	**Contribution**
Phad et al. (2015)	Design and Analysis of a Brake Calliper	Mesh size of 0.84 with tetra element. Loads were applied to the calliper body including reaction force due to fluid pressure, reaction force due to clamping force and frictional force on pads. Cylindrical support is given at mountings. Stress distribution and deformation results from static structural analysis.
Rajaram and Sudharsan (2005)	Optimization of calliper housing using FEM	10 Noded Tetrahedron with varying mesh size was obtained. Loads including reaction force due to fluid pressure and reaction force due to clamping force. Maximum stress, maximum deflection and housing deflection results from FEA.

2.5 MULTIPLE CRITERIA DECISION MAKING (MCDM) IN DESIGN SELECTION

In this study, Quality Function Deployment (QFD) was used to translate customer needs into technical requirements for brake calliper. QFD is a well-known technique used for designing products or services to reflect customer requirements. While Super Decision software based on Analytical Hierarchy Process (AHP) method helps to make decision when deals with problem with many criteria. Super Decision software was used to select the best floating brake calliper among alternative designs.

2.5.1 Quality function deployment (QFD)

(Jaiswal, 2012) have highlighted that Quality Function Deployment (QFD) is a method applied in the beginning stages of the design phase to transform customer demands into technical requirements, to deploy the functions forming quality and approaches for obtaining the design quality into components and subsystems, finally define elements of the fabrication method.

(Kazemzadeh, 2009 and Chen et al. 2012) have reported that Quality Function Deployment (QFD) is a well-known technique used for designing products or services to reflect customer requirements, as “Voice of Customer”. House of Quality (HOQ), being the first phase of QFD, is the fundamental and strategic importance in the QFD method. The function of HOQ is to translate customer needs into technical requirements based on product performance. HOQ was enable a decision maker to set performance targets for a product or service by using a weighted-sum multi-objective decision criterion, benchmarking analysis and technical importance ranking. **Figure 2.16** presents an illustration of four QFD matrices and **Figure 2.17** presents an illustration of House of Quality chart.

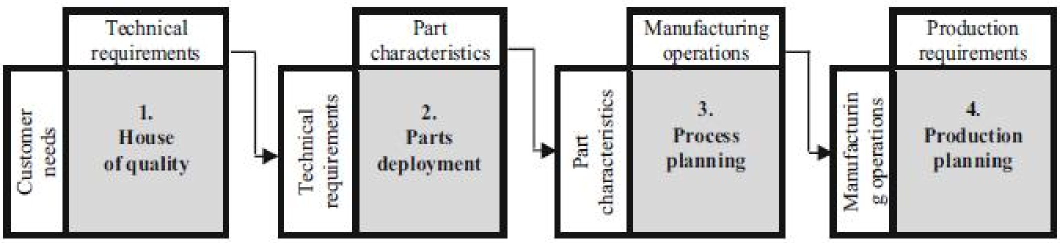


Figure 2.16: An illustration of four QFD matrices

Source: Kazemzadeh (2009)

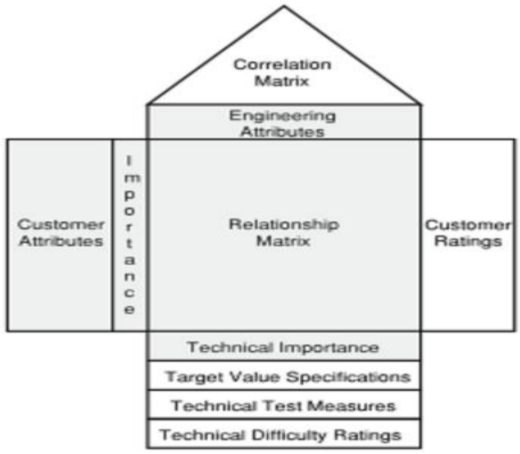


Figure 2.17: An illustration of House of Quality chart

Source: Chen et al. (2012)

(Kazemzadeh, 2009) have highlighted seven basic steps are required to construct a HOQ. The first step is to identify what customer requirements for a floating brake calliper. Second step is to determine the relative importance of customer needs. Third step is to carried out competitive analysis or benchmarking. Forth step is to determine technical requirements or design parameters response to the customer needs. Fifth step is prepare the relationship matrix between customer requirements and technical requirements. Sixth step is prepare the correlation matrix among the technical requirements. Seventh step is rank the technical requirements and defining targets. **Figure 2.18** presents an illustration of House of Quality chart.

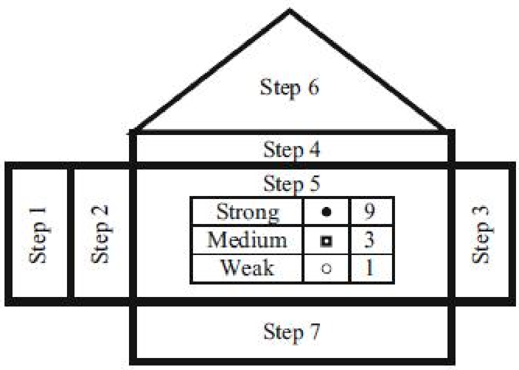


Figure 2.18: An illustration of House of Quality chart with clear steps

Source: Kazemzadeh (2009)

(Padagannavar, P., 2016) have highlighted the application of QFD on a car dashboard. The specification for choosing a dashboard unit is analysed with customer's preference and converted into engineering characteristics. The voice of customer is taken as an initial step and rated on importance and the house of quality diagram is figured out. QFD is a perfect method to solve the current problem and particularly the house of quality matrix which is effective approach to satisfy the customer expectation and design the product accordingly. **Figure 2.19** presents an illustration of House of Quality chart for design of car dashboard.

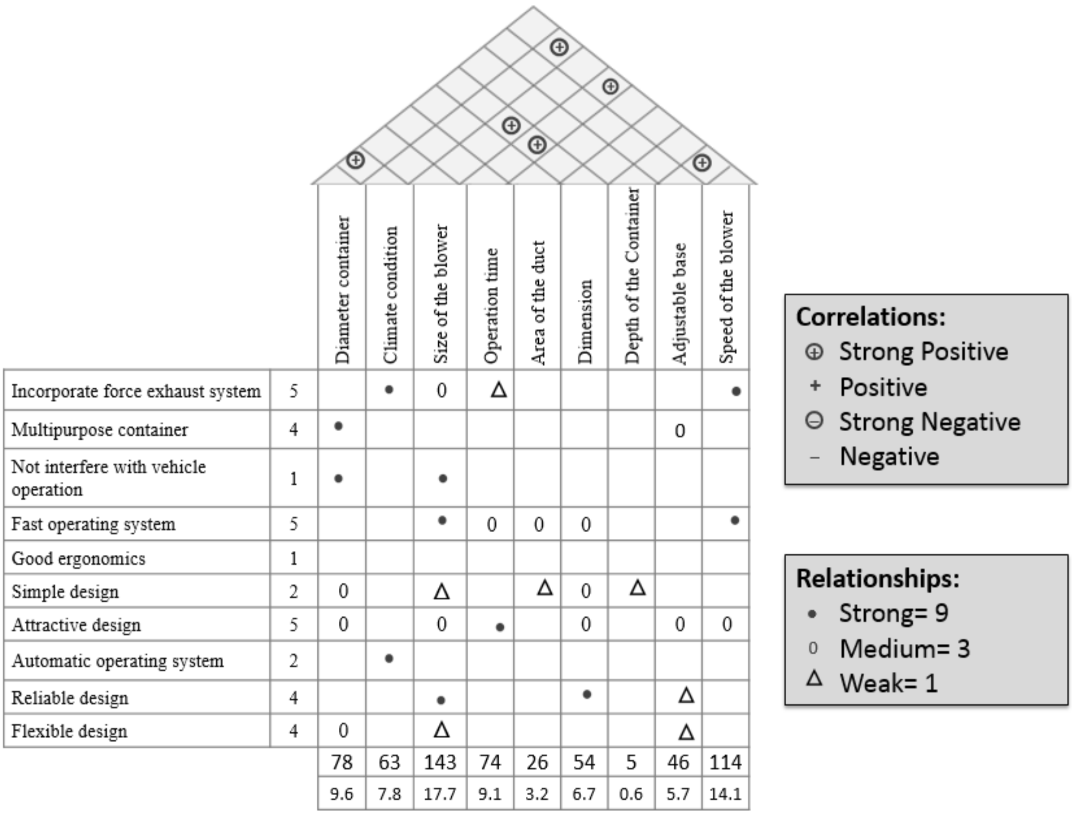


Figure 2.19: An illustration of House of Quality chart for design of car dashboard

Source: Padagannavar, P. (2016)

Table 2.13 has listed the summary on Quality Function Deployment (QFD) in this study.

Table 2.13: Review table on Quality Function Deployment (QFD)

Author	**Title of Paper**	**Contribution**
Kazemzadeh (2009)	Integration of marketing research techniques into house of quality and product family design.	Quality Function Deployment (QFD) is a well-known technique used for designing products or services to reflect customer requirements. House of Quality (HOQ), being the first phase of QFD, is the fundamental and strategic importance in the QFD method.
Chen et al. (2012)	Decision-based design: Integrating consumer preferences into engineering design.	QFD was developed to link the product planning directly to the "Voice of Customer". The function of HOQ is to translate customer needs into technical requirements based on product performance. HOQ was enable a decision maker to set performance targets for a product or service by using a weighted-sum multi-objective decision criterion, benchmarking analysis and technical importance ranking.
Padagannavar, P. (2016)	Automotive product design and development of car dashboard using quality function deployment.	Highlighted the application of QFD on a car dashboard. QFD is a perfect method to solve the current problem and particularly the house of quality matrix which is effective approach to satisfy the customer expectation and design the product accordingly.

2.5.2 Analytical Hierarchy Process (AHP)

(Ishizaka and Labib, 2011) have stated that AHP is a Multi Criteria Decision Making (MCDM) method helping a decision-maker deal with a complicated problem which consist of various subjective and conflicting criteria. Several AHP supporting software packages have been established nowadays including Expert ChoiceDecision Lens, Superdecision, HIPRE 3+, RightChoiceDSS, Criterium, EasyMind, Questfox, ChoiceResults, AHPProject, 123AHP, Excel template.

(Sivaraos et al., 2014) have used Analytical Hierarchy Process (AHP) as a decision making method to determine the optimum keyless grill locking system among three alternative designs concept. **Figure 2.20** presents an illustration of hierarchy for the keyless grill locking system concept selection problem. **Table 2.14** listed overall score for each design concept.

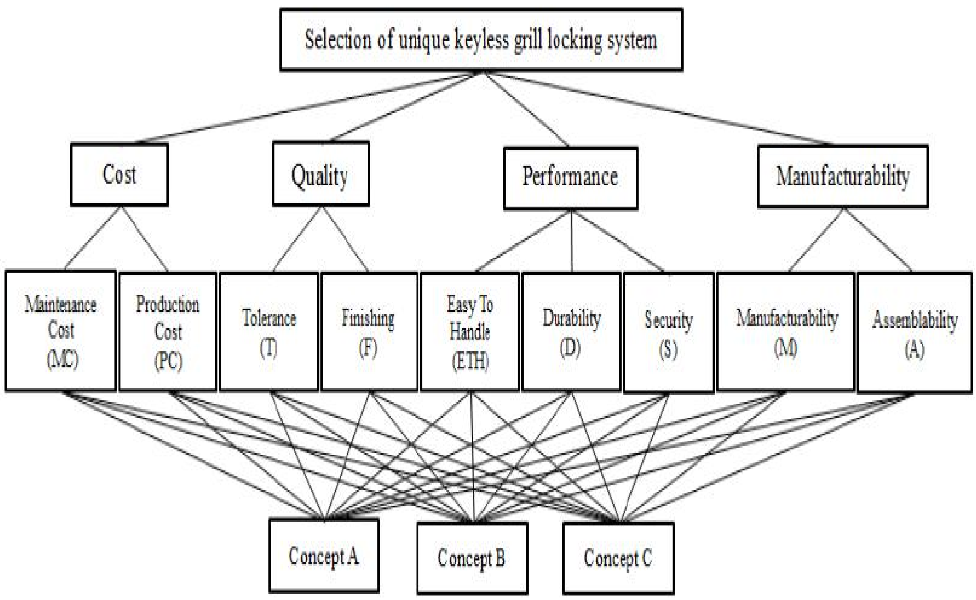


Figure 2.20: An illustration of hierarchy for the keyless grill locking system concept selection problem

Source: Sivaraos et al. (2014)

Table 2.14: Overall score for each design concept.

Sub criteria	Concept A	Concept B	Concept C
Maintenance cost	0.0234	0.0544	0.2042
Production cost	0.0160	0.0416	0.0364
Tolerance	0.0299	0.0664	0.1911
Finishing	0.0075	0.0111	0.0390
Easy to handle	0.0092	0.0161	0.0420
Durability	0.0452	0.0057	0.0164
Security	0.0097	0.0023	0.0105
Manufacturability	0.0218	0.0055	0.0342
Assemblability	0.0225	0.0063	0.0327
Preference	0.1852	0.2094	0.6064
Ranking	3	2	1

Source: Sivaraos et al. (2014)

(Hambali et al., 2012) have used Analytical Hierarchy Process (AHP) as a decision making method to determine the most appropriate automotive housing side mirror design concept among five alternative designs concept. **Figure 2.21** presents an illustration of design options of housing side mirror.

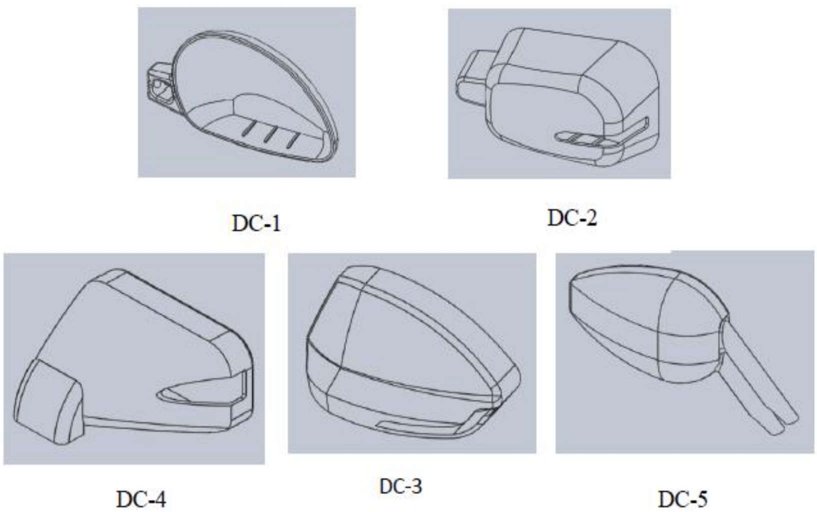


Figure 2.21: An illustration of design options of housing side mirror

Source: Hambali et al. (2012)

(Hambali et al., 2009) have proposed the use of Analytical Hierarchy Process (AHP) in the conceptual design stage to select the most appropriate automotive composite bumper beam design concept among eight alternative designs using Expert Choice software based on AHP methodology. **Figure 2.22** presents an illustration of design options of bumper beam.

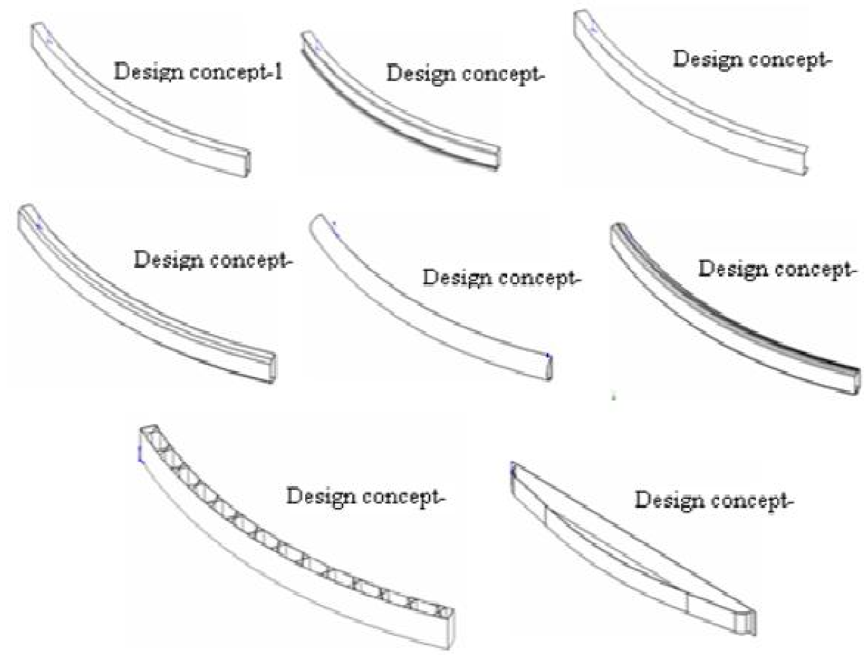


Figure 2.22: An illustration of design options of bumper beam

Source: Hambali et al. (2009)

Table 2.15 has listed the summary on Analytical Hierarchy Process (AHP) in this study.

Table 2.15: Review table on Analytical Hierarchy Process (AHP)

Author	**Title of Paper**	**Contribution**
Ishizaka and Labib (2011)	Review of the main developments in the analytic hierarchy process.	AHP is a Multi Criteria Decision Making (MCDM) method helping a decision-maker deal with a complicated problem which consist of various subjective and conflicting criteria.
Sivaraos et al. (2014)	AHP Based Decision-Making in Concept Selection of Keyless Grill Locking System	Used AHP to determine the optimum keyless grill locking system among three alternative designs concept.
Hambali et al. (2012)	Development of Conceptual Design of Car Housing Side Mirror using Integrated Approach	Used AHP to determine the most appropriate automotive housing side mirror design concept among five alternative designs concept.
Hambali et al. (2009)	Application of Analytical Hierarchy Process in the design concept selection of automotive composite bumper beam during the conceptual design stage	Used AHP to select the most appropriate automotive composite bumper beam design concept among eight alternative designs.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This study has deal with two parts, material selection and design selection of floating brake calliper. After validate for appropriate material, followed by select optimum design. In design selection, it involve four main stages. Firstly, apply QFD (Quality Function Deployment) approach to link the relationship between customer needs and design parameters and rank the design parameters based on product performance. Secondly, modelling of different 3D floating brake calliper designs using 3D modelling software, CatiaV5R17. Third stage is analyse the models based on important design selection parameters using Finite Element Analysis (FEA) via ANSYS simulation software. Forth stage is evaluate and select the best floating brake calliper design among those alternative designs using Analytical Hierarchy Process (AHP) software.

3.2 METHODOLODY

3.2.1 Material selection

A 3D floating brake calliper with actual dimensions for the model PROTON WIRA is created. This original model is use for validation on material chosen. Both Gray cast iron and Magnesium hybrid MMC, AZ31-14.0SiC_{micro}-1.0SiC_{nano} brake calliper are analysed for static structural analysis using ANSYS 15.0 workbench. Design parameters including total deformation, equivalent von misses stress and equivalent elastic strain are determined from FEA results. Through the comparison on both product performance, we can know which materials is considered better for selection of brake calliper. **Figure 3.1** presents an illustration of flowchart for methodology in material selection.

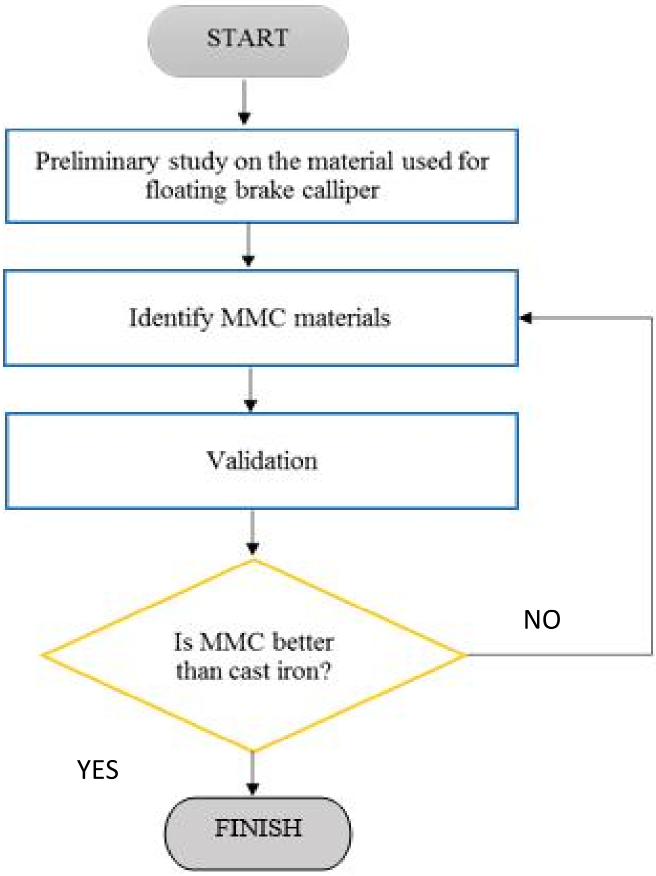


Figure 3.1: Flowchart for methodology in material selection

3.2.2 Design selection

After determine the material used, the next part is design selection to select optimum floating brake calliper design based on product performance. A successful brake calliper design only can achieved while both material selection and design fulfil the requirements to perform high product performance. **Figure 3.2** presents an illustration of flowchart for methodology in design selection.

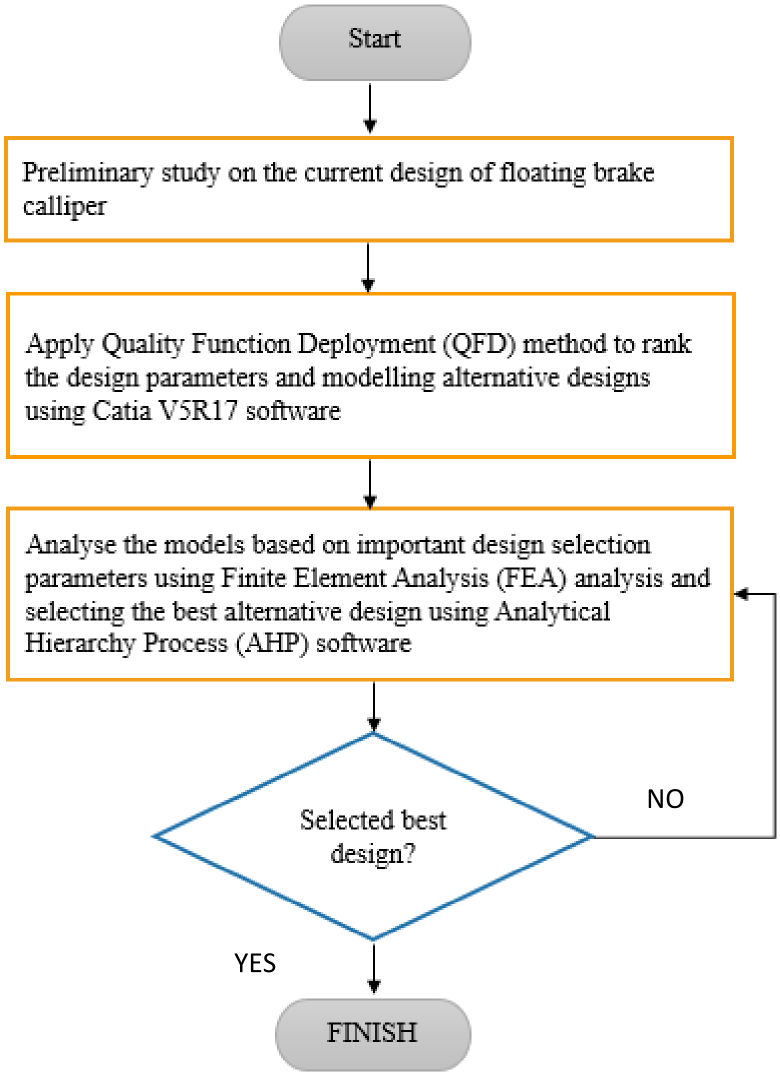


Figure 3.2: Flowchart for methodology in design selection

3.2.2.1 Application of QFD (Quality Function Deployment)

QFD (Quality Function Deployment) is a method to link the relationship between customer's needs and product performance. The House of Quality (HOQ) provide a framework with clear steps to rank the design parameters based on product performance. The first step is to identify customer requirements for a floating brake calliper. Second step is to determine the relative importance of customer needs. Third step determine design parameters based on product performance or how the product response to the customer needs. Fourth step is prepare the relationship matrix between customer requirements and product performance. Fifth step is prepare the correlation matrix among the technical requirements. Sixth step is rank the technical requirements according importance rating. **Figure 3.3** presents an illustration of House of Quality (HOQ) chart of floating brake calliper.

The importance rating based on HOQ is expressed as in **Eq. (3.1).**

$$\text{Importance rating} = \Sigma\,(\text{Priority} \times \text{Relationship}) \quad (3.1)$$

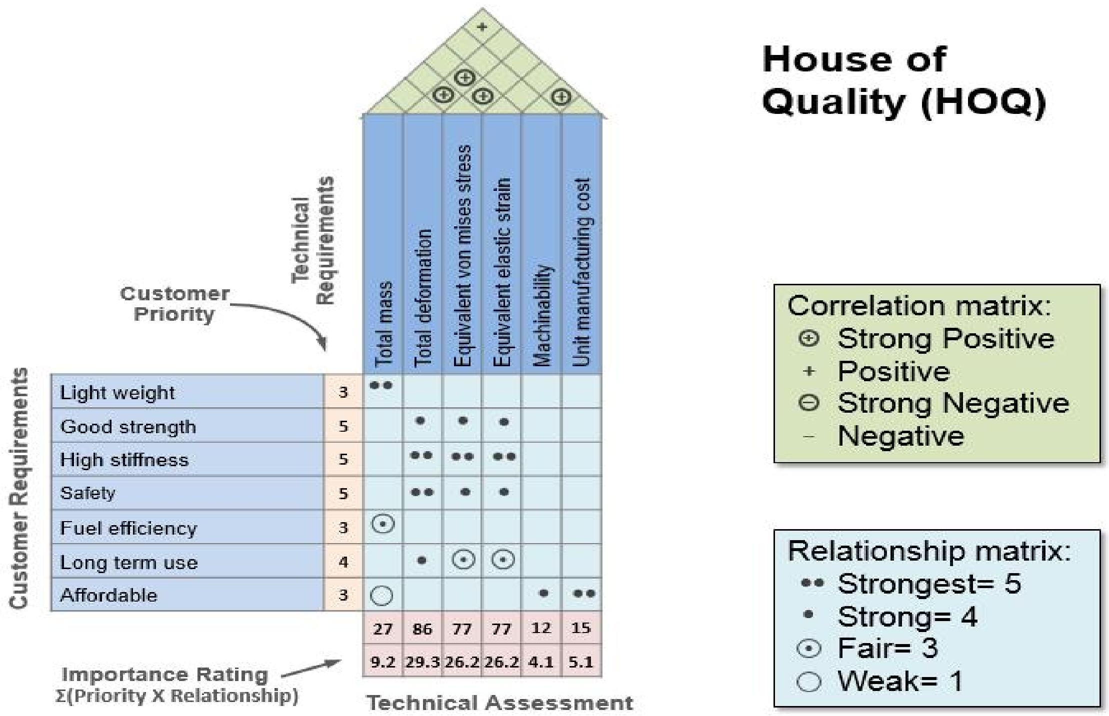


Figure 3.3: House of Quality (HOQ) chart of floating brake calliper

3.2.2.2 Modelling of floating brake calliper models

The design process are started with preliminary study on the current design of floating brake calliper. **Figure 3.4** presents an illustration of original floating brake calliper for the model PROTON WIRA. It is made up of Gray cast iron. The original model is modified to six (6) different designs by using 3D modelling software, CatiaV5R17. The original brake calliper have been modified to six alternative designs with variations in bridge design. The bridge design features of original model were modified to row rib, column rib, cross rib, X -rib, I -rib and H –rib, shown in **Appendices A.**

(a)

(b)

Figure 3.4 (a) and (b) presents an illustration of original floating brake calliper

3.2.2.3 Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is applied to the proposed six (6) calliper models using ANSYS simulation software. The six (6) calliper models are analysed based on important design selection parameters. Three stages are involved; pre-processing stage include which type of analysis, material properties, select fine element size of mesh analysis, loads and boundary condition are defined, then the; processing stage where the desired result is computed and solved; and the results are interpreted during post-processing stage. **Figure 3.5** presents an illustration of flowchart for FEA analysis.

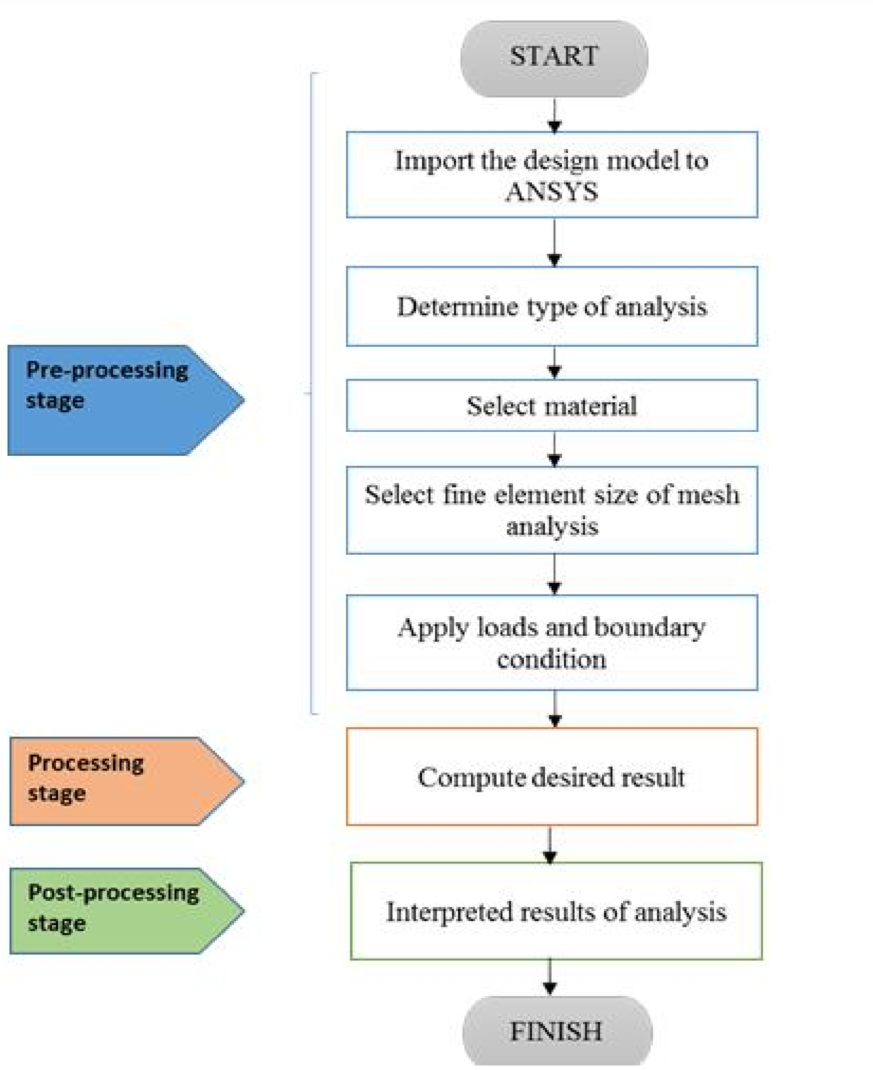


Figure 3.5: Flowchart for FEA analysis

Static structural analysis

- **Material properties**

Table 3.1 listed Material properties of Gray cast iron and Magnesium hybrid MMC

Table 3.1: Material properties of Gray cast iron and Magnesium hybrid MMC

Properties	Gray cast iron	Magnesium hybrid MMC ($AZ31\text{-}14.0SiC_{micro}\text{-}1.0SiC_{macro}$)
Density, ρ (kg/m^3)	7200	1995
Young's Modulus, E (GPa)	100	103
Poisson's Ratio, υ	0.28	0.27
Tensile Yield Strength, (MPa)	276	300
Tensile Ultimate Strength, (MPa)	250	380

Source: M.Yaswanth (2015); K.Sowjanya (2013); Jun et al. (2014); Kumar et al. (2015); Bettles and Barnett (2012); Champbell (2012); Zhou et al. (2013); Rashad et al. (2015)

The material properties of Magnesium hybrid MMC is expressed as in **Eq. (3.2)**. (Debnath et al., 2012; Prasad et al., 2014; Krishna et al., 2016)

$$X_{hybrid} = X_1V_1 + X_2V_2 + X_3V_3 \qquad (3.2)$$

where X_{hybrid} is the material properties of final hybrid composites; X_1, X_2 *and* X_3 represent the material properties of magnesium alloy and it's reinforcement materials; V_1, V_1, and V_1 represent the volume fraction of magnesium alloy and it's reinforcement materials.

* The density, ρ of AZ31 magnesium alloy and SiC particles are 1780kg/m^3 and 3210kg/ m^3 respectively. Based on calculations, density of AZ31-14.0microSiC-1.0nanoSiC is 1995kg/m^3.

* The Young's Modulus, E of AZ31 magnesium alloy and SiC particles are 45GPa and 430GPa respectively. Based on calculations, Young's Modulus, E of AZ31-14.0microSiC-1.0nanoSiC is 103GPa.

* The Poisson's Ratio, υ of AZ31 magnesium alloy and SiC particles are 0.3υ and 0.14υ. Based on calculations, Poisson's Ratio, υ of AZ31-14.0microSiC-1.0nanoSiC is 0.27υ.

- **Meshing**

A default mesh is generated automatically. To improve the mesh quality, additional control be added to the default mesh before solving. Furthermore, mesh parameters such as element quality, skewness and orthogonal quality were considered. An average element mesh quality of 0.8 and above is considered acceptable. Skewness and Orthogonal quality mesh metrics spectrum were shown in **Figure 3.7**. In order to achieve this mesh quality, different meshing techniques were used. There are three advanced size functions can be employed: proximity, curvature and fixed in Ansys. Both Proximity and Curvature were turned on for this model in order to have a much better mesh along the curve regions and varying cross sections. Out of different element types like tetrahedrons, multizone, hex dominant and sweep, "Patch Conforming" mesher under "Tetrahedrons" were the most suitable as they capture the curvatures more accurately as compared to other method. Refined mesh consisting of 457326 nodes and 302619 elements have shown in **Figure 3.6**. Through the suitable meshing method, mesh parameter like average element quality have achieved 0.82, average skewness have reached 0.26, and average orthogonal quality have achieved 0.85 shown in **Figure 3.8, Figure 3.9 and Figure 3.10**.

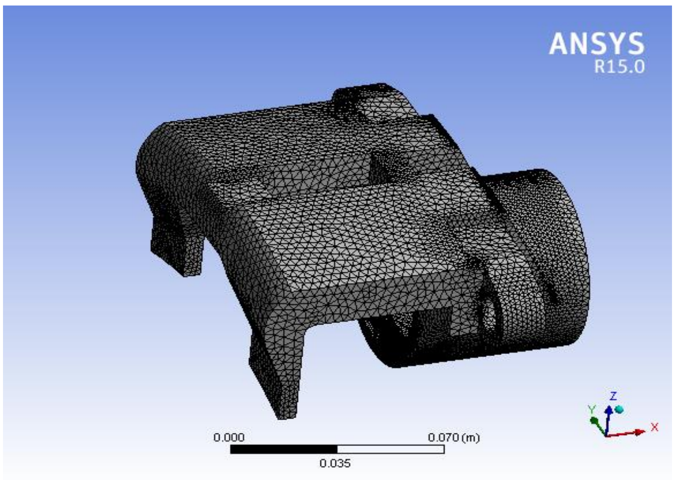
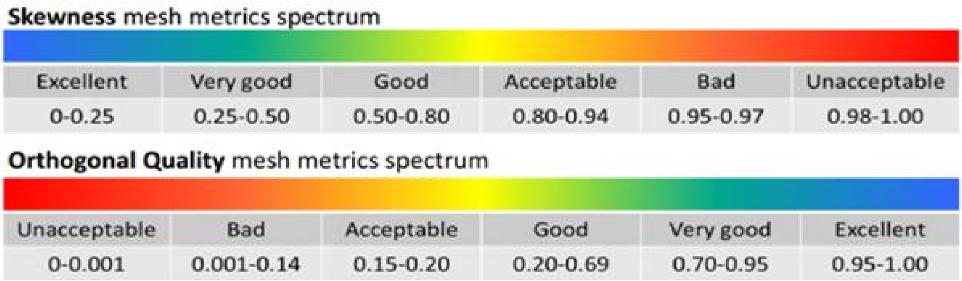


Figure 3.6: Refined mesh original brake calliper model



Skewness mesh metrics spectrum

Excellent	Very good	Good	Acceptable	Bad	Unacceptable
0-0.25	0.25-0.50	0.50-0.80	0.80-0.94	0.95-0.97	0.98-1.00

Orthogonal Quality mesh metrics spectrum

Unacceptable	Bad	Acceptable	Good	Very good	Excellent
0-0.001	0.001-0.14	0.15-0.20	0.20-0.69	0.70-0.95	0.95-1.00

Figure 3.7: Skewness and orthogonal quality mesh metrics spectrum

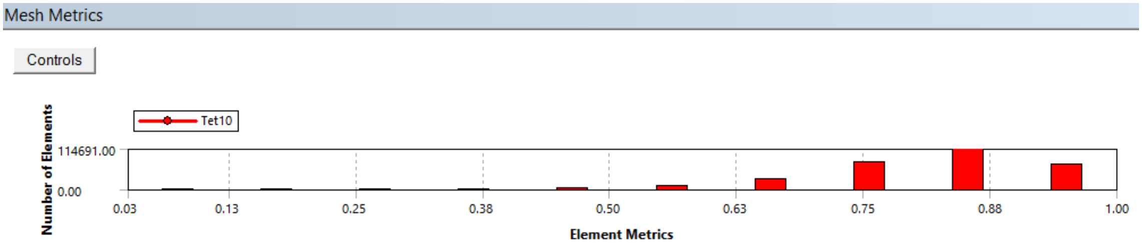


Figure 3.8: Element quality mesh metrics bar graph

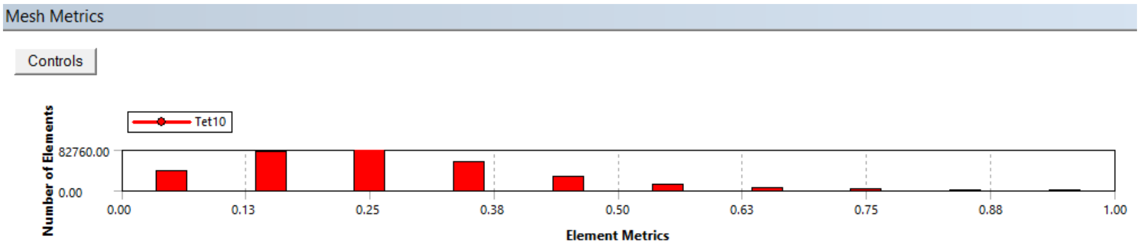


Figure 3.9: Skewness mesh metrics bar graph

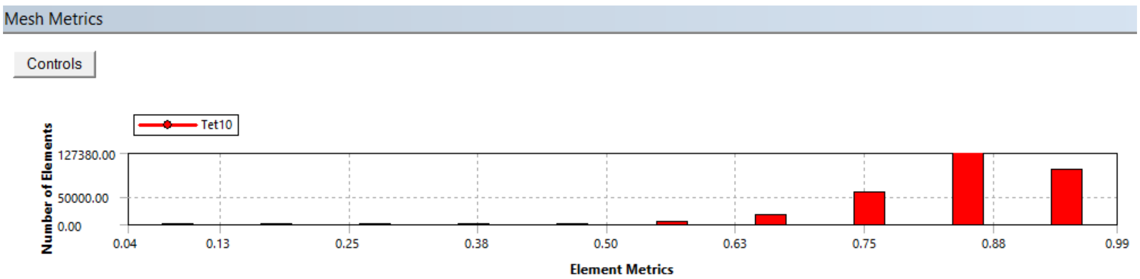


Figure 3.10: Orthogonal quality mesh metrics bar graph

- **Loads and boundary condition**

According to (Rajaram and Sudharsan, 2005), the brake pipeline pressure (Fluid pressure) variation would be approximately:

- 1-2 MPa for low level braking
- 2-4 MPa for medium level braking
- 4-7 MPa for panic braking.

Calliper housing is subjected to mainly following loads:

- Force due to Fluid Pressure on the inner face of the cylinder
- Reaction Force on finger area due to Fluid Pressure

Both loads have the same values because they are equal and opposite force caused due to Fluid Pressure. The force due to Fluid Pressure on the inner face of the cylinder is expressed as in **Eq. (3.3)**.

$$F = P \times A \tag{3.3}$$

Area of cylinder is expressed as in **Eq. (3.4)**.

$$A = \frac{\pi}{4} D^2 \tag{3.4}$$

Given diameter of cylinder, D = 55mm = 0.055m

$A = \frac{\pi}{4} D^2$

$= \frac{\pi}{4} (0.055^2)$

$= 0.002376\ m^2$

Assumed, P= 7MPa (panic braking)

$F = P \times A$

$= 7(10^6)\ \text{Pa} \times 0.002376\ m^2$

= 16632 N

= 16.632 kN

3.2.2.4 Analytical Hierarchy Process (AHP)

AHP is a Multi Criteria Decision Making (MCDM) method helping a decision-maker deal with a complicated problem which consist of various subjective and conflicting criteria. In this study, Super Decision software based on AHP method is choose as multi-criteria decision making tool. Based on the weight and ranking obtained from QFD, best brake calliper design is achieved through evaluate and ranking among alternative designs. Basic steps based on AHP method:

Step 1: Identify the problem and state objective.

Step 2: Construct a hierarchy framework consists of four levels including goal, criteria, sub-criteria and alternatives.

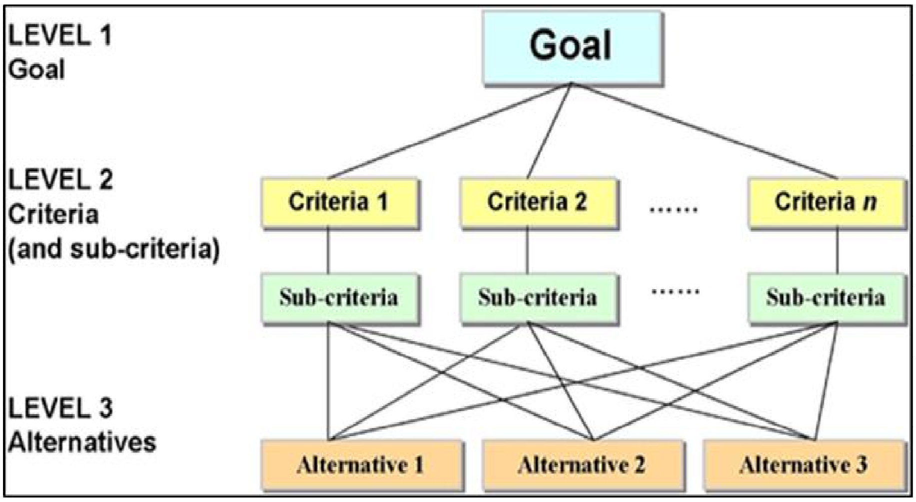


Figure 3.11: A typical hierarchy AHP

Step 3: Develop a set of pairwise comparison matrices to compare each element in the corresponding level. If there are n numbers of objectives, (n x n) pairwise comparison matrix is expressed as in **Eq. (3.5)**.

$$A = a_{ij} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \quad (3.5)$$

AHP is capable to convert the importance from human perception into a numerical value. While making the decision selection, a_{ij} indicates how much important the i_{th} objective is as compare to j_{th} objective. The possible assessment values of a_{ij} are illustrated in **Table 3.2**.

Table 3.2 listed Scale for pair-wise comparison.

Table 3.2: Scale for pair-wise comparison

a_{ij} value	**Definition**	**Explanation**
1	Equal important	Two activities contribute equally to objective
3	Moderate importance	Experience and judgement strongly favor one activity over another
5	Strong importance	Experience and judgement strongly favor one activity over another
7	Very stong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8,	Intermediate values between the two adjacent judgements	When compromise is needed

Once completed, sum up the entries in column j and use the sum to divide each entry in column j of pairwise comparison matrix A. A new matrix, Aw is expressed as in **Eq. (3.6)**.

$$Aw = \begin{bmatrix} \frac{a_{11}}{\sum a_{i1}} & \frac{a_{12}}{\sum a_{i2}} & \cdots & \frac{a_{1n}}{\sum a_{in}} \\ \cdots & \cdots & \ddots & \vdots \\ \frac{a_{n1}}{\sum a_{i1}} & \frac{a_{n2}}{\sum a_{i2}} & \cdots & \frac{a_{nn}}{\sum a_{in}} \end{bmatrix} \tag{3.6}$$

Compute the priority vector (PV) by summing the entries in row i and dividing numbers of objectives to form the column vector of PV, is expressed as in **Eq. (3.7)**.

$$PV = \frac{\frac{a_{n1}}{\sum a_{i1}} + \frac{a_{n2}}{\sum a_{i2}} + \ldots + \frac{a_{nn}}{\sum a_{in}}}{n} \tag{3.7}$$

The sum of the entries in column vector of PV will be 1, where PV represents the relative degree of importance of the selected n objectives.

Step 4: Implement the Eigen value method, calculate the Consistency Index (CI), and determine Consistency Ratio (CR). Start the judgments consistency of the pairwise comparison matrix by following the sub-steps shown next:

a. Compute matrix A with column vector of PV.

$$A.PV = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \begin{bmatrix} PV_1 \\ PV_2 \\ \vdots \\ PV_n \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \tag{3.8}$$

b. Compute the Eigen value (λmax).

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{ith\ entry\ in\ A.PV}{ith\ entry\ in\ PV} \tag{3.9}$$

c. Compute the Consistency Index (CI).

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.10}$$

d. Compare CI and RI

At this stage, Consistency Index (CI) is compared with Random Index (RI) with the appropriate value of n to ensure the satisfactory of consistency degree. Decision-maker may detect the consistency of his judgment on weighting estimation for various criteria, if the CI value is significantly smaller than RI value. The RI values for different numbers of n are shown in **Table 3.3**.

Table 3.3: Table of Random Index (RI)

n	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

e. Compute the Consistency Ratio (CR).

$$CR = \frac{CI}{RI} \tag{3.11}$$

The degree of consistency is satisfactory if CR<0.10, otherwise, there are inconsistencies if CR>0.10. Based on Saaty, the AHP result is insignificant if CR value is higher than 0.10. Thus, judgments should be re-examined and modified as necessary in order to reduce the inconsistency to 0.10 or lower.

Step 5: Repeat step 3 and 4 in order to have the desired normalized values for each sub-criteria of all levels.

Step 6: Analyse the normalized values and drive solution to the problem.

In the end, sensitivity analysis was performed to show the influence of changing different parameters of the model on the choice of the best floating brake calliper. (Al-Oqla, F.M et al., 2012)

3.3 CONCLUSIONS

The expected outcome from this research is to propose a high performance floating brake calliper using Magnesium hybrid MMC materials to replace the conventional brake calliper and innovation in design alternatives for automotive industry.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

In this chapter, FEA results of static structural analysis in ANSYS Workbench 15.0 for original brake calliper made of Gray cast iron and Magnesium hybrid MMC were shown. Results revealed that Magnesium hybrid MMC is better than Gray cast iron in considered of material selection for floating brake calliper. FEA results of static structural analysis for six alternative designs which made of Magnesium hybrid MMC showing each of them have their own respective advantages on certain criteria. Superdecision software based on AHP method have been used to select the best performace floating brake calliper design.

4.2 FEA SIMULATION RESULTS

In QFD phase, light weight, good strength and high stiffness, safety, fuel efficiency, long term use, affordable were the important criteria considered for selection of brake calliper. Design parameters on product performance such as total mass, total deformation, equivalent von misses stress, equivalent elastic strain, machinability and unit manufacturing cost showing certain relationship to those important criteria. According to the customer priority ranking, a high performance brake calliper should be safe, good strength and high stiffness. Through the relationship matrix calculation, total deformation was obtained the highest rating with respect to the customer requirements among other design parameters.

For validation of materials, original brake calliper made of Gray cast iron and Magnesium hybrid MMC were analysed for static structural analysis in ANSYS Workbench 15.0 to investigate design parameters on product performance. Total deformation, equivalent von misses stress and equivalent elastic strain were determined from FEA analysis. **Figure 4.1** and **Figure 4.2** presents FEA results of Gray cast iron and Magnesium hybrid MMC original brake calliper. **Table 4.1** listed the summary results of structural analysis for both Gray cast iron and Magnesium hybrid MMC original brake calliper.

Table 4.1: Summary results of structural analysis for Gray cast iron and Magnesium hybrid MMC brake calliper.

Properties	**Gray cast iron**	**Magnesium hybrid MMC (AZ31-14.0SiC$_{micro}$ -1.0SiC$_{nano}$**	**Percentage of improvement (%)**
Total mass, kg	2.17250	0.60196	72.29
Max. Total Deformation, m	0.00080428	0.00078205	2.76
Max. Equivalent Stress, Pa	7.5159e8	7.5834e8	0.89
Max. Equivalent Elastic Strain, m/m	0.0081128	0.0078753	2.93

Validation of material using original brake calliper:

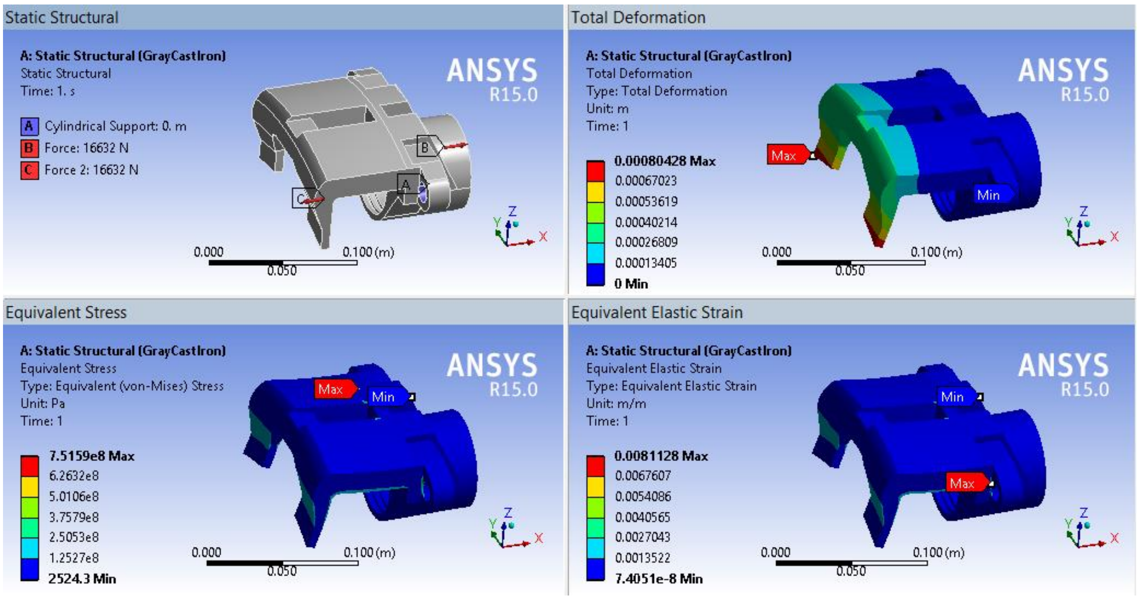


Figure 4.1: FEA results of Gray cast iron original brake calliper

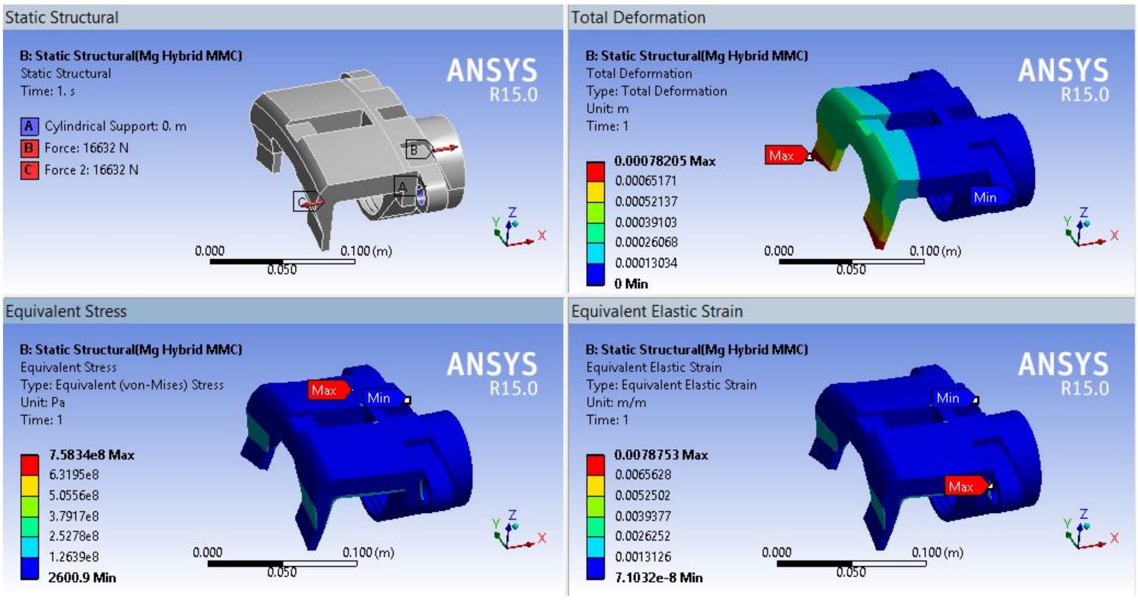


Figure 4.2: FEA results of Magnesium hybrid MMC original brake calliper

Figure 4.3 presents an illustration of stress-strain curve. Before the yield point is reached, the stress and strain initially increase with a linear relationship. In this linear region, the line obeys the relationship defined as Hooke's Law where the ratio of stress to strain is a constant. In this region of the curve, when the stress is reduced, the part will return to its original shape. The slope of the line in this region where stress is proportional to strain is called the modulus of elasticity or *Young's modulus*. It is a measure of the stiffness of a given material. The greater the *Young's modulus* of a material, the greater the stiffness of the part because when large stress subjected to the part will produce small strain, means more resistance to deformation.

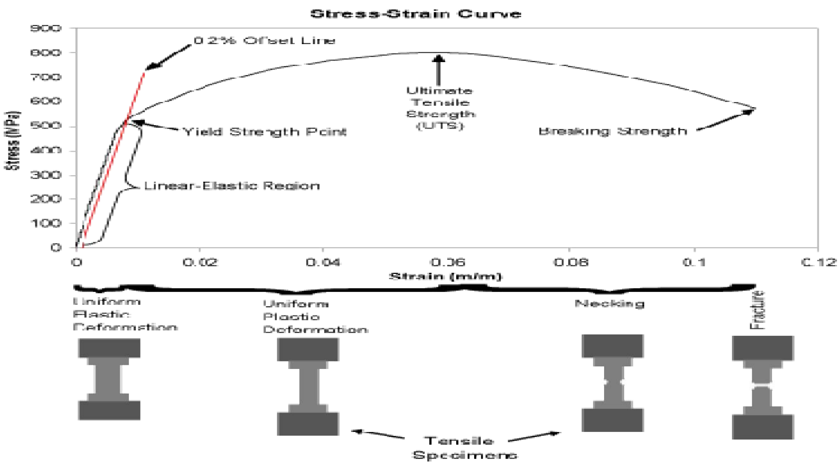


Figure 4.3: An illustration of stress-strain curve

Magnesium hybrid MMC was stiffer than Gray cast iron since it possess larger *Young's modulus* than Gray cast iron. During validation of material used for original brake calliper using FEA analysis, results revealed that brake calliper made of Magnesium hybrid MMC have smaller total deformation distribution and maximum equivalent elastic strains compared to Gray cast iron which reduced by 2.76% and 2.93% respectively. Moreover, Magnesium hybrid MMC brake calliper had reduced the weight almost 72.29% to the Gray cast iron calliper. When it comes to compare the maximum equivalent von misses stress, stress distribution of Magnesium hybrid MMC brake calliper was exceed the Gray cast iron calliper by 0.89%. This is because capability of Magnesium hybrid MMC brake calliper to withstand high stress during clamping action in order to prevent deflection of brake calliper is better than Gray cast iron calliper within the same design.

In fact, larger von misses stress implies that the material is closer to the yield point. When the stress exceed yield point, the sample had suffered some level of permanent distortion which mean it does not return to its original shape. Von misses stress means the stresses which act to distort the shape of the part. So, engineers will typically try to design such that the peak stresses as low as possible to reduce the distortion of material, reported by (Capinc, 2014). Original Magnesium hybrid MMC brake calliper was modified to few alternative designs to improve the performance of brake calliper. The desired FEA analysis results are low maximum equivalent von misses stress, small total deformation and low equivalent elastic strain.

Through the study of literature review, deflection of brake callipers, also known as "bending of bridge" was highlighted as the priority problem that affected the performance of brake calliper. However, this problem can be improved by bridge design features, as (Sergent et al., 2013) stated that bridge design features are the most important in maintaining structural stiffness. According to (Stahl and Giese, 2004), flexural strength can be enhanced by ribs structure on floating brake calliper design.

In this research, an original brake calliper 3D model was created in Catia V5R21. The original brake calliper have been modified to six alternative designs with variations in bridge design. The bridge design features of original model were modified to row rib, column rib, cross rib, X -rib, I -rib and H –rib as shown in **Appendix A**. To investigate design parameters on product performance of each alternative design model, each model were analysed for static structural analysis in ANSYS Workbench 15.0. Total deformation, equivalent von misses stress and equivalent elastic strain were determined from FEA analysis. **Figure 4.4, 4.5, 4.6, 4.7, 4.8, 4.9** presents FEA results of each proposed alternative designs. **Table 4.2** listed the summary results of structural analysis for original brake calliper design and six proposed alternative designs.

Alternative Design 1 (Row rib):

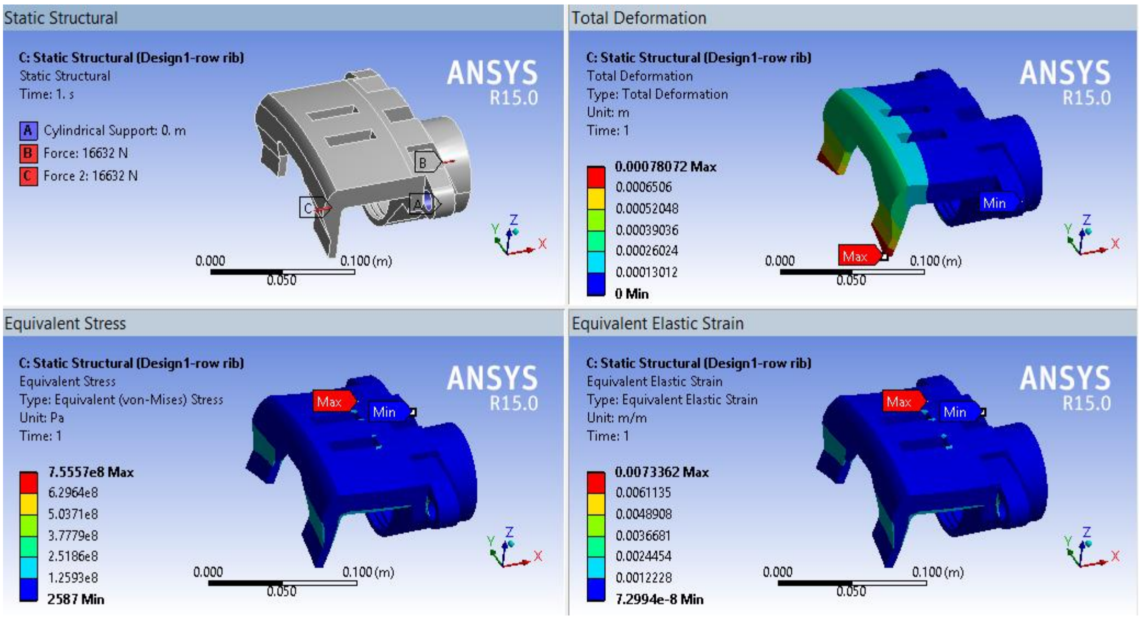


Figure 4.4: FEA results of alternative design 1

Alternative Design 2 (Column rib):

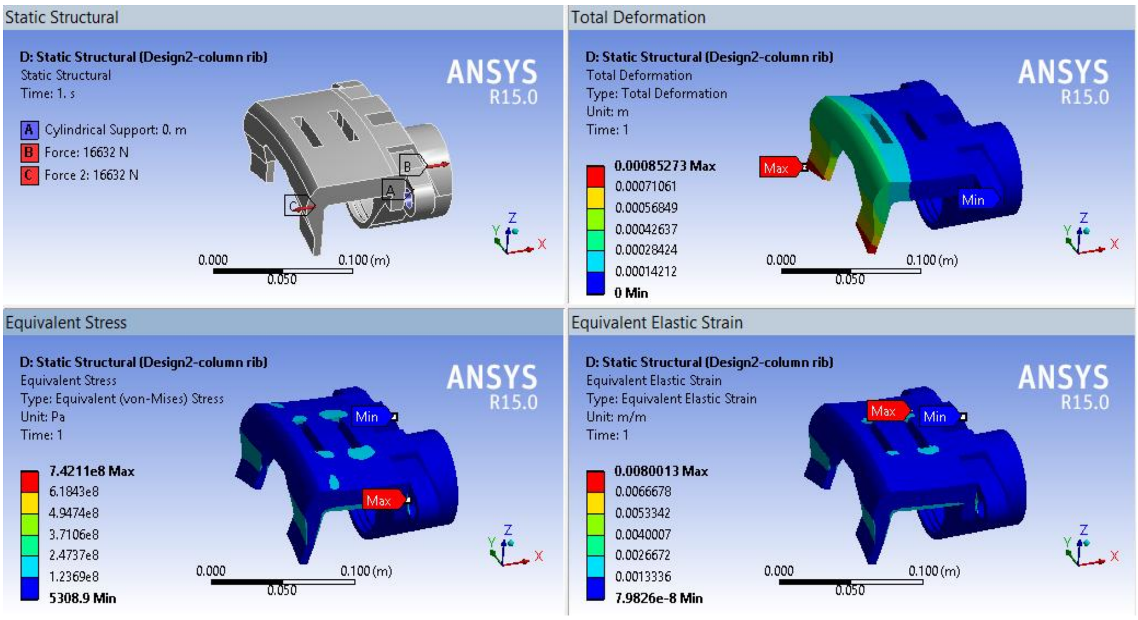


Figure 4.5: FEA results of alternative design 2

Alternative Design 3 (Cross rib):

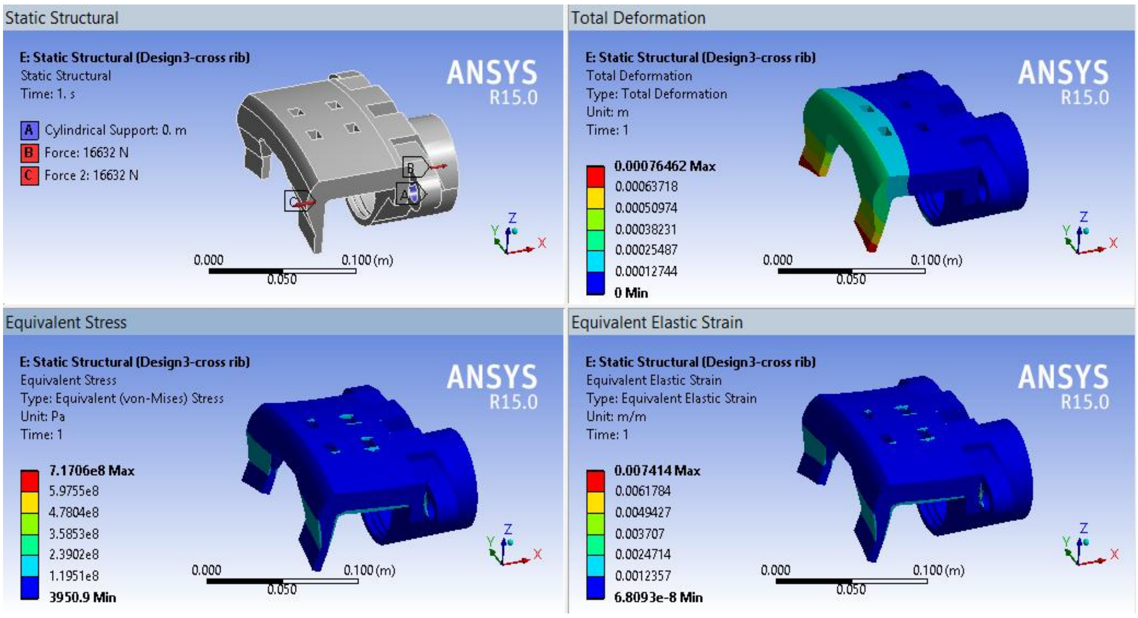


Figure 4.6: FEA results of alternative design 3

Alternative Design 4 (X -rib):

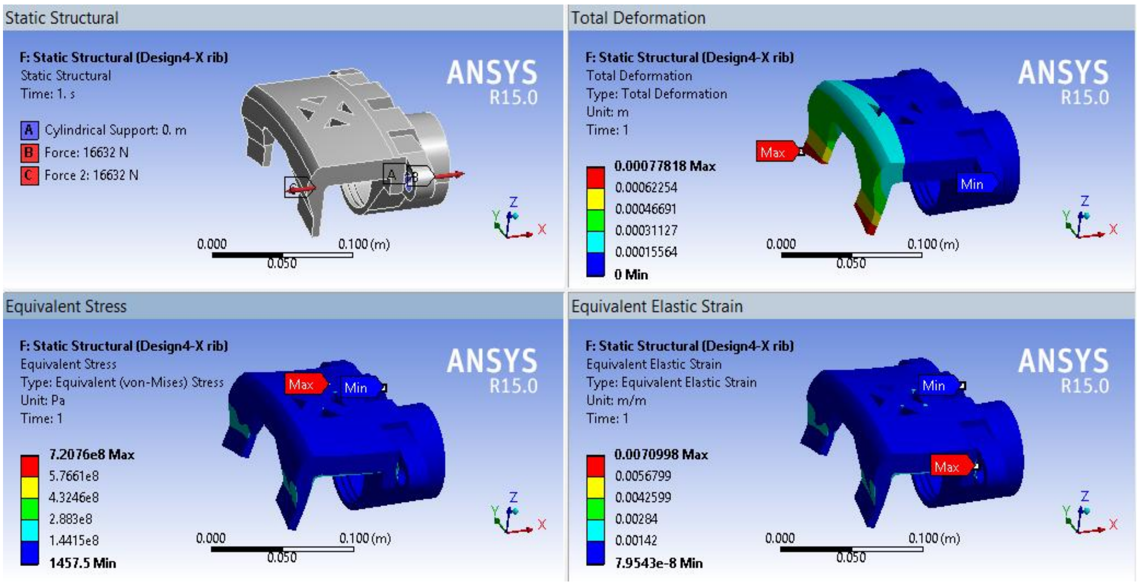


Figure 4.7: FEA results of alternative design 4

Alternative Design 5 (I -rib):

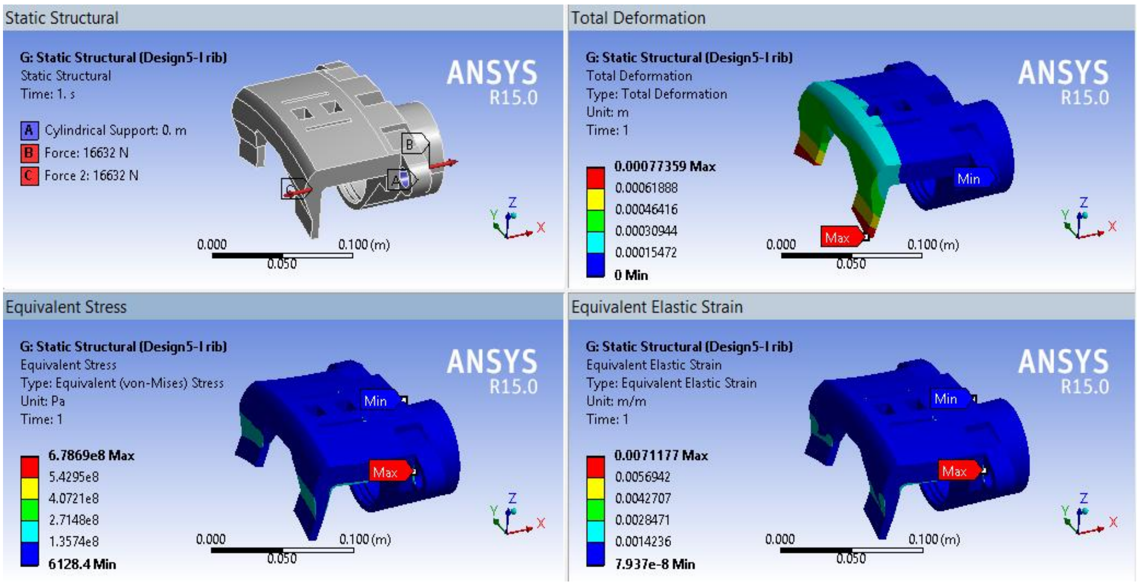


Figure 4.8: FEA results of alternative design 5

Alternative Design 6 (H -rib):

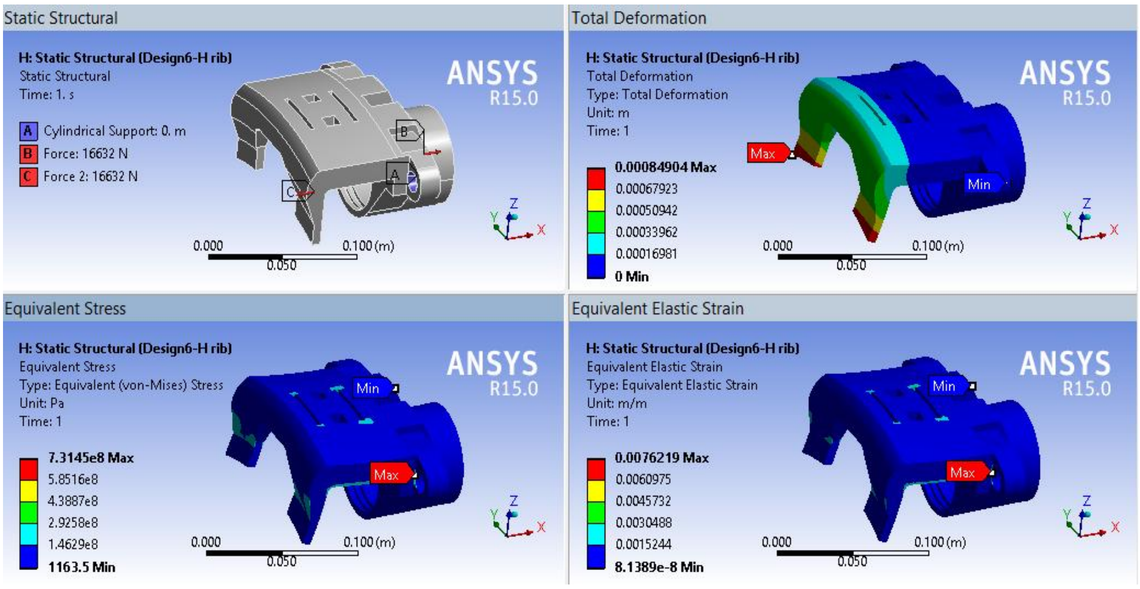


Figure 4.9: FEA results of alternative design 6

Table 4.2: Summary results of structural analysis for original brake calliper design and six alternative designs

Design	Total mass, kg	Total deformation, m	Equivalent von misses stress, Pa	Equivalent elastic strain, m/m
Original Design (Without rib)	0.60196	0.00078205	7.5834e8	0.0078753
Alternative Design 1 (Row rib)	0.60703	0.00078072	7.5557e8	0.0073362
Alternative Design 2 (Column rib)	0.60959	0.00085273	7.4211e8	0.0080013
Alternative Design 3 (Cross rib)	0.61980	0.00076462	7.1706e8	0.0074140
Alternative Design 4 (X -rib)	0.61722	0.00077818	7.2076e8	0.0070998
Alternative Design 5 (I -rib)	0.61240	0.00077359	6.7869e8	0.0071177
Alternative Design 6 (H -rib)	0.61597	0.00084904	7.3145e8	0.0076219

The modified bridge design features of original brake calliper model were fixed within area of 40mm length × 36mm wide. Alternative design 1 with row rib brings some overall improvement as compared to original brake calliper without rib, which provides 0.17% of reduction of total deformation, 0.37% of reduction of equivalent von misses stress and 6.85% of reduction of equivalent elastic strain. Row rib act as support structure to prevent risk of bending of bridge. However, when considering the mass, the total mass increased by 0.84%.

For alternative design 2 with column rib, equivalent von misses stress was decrease dramatically about 2.14% against the original brake calliper design. But, total deformation and equivalent elastic strain went up sharply by 8.29% and 1.57% respectively. Column rib is far less effective than row rib. When the brake calliper subjected to stress during clamping, column rib failed to withstand the stress, results in brake calliper opening up slightly. Column rib act as detriment rib which leads to large deflection. Moreover, the total mass rose by 1.25%.

When looking at alternative design 3 with cross rib, which combination of row rib and column rib, gives the most stiffness improvement as compared to alternative design 1 and alternative design 2. It seems the most efficient in reducing calliper opening up, which total deformation dropped by 2.23%, equivalent von misses stress dropped by 5.44% and equivalent elastic strain dropped by 5.86%. However, the mass was increased by 2.88% which heavier than alternative design 1 and design 2.

It is interesting to note that the alternative design 4 with X –rib shows the most equivalent elastic strain improvement, which reduced by 9.85% against original design and 4.24% against the alternative design 3 respectively. In addition, the total deformation, equivalent von misses stress and total mass of design 4 and design 3 seems to be levelled off.

Alternative design 5 and alternative design 6 combine both individual row rib and column rib. Alternative design 5 is I –rib with combination of 2 row rib and 1 column rib shows better overall improvement than alternative design 1. Alternative design 6 is H –rib with combination of 1 row rib and 2 column rib shows better overall improvement than alternative design 2. Alternative design 5 and alternative design 6 are heavier than design 1 and 2 about approximately 0.82 % but lighter than design 3 and 4 about approximately 0.81%. In short, combination of two or more single features shows better overall improvement than single feature.

4.3 AHP RESULTS

Each floating brake calliper design have their own respective advantages on certain criteria. The process of high performance floating brake calliper is a multi-criteria decision-making problem with conflicting and diverse objectives. Super Decision Sofware based on Analytical Hierarchu Process (AHP) was used to make decision. AHP is a widely used multi-criteria decision making tool designed to solve a problem deals with multi-criteria. A hierachy framework was builed to ease the decision-making. **Figure 4.10** presents an illustration of AHP hierarchy framework.

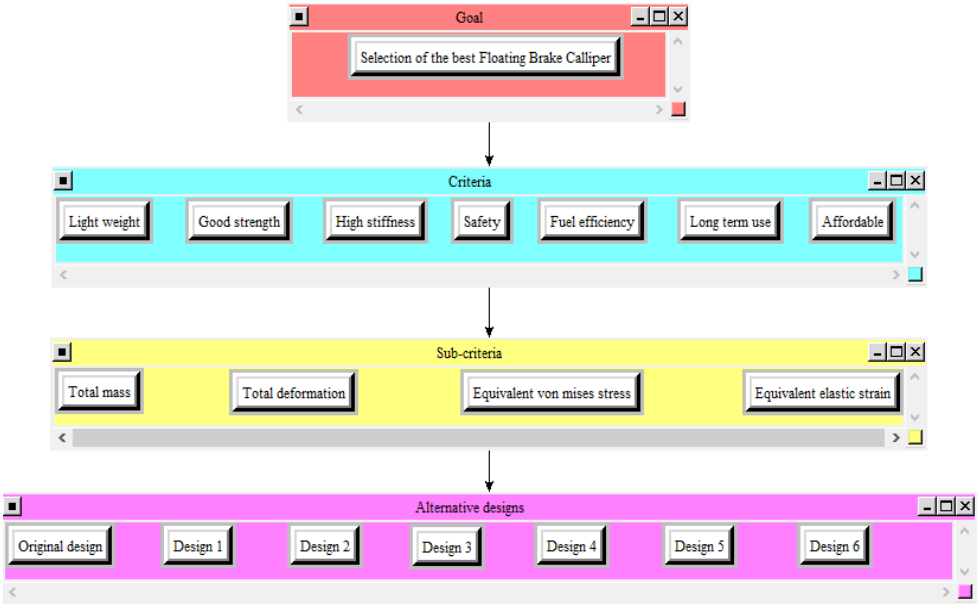


Figure 4.10: An illustration of AHP hierarchy framework

The hierachy structure consist of four level of cluster: goal, criteria, sub-criteria and alternative designs. The element in each level called nodes. Goal is the objective that want to be achieved in this study which is to select the best floating brake calliper among those alternative designs. The criteria is the factor that need to be considered, which is referred to the customer requirement based on QFD. The criteria is further breakdown to sub-criteria which is reffered to the design parameters based on QFD. The bottom cluster is the alternative designs that need to be compared. All the levels were undergo pair-wise comparison matrix to perform the priority of the nodes of each level. The ranking of pair-wise comparison between sub-criteria is referring to the **Table 4.2**.

A set of questionnaire was used to determine which node is dominant, namely: extreme, very strong, moderate and equal importance by entering the scale according the weights based on QFD. When nodes compared with itself is always assigned the value of “1” in matrix. **Figure 4.11** presents a questionnaire between criteria with respect to goal. **Figure 4.12** presents the pair-wise comparison between criteria and resulting contribution of criteria to goal, where good strength, high stiffness and safety are the important criteria against the goal with a total aggregate weight of 0.23529.

Pairwise comparison of criteria with respect to goal:

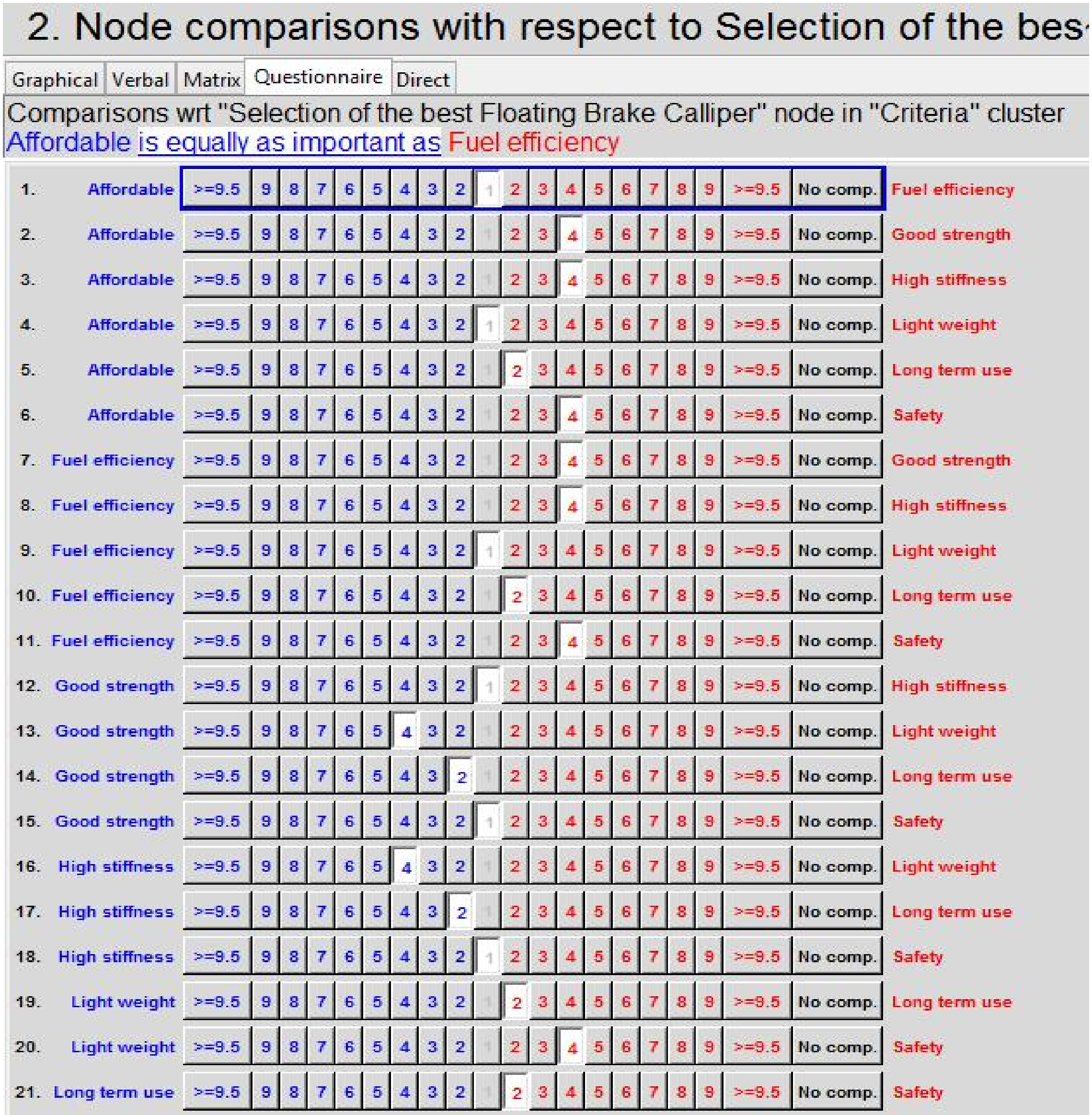


Figure 4.11: Questionnaire between criteria with respect to goal

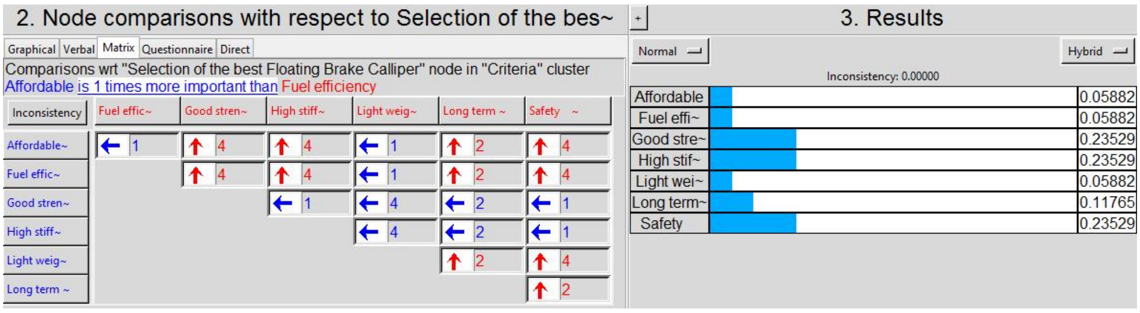


Figure 4.12: Pair-wise comparison between criteria and resulting contribution of criteria to goal

On the other hand, pair-wise comparison of the sub-criteria with respect to each criteria are shown. Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to light weight criteria are shown in **Figure 4.14**, where the most priority was total mass with a total aggregate weight of 0.75000. Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to good strength criteria are shown in **Figure 4.16**, where the priority were equivalent elastic strain, equivalent von mises stress and total deformation with a total aggregate weight of 0.32000. Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to high stiffness criteria are shown in **Figure 4.18**, where the priority were equivalent elastic strain, equivalent von mises stress and total deformation with a total aggregate weight of 0.32143. Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to safety criteria are shown in **Figure 4.20**, where the most priority was total deformation with a total aggregate weight of 0.44877. Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to fuel efficiency criteria are shown in **Figure 4.22**, where the most priority was total mass with a total aggregate weight of 0.70000. Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to long term use criteria are shown in **Figure 4.24**, where the most priority was total deformation with a total aggregate weight of 0.44733. Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to affordable criteria are shown in **Figure 4.26**, where the most priority was total mass with a total aggregate weight of 0.40000.

Pairwise comparison of sub-criteria with repect to criteria:

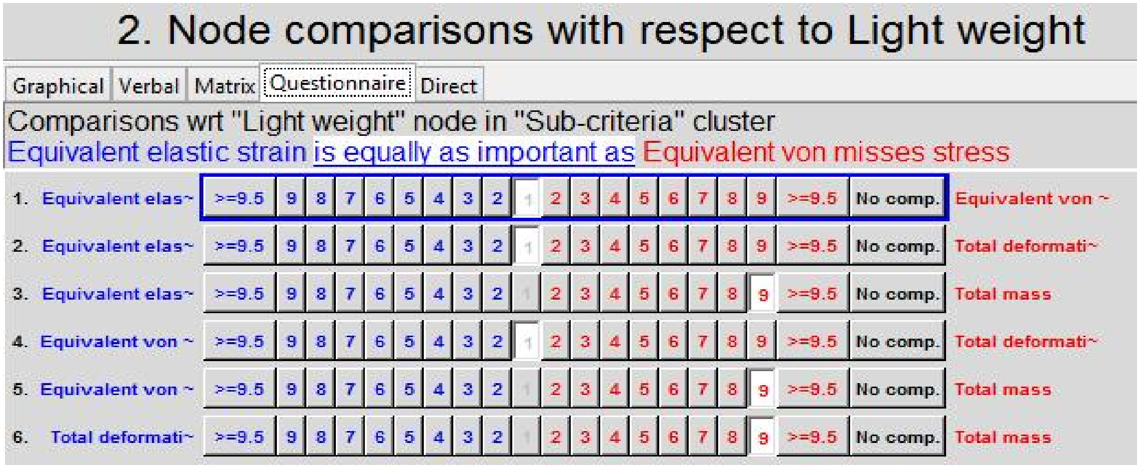


Figure 4.13: Questionnaire between sub-criteria with respect to light weight criteria

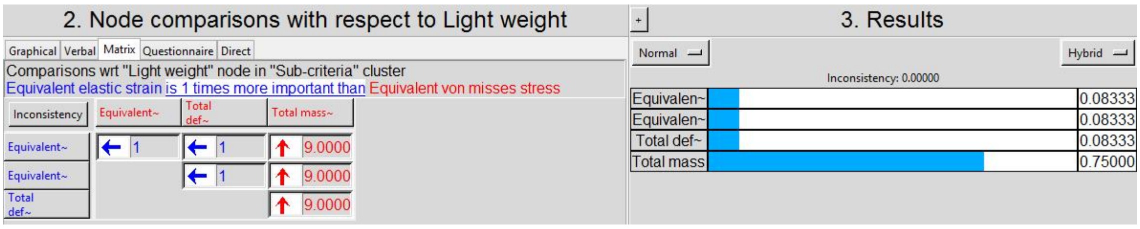


Figure 4.14: Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to light weight criteria

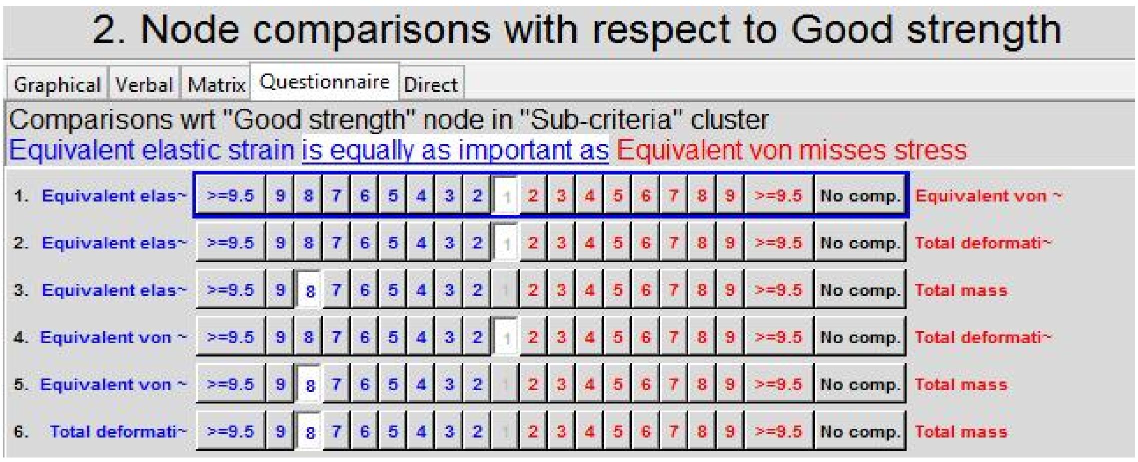


Figure 4.15: Questionnaire between sub-criteria with respect to good strength criteria

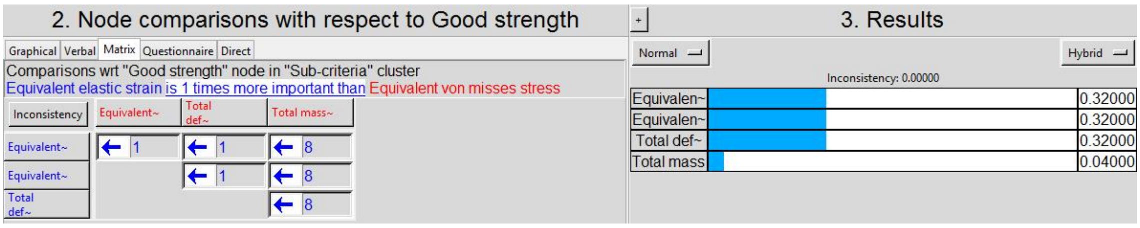


Figure 4.16: Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to good strength criteria

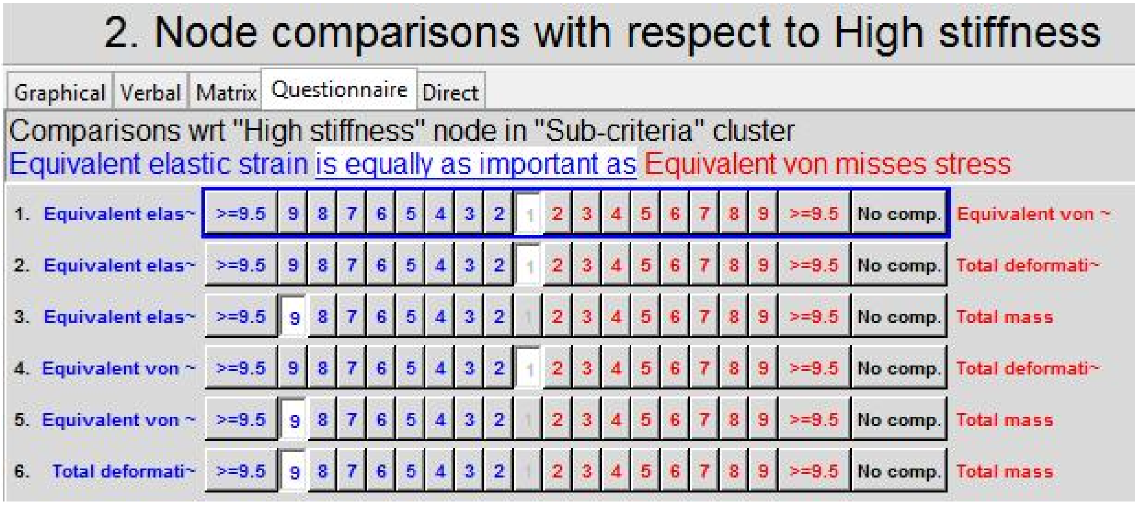


Figure 4.17: Questionnaire between sub-criteria with respect to high stiffness criteria

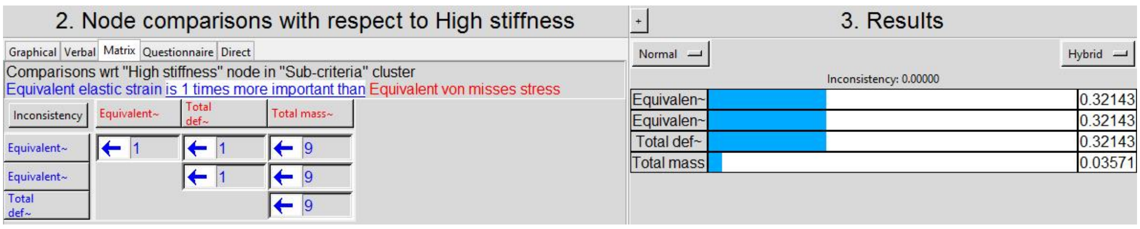


Figure 4.18: Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to high stiffness criteria

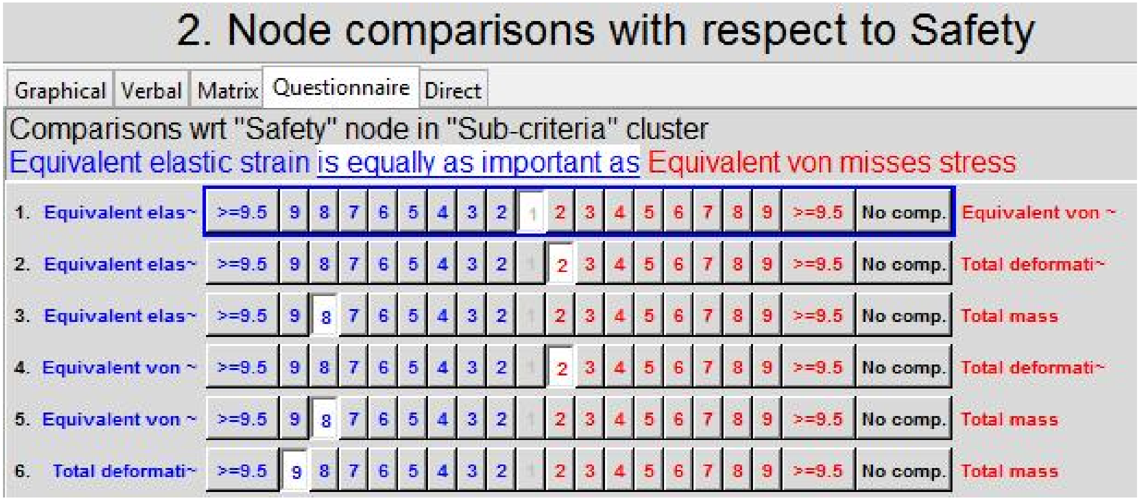


Figure 4.19: Questionnaire between sub-criteria with respect to safety criteria

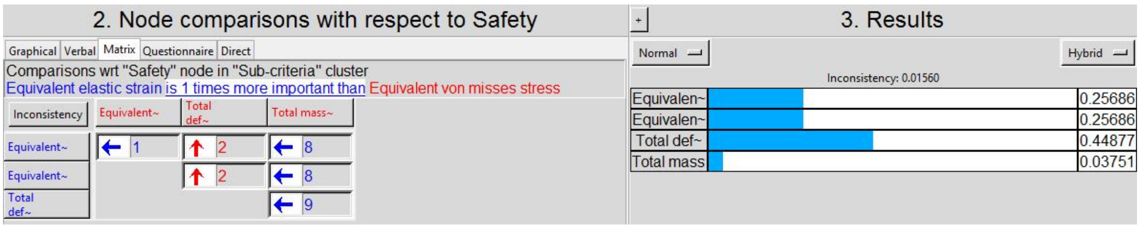


Figure 4.20: Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to safety criteria

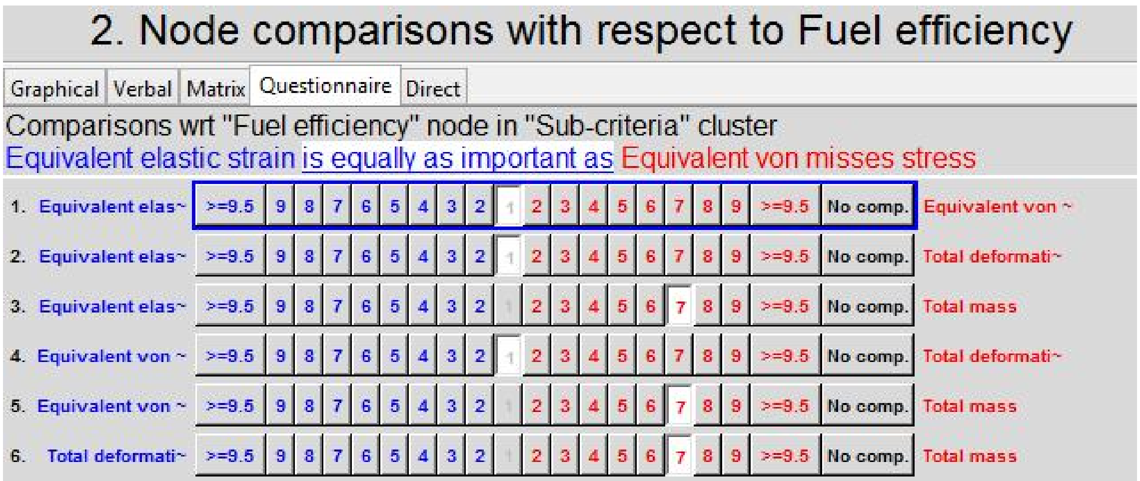


Figure 4.21: Questionnaire between sub-criteria with respect to fuel efficiency criteria

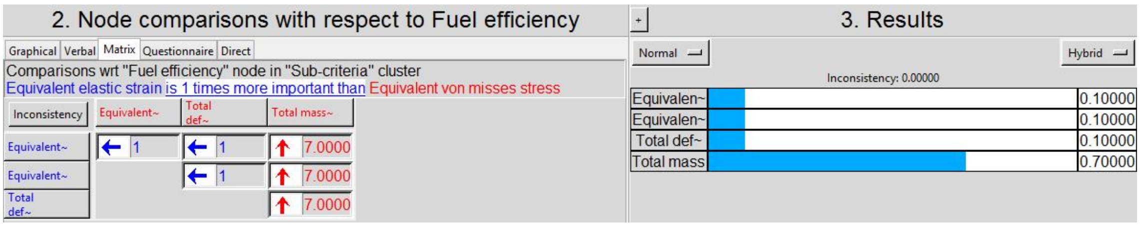


Figure 4.22: Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to fuel efficiency criteria

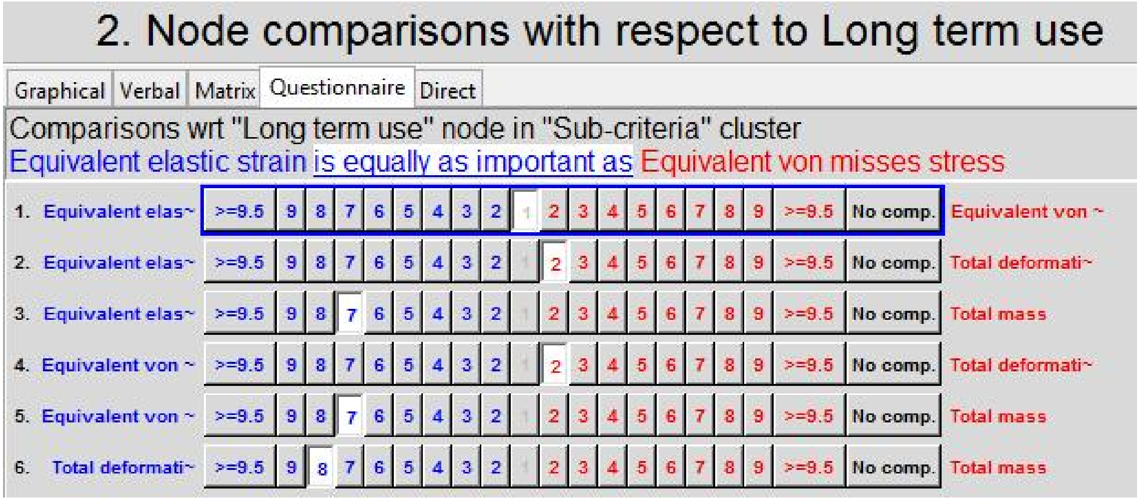


Figure 4.23: Questionnaire between sub-criteria with respect to long term use criteria

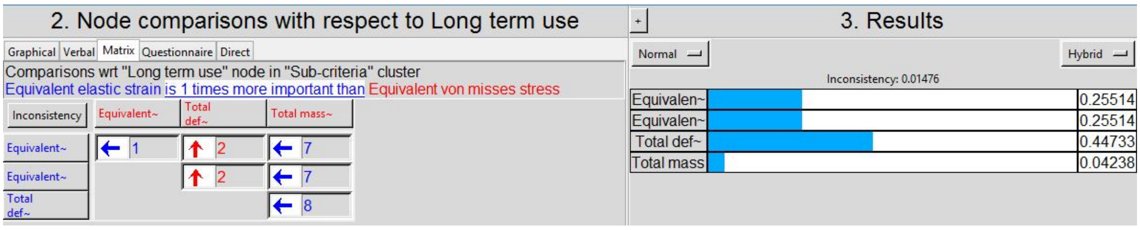


Figure 4.24: Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to long term use criteria

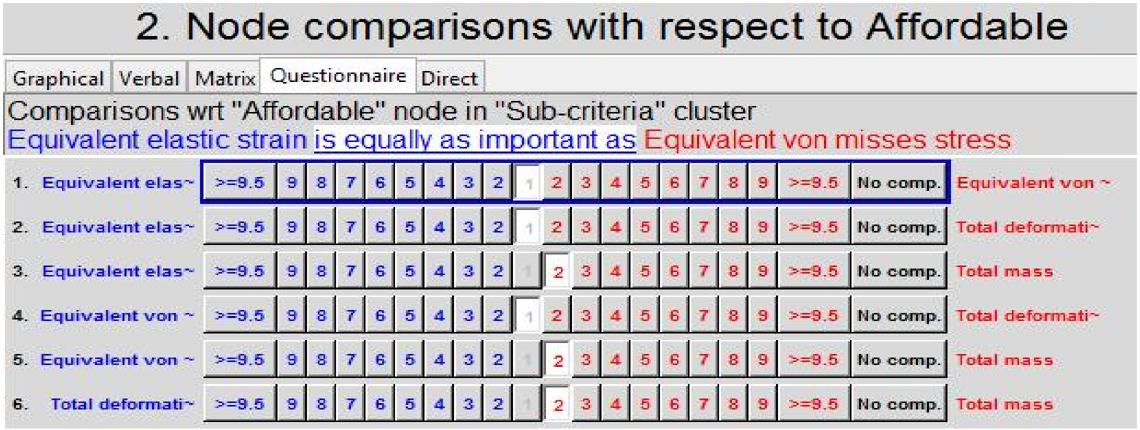


Figure 4.25: Questionnaire between sub-criteria with respect to affordable criteria

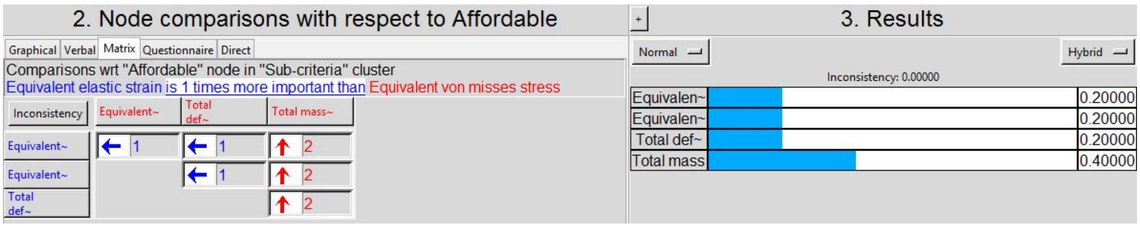


Figure 4.26: Pair-wise comparison between sub-criteria and resulting contribution of sub-criteria to affordable criteria

Next, pair-wise comparison of the alternative designs with respect to each sub-criteria are shown. Pair-wise comparison between alternative designs and resulting contribution of alternative designs to total mass sub-criteria are shown in **Figure 4.28**, where the most priority was Original design with a total aggregate weight of 0.42866. Pair-wise comparison between alternative designs and resulting contribution of alternative designs to total deformation sub-criteria are shown in **Figure 4.30**, where the most priority was Design 3 with a total aggregate weight of 0.26438. Pair-wise comparison between alternative designs and resulting contribution of alternative designs to equivalent von mises stress sub-criteria are shown in **Figure 4.32**, where the most priority was Design 5 with a total aggregate weight of 0.47253. Pair-wise comparison between alternative designs and resulting contribution of alternative designs to equivalent elastic strain sub-criteria are shown in **Figure 4.34**, where the priority were Design 4 and Design 5 with a total aggregate weight of 0.29425.

Pairwise comparison of alternative designs with respect to sub-criteria:

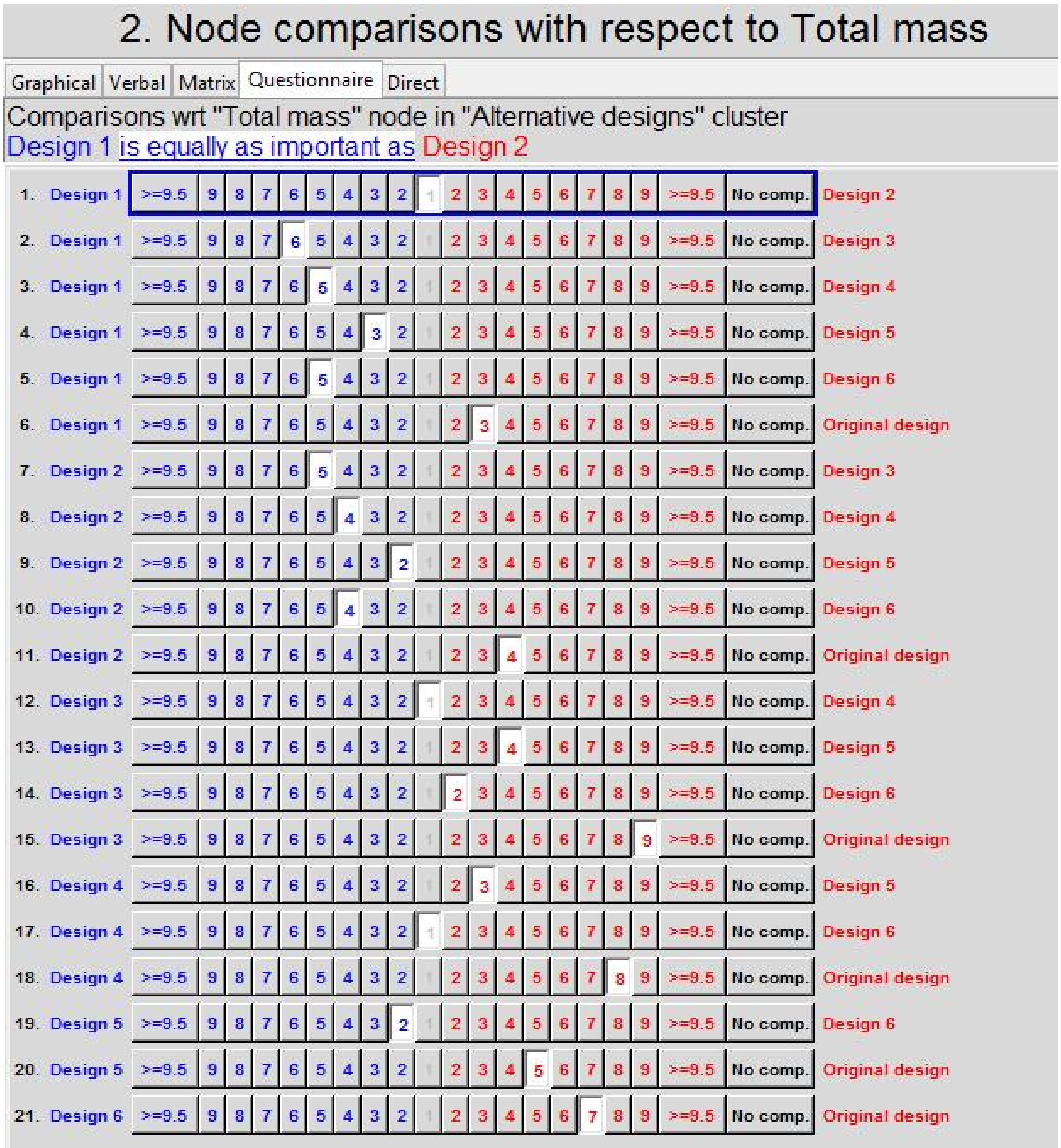


Figure 4.27: Questionnaire between alternative designs with respect to total mass sub-criteria

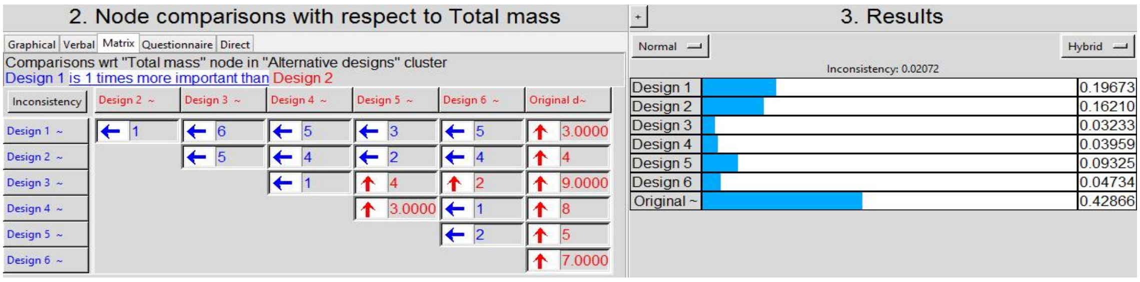


Figure 4.28: Pair-wise comparison between alternative designs and resulting contribution of alternative designs to total mass sub-criteria

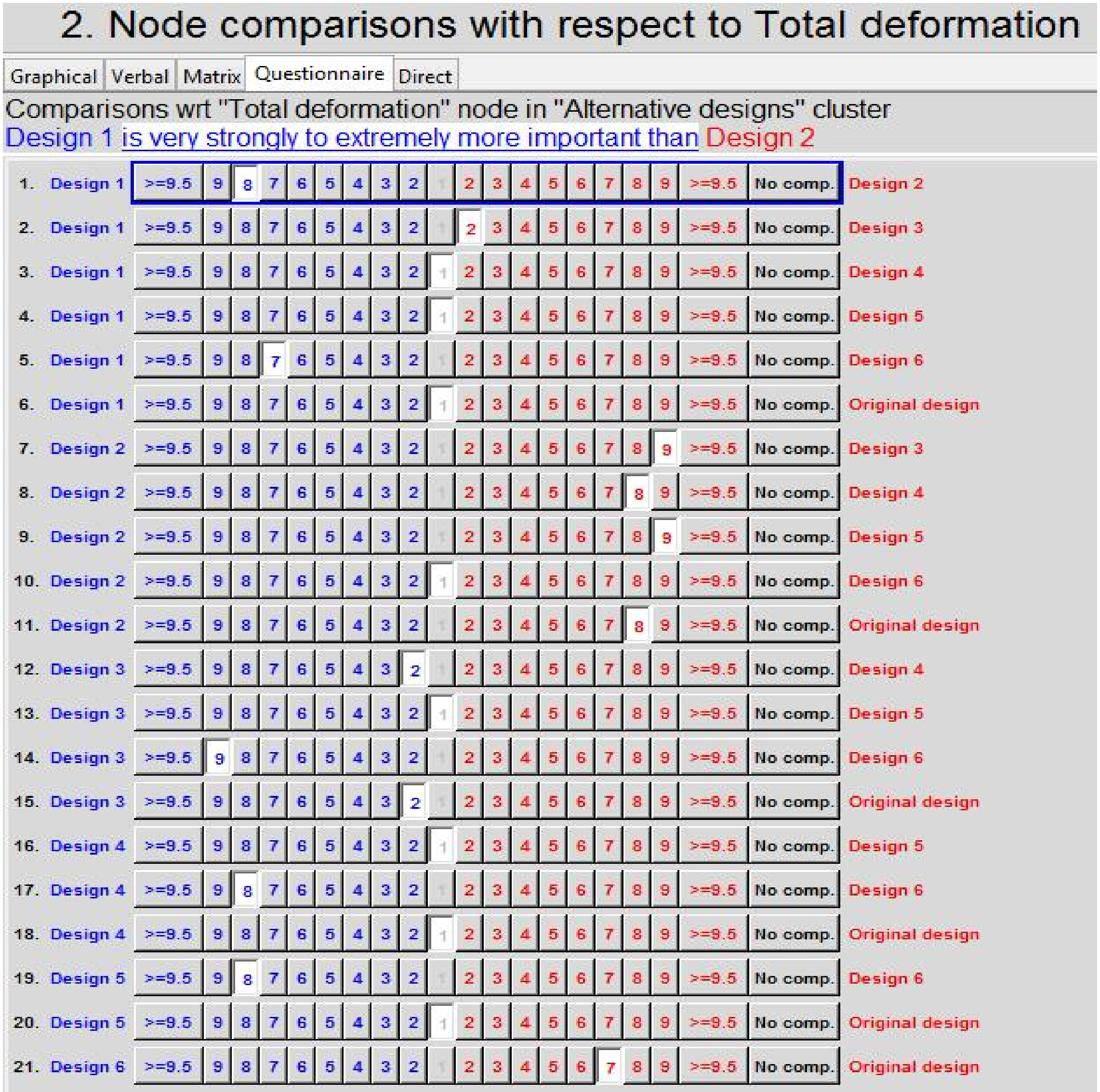


Figure 4.29: Questionnaire between alternative designs with respect to total deformation sub-criteria

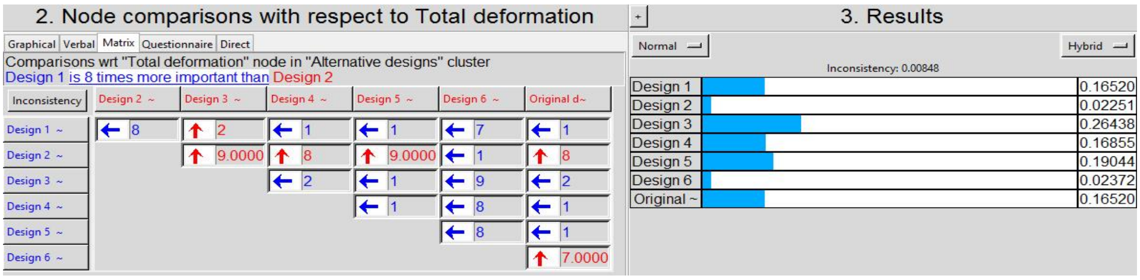


Figure 4.30: Pair-wise comparison between alternative designs and resulting contribution of alternative designs to total deformation sub-criteria

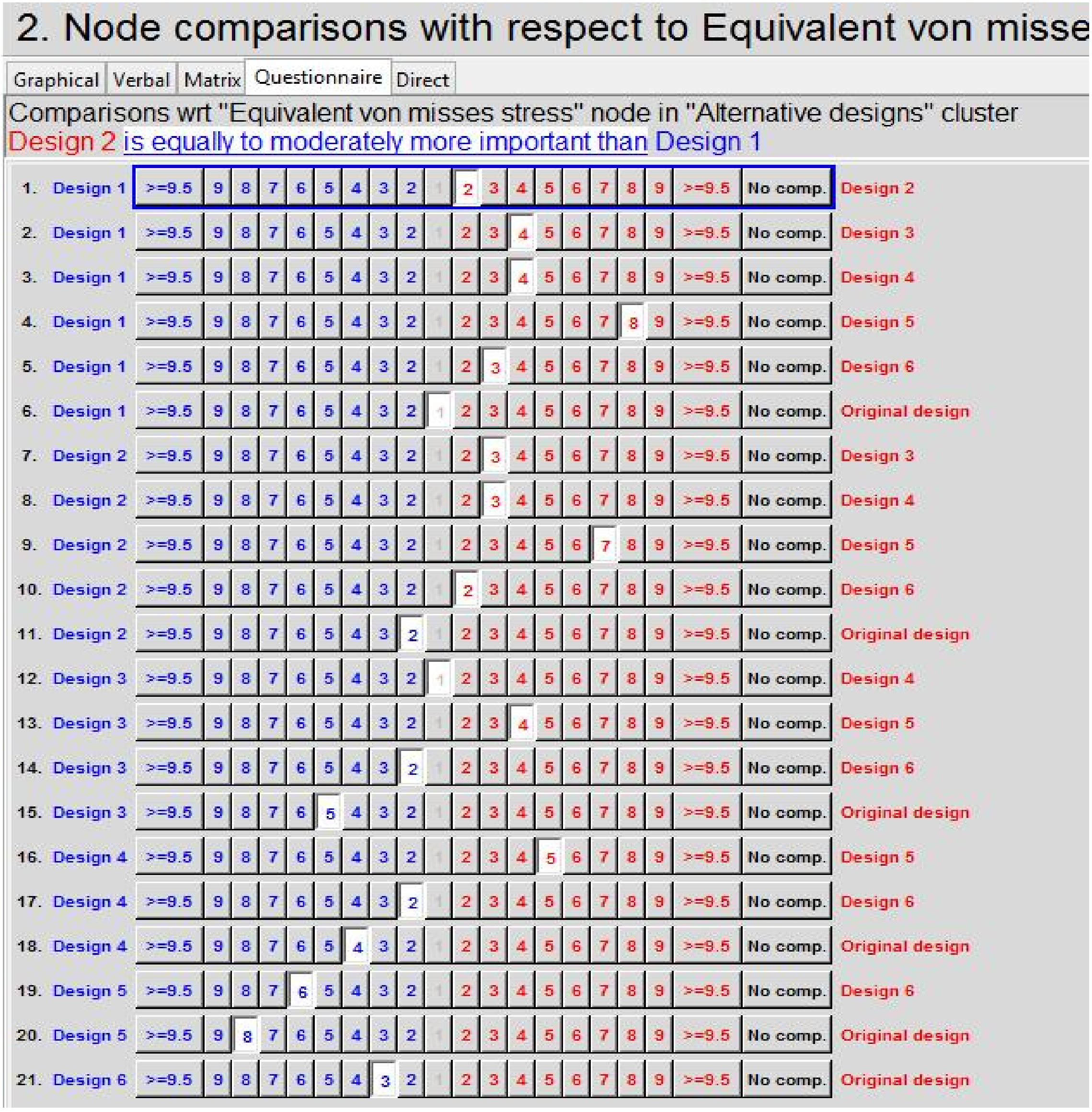


Figure 4.31: Questionnaire between alternative designs with respect to equivalent von mises stress sub-criteria

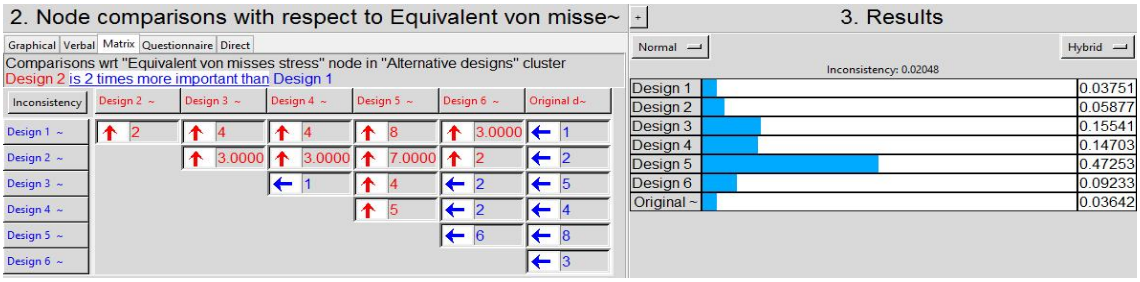


Figure 4.32: Pair-wise comparison between alternative designs and resulting contribution of alternative designs to equivalent von mises stress sub-criteria

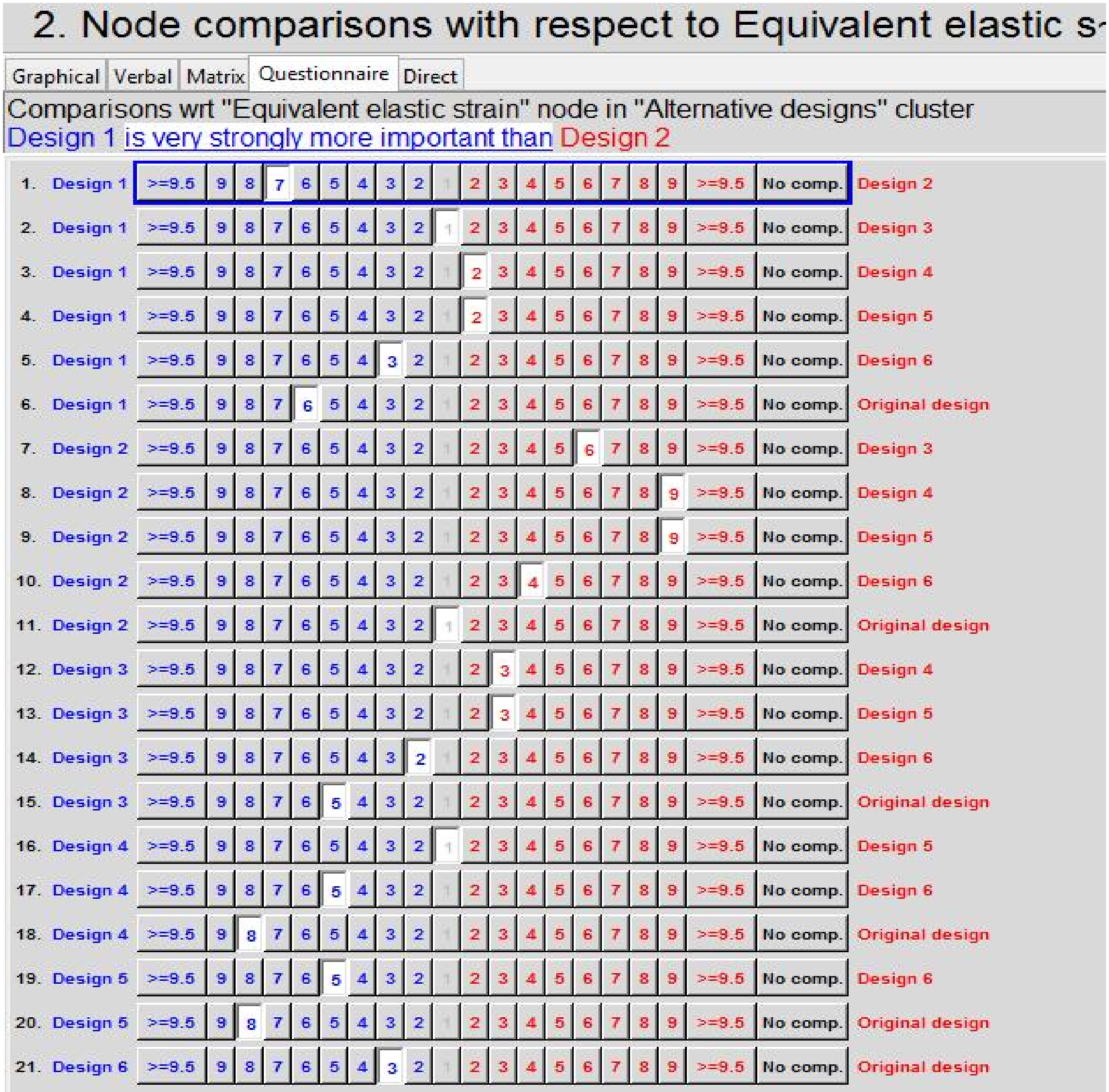


Figure 4.33: Questionnaire between alternative designs with respect to equivalent elastic strain sub-criteria

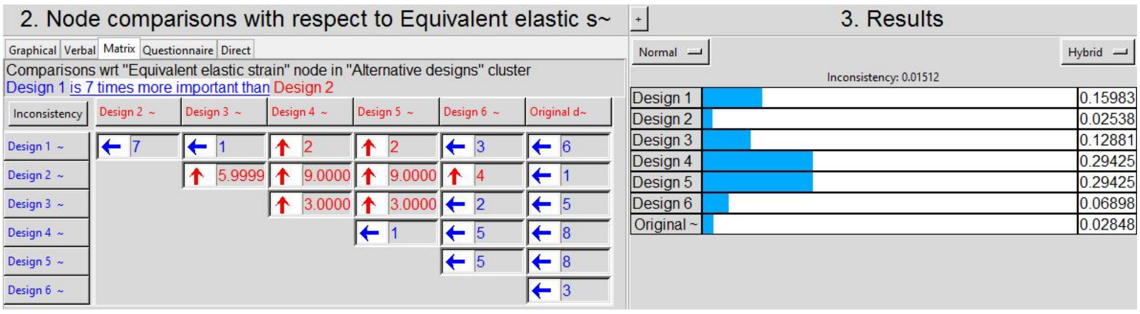


Figure 4.34: Pair-wise comparison between alternative designs and resulting contribution of alternative designs to equivalent elastic strain sub-criteria

4.3.1 Sensitivity Analysis

Finally, **Figure 4.35** demonstrate the priorities of the alternative designs. Obviously, the results are in the favour of the Design 5 (I -rib) with weight of 0.27993. The best floating brake calliper have been identified, a sensitivity analysis was performed to show the influence of changing different parameters of the model on the choice of the best floating brake calliper. Sensitivity analysis of light weight, fuel efficiency and affordable criteria shown in **Table 4.3**. First, consider the light weight criteria. By increasing the weight of this criteria by 25%, while reducing other criteria by 25%. It has been noticed that Design 5 (I -rib) is also the best choice with a weight of 0.2605 as shown in **Figure 4.36.** Then, consider the fuel efficiency criteria. By increasing the weight of this criteria by 25%, while reducing other criteria by 25%. It has been noticed that Design 5 (I -rib) still the best choice with a weight of 0.2622 as shown in **Figure 4.37**. Next, consider the affordable criteria. By increasing the weight of this criteria by 25%, while reducing other criteria by 25%. It has been noticed that Design 5 (I -rib) still the best choice with a weight of 0.2724 as shown in **Figure 4.38**.

The sensitivity analysis presented here demonstrates how consistent the decision is. The Design 5 (I –rib) as the best alternative remain the same even with significant changes on the criteria weights. This mean that the study was not sensitive to a small change on the criteria weights.

Super Decisions Main Window: FinalAHP.sdmod: Pri...

Here are the priorities.

Icon	Name	Normalized by Cluster	Limiting
No Icon	Design 1	0.13446	0.044821
No Icon	Design 2	0.05204	0.017346
No Icon	Design 3	0.16694	0.055648
No Icon	Design 4	0.17763	0.059209
No Icon	Design 5	0.27993	0.093310
No Icon	Design 6	0.05691	0.018970
No Icon	Original design	0.13209	0.044029

(a)

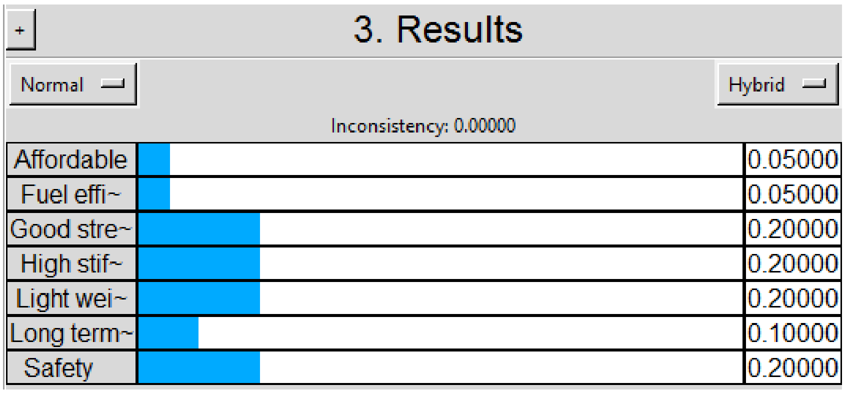
Graphic	Alternatives	Total	Normal	Ideal	Ranking
	Design 1	0.0448	0.1345	0.4803	4
	Design 2	0.0173	0.0520	0.1859	7
	Design 3	0.0556	0.1669	0.5964	3
	Design 4	0.0592	0.1776	0.6345	2
	Design 5	0.0933	0.2799	1.0000	1
	Design 6	0.0190	0.0569	0.2033	6
	Original design	0.0440	0.1321	0.4719	5

(b)

Figure 4.35: (a) and (b) Priorities of the alternative designs

Table 4.3: Sensitivity analysis of light weight, fuel efficiency and affordable criteria

Criteria	**Customer Priority (Original)**	**Light weight +25% Other -25%**	**Fuel efficiency +25% Other -25%**	**Affordable +25% Other -25%**
Light weight	3	3.75	2.25	2.25
Good strength	5	3.75	3.75	3.75
High stiffness	5	3.75	3.75	3.75
Safety	5	3.75	3.75	3.75
Fuel efficiency	3	2.25	3.75	2.25
Long term use	4	3	3	3
Affordable	3	2.25	2.25	3.75

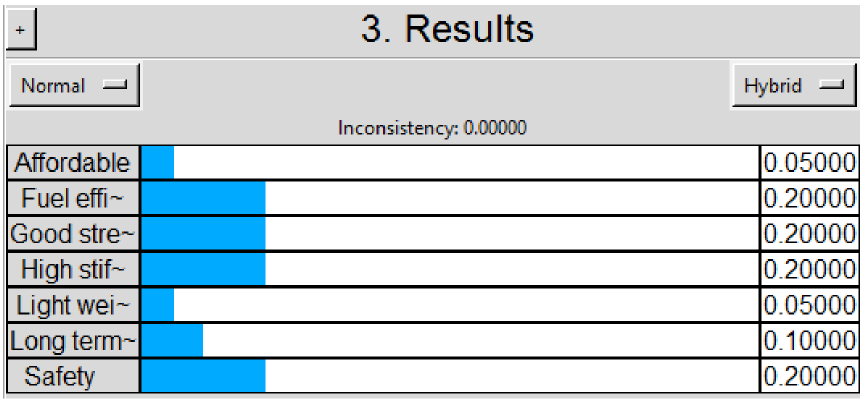


(a)

Graphic	Alternatives	Total	Normal	Ideal	Ranking
	Design 1	0.0470	0.1410	0.5412	5
	Design 2	0.0213	0.0638	0.2449	6
	Design 3	0.0508	0.1524	0.5851	4
	Design 4	0.0543	0.1630	0.6260	3
	Design 5	0.0868	0.2605	1.0000	1
	Design 6	0.0187	0.0560	0.2150	7
	Original design	0.0545	0.1634	0.6272	2

(b)

Figure 4.36: Sensitivity analysis of the light weight criteria, (a) the new assigned weights and (b) the resulting scores of the alternative designs



(a)

Graphic	Alternatives	Total	Normal	Ideal	Ranking
	Design 1	0.0468	0.1404	0.5355	5
	Design 2	0.0209	0.0628	0.2397	6
	Design 3	0.0512	0.1535	0.5855	4
	Design 4	0.0548	0.1643	0.6266	2
	Design 5	0.0874	0.2622	1.0000	1
	Design 6	0.0187	0.0561	0.2140	7
	Original design	0.0536	0.1607	0.6131	3

(b)

Figure 4.37: Sensitivity analysis of the fuel efficiency criteria, (a) the new assigned weights and (b) the resulting scores of the alternative designs

3. Results

Normal Hybrid

Inconsistency: 0.00000

Affordable	0.20000
Fuel effi~	0.05000
Good stre~	0.20000
High stif~	0.20000
Light wei~	0.05000
Long term~	0.10000
Safety	0.20000

(a)

Graphic	Alternatives	Total	Normal	Ideal	Ranking
	Design 1	0.0457	0.1370	0.5028	5
	Design 2	0.0190	0.0571	0.2097	6
	Design 3	0.0534	0.1603	0.5883	3
	Design 4	0.0572	0.1716	0.6300	2
	Design 5	0.0908	0.2724	1.0000	1
	Design 6	0.0189	0.0567	0.2083	7
	Original design	0.0483	0.1449	0.5319	4

(b)

Figure 4.38: Sensitivity analysis of the affordable criteria, (a) the new assigned weights and (b) the resulting scores of the alternative designs

4.4 CONCLUSIONS

Results revealed that Magnesium hybrid MMC is better than cast iron in considered of material selection for floating brake calliper. Bridge features with combination of two or more single features shows better overall improvement than single feature. Super Decision software have identified Alternative Design 5 (I -rib) was the best floating brake calliper among those alternative designs with weight of 0.27993.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This project is focused on the material selection and design selection of floating brake calliper. The project started by studying a current caliper design. The detail review of the thesis is about the advantages of Magnesium hybrid MMC to replace the currently used Gray cast iron floating brake calliper and proposed few innovative alternative designs with different bridge structures to improve the performance of floating brake calliper.

5.2 CONCLUSIONS

The material of a brake calliper body must be rigid to allow less deflection and should be light to reduce the final weight. Magnesium hybrid MMC, AZ31-14.0SiC_{micro}-1.0SiC_{nano} can be a good alternative to replace Gray cast iron as it potentially met the present demands for high performance floating brake calliper. The Magnesium hybrid MMC used in replace the Gray cast iron has reduced the weight of the floating brake calliper by 72.29%, maximum total deformation distribution by around 2.76% and maximum equivalent elastic strain by 2.93%. Bridge design features are most important in maintaining structural stiffness to reduce deflection. Combination of single features gives the most stiffness improvement. Flexural strength can be enhanced by ribs structure on floating brake calliper design whilst weight reduced simultaneously. Alternative Design 5 with bridge features of combination of two row rib and one column rib is selected as the best floating brake calliper among alternative designs. It can be concluded that floating brake calliper made of Magnesium hybrid MMC with combination of more than one rib structure bridge design features could performed better performance and safer than conventional brake calliper.

5.3 RECOMMENDATIONS OF THE FUTURE RESEARCH

The innovative floating brake calliper designs were proposed as a primary attempt to provide a floating brake calliper with reduced weight and less total deformation distribution. For future studies, recommendation can be done regarding the reduction in weight of the floating brake calliper which is removing the material in areas where there is less stress distribution. As floating brake calliper is an assembly of different part, vibration analysis can be done for further prove the effectiveness of the design. With continuous research, these fresh designs could be act as benchmark for further developed and tested for automotive applications.

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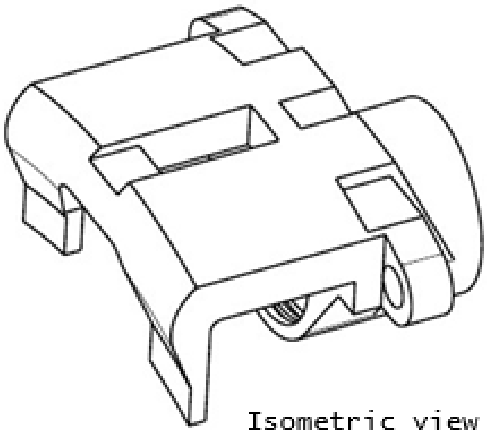
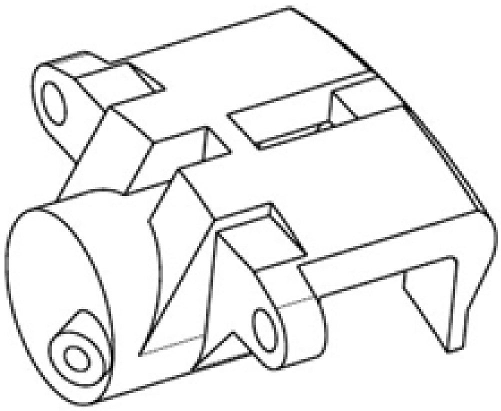
APPENDICES A

DETAILED DRAWING OF FLOATING BRAKE CALLIPER DESIGNS

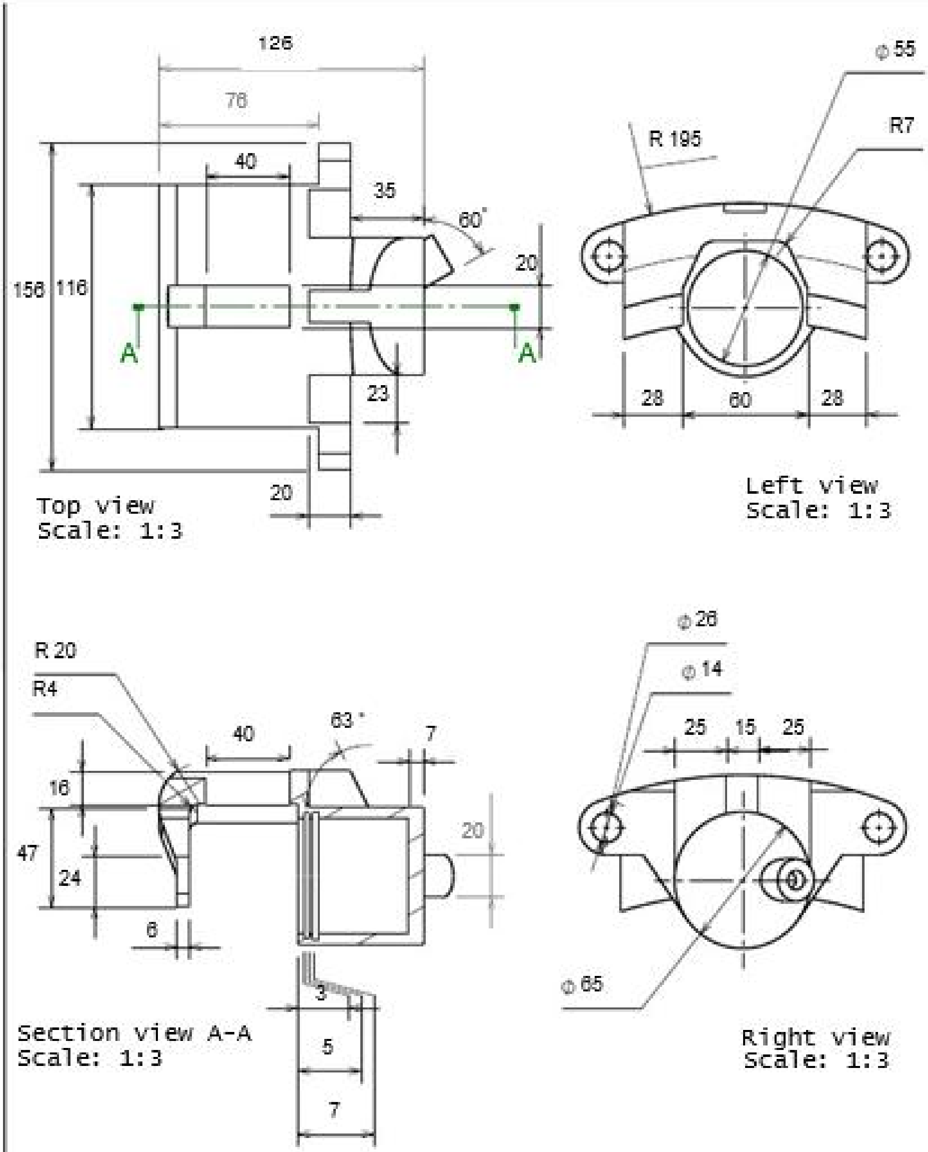


Isometric view A
Scale: 1:2

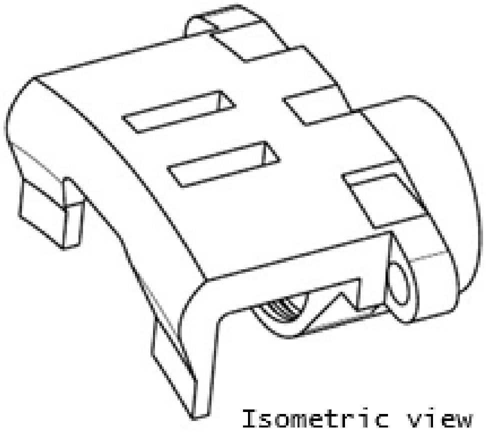


Isometric view B
Scale: 1:2

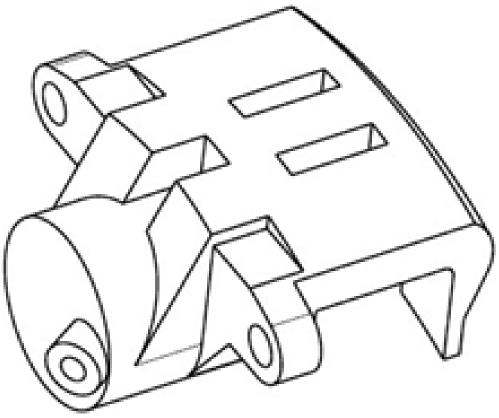
This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 02/11/2015	DRAWING TITLE: Original model Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.60196	SCALE 1:2	SHEET 1/14



This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 02/11/2015	DRAWING TITLE: Original model Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.60196	SCALE 1:3	SHEET 2/14

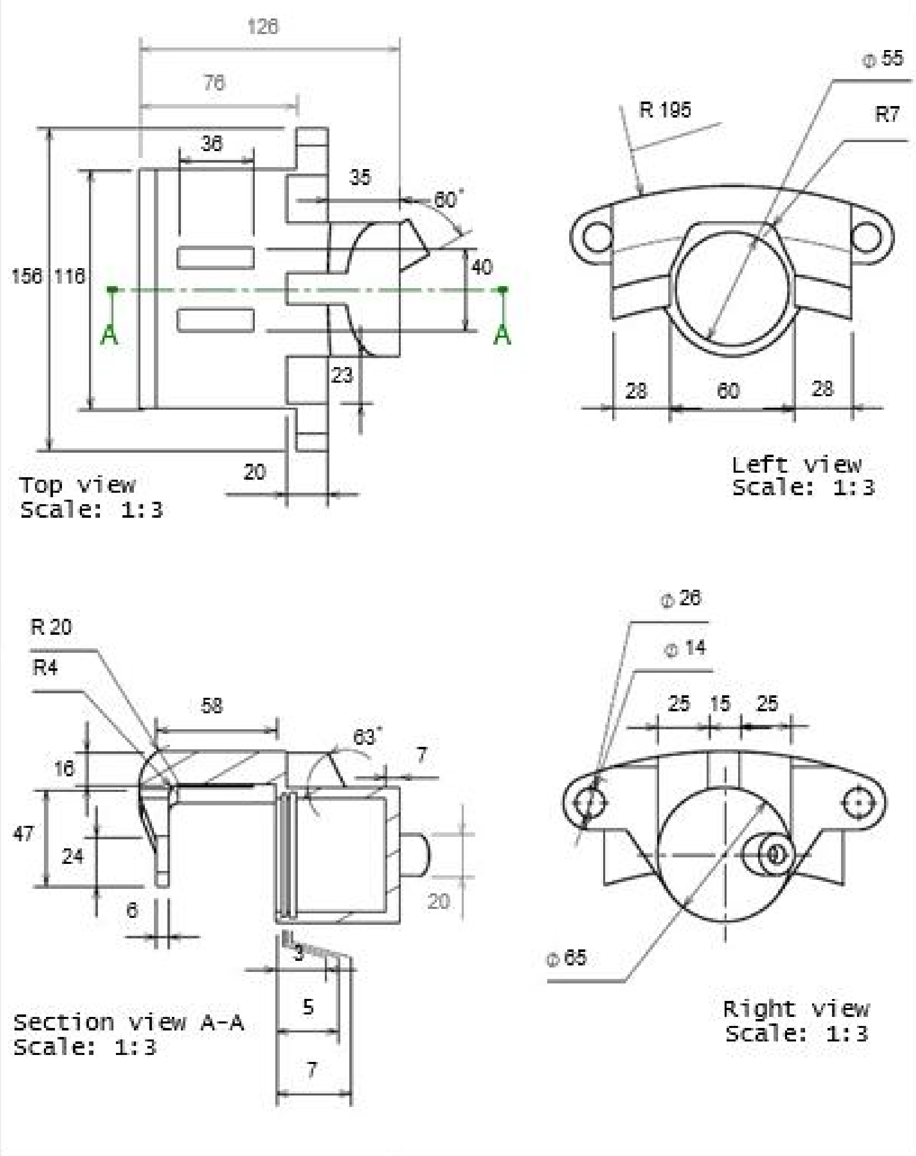


Isometric view A
Scale: 1:2

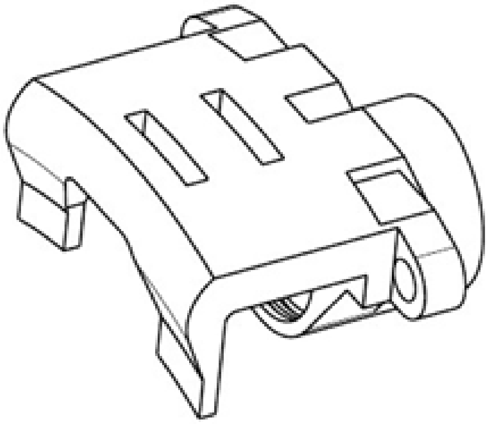


Isometric view B
Scale: 1:2

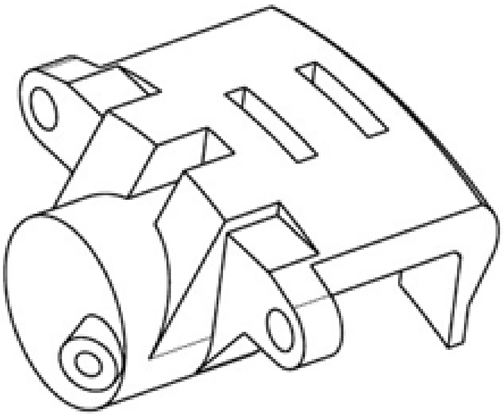
This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 15/11/2015	DRAWING TITLE: Design 1 (row rib) Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.60703	SCALE 1:2	SHEET 3/14



This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 15/11/2015	DRAWING TITLE: Design 1 (row rib) Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.60703	SCALE 1:3	SHEET 4/14

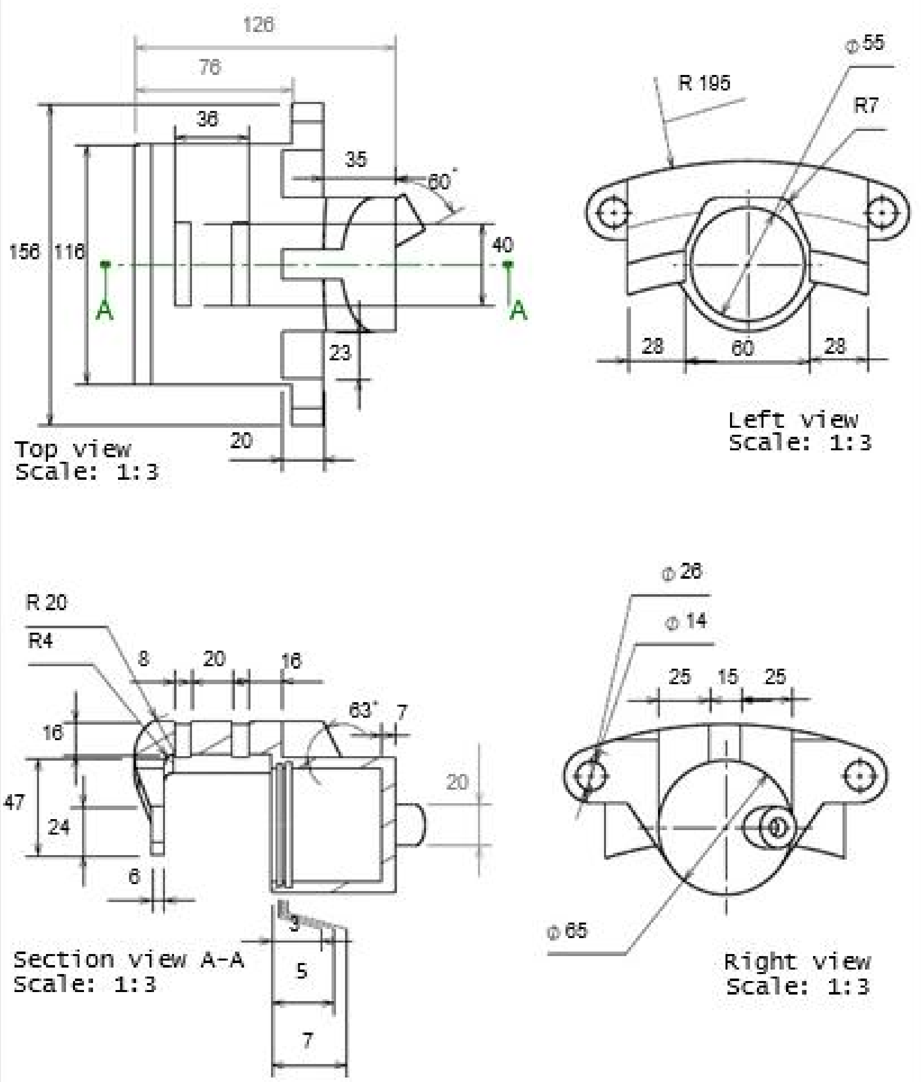


Isometric view A
Scale: 1:2

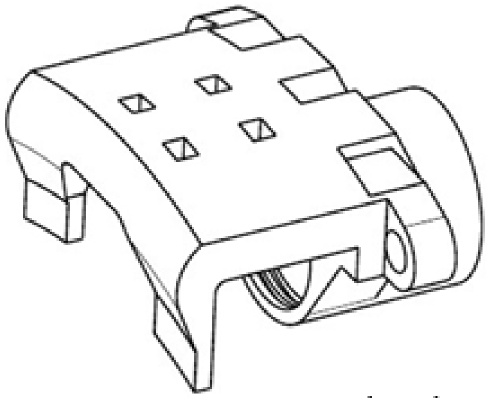


Isometric view B
Scale: 1:2

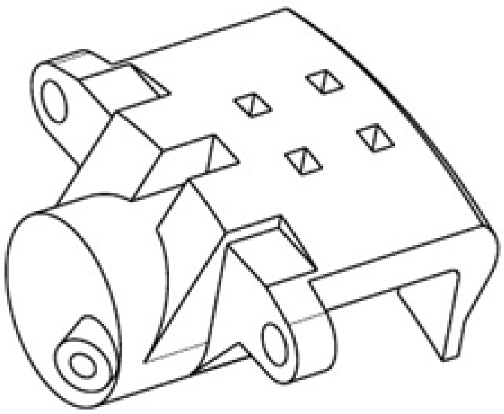
This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 29/11/2015	DRAWING TITLE: Design 2 (column rib) Floating Brake Calliper		
CHECKED BY DR. NANANG	DATE	MASS (kg) 0.60959	SCALE 1:2	SHEET 5/14



This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 29/11/2015	DRAWING TITLE: Design 2 (column rib) Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.60959	SCALE 1:3	SHEET 6/14

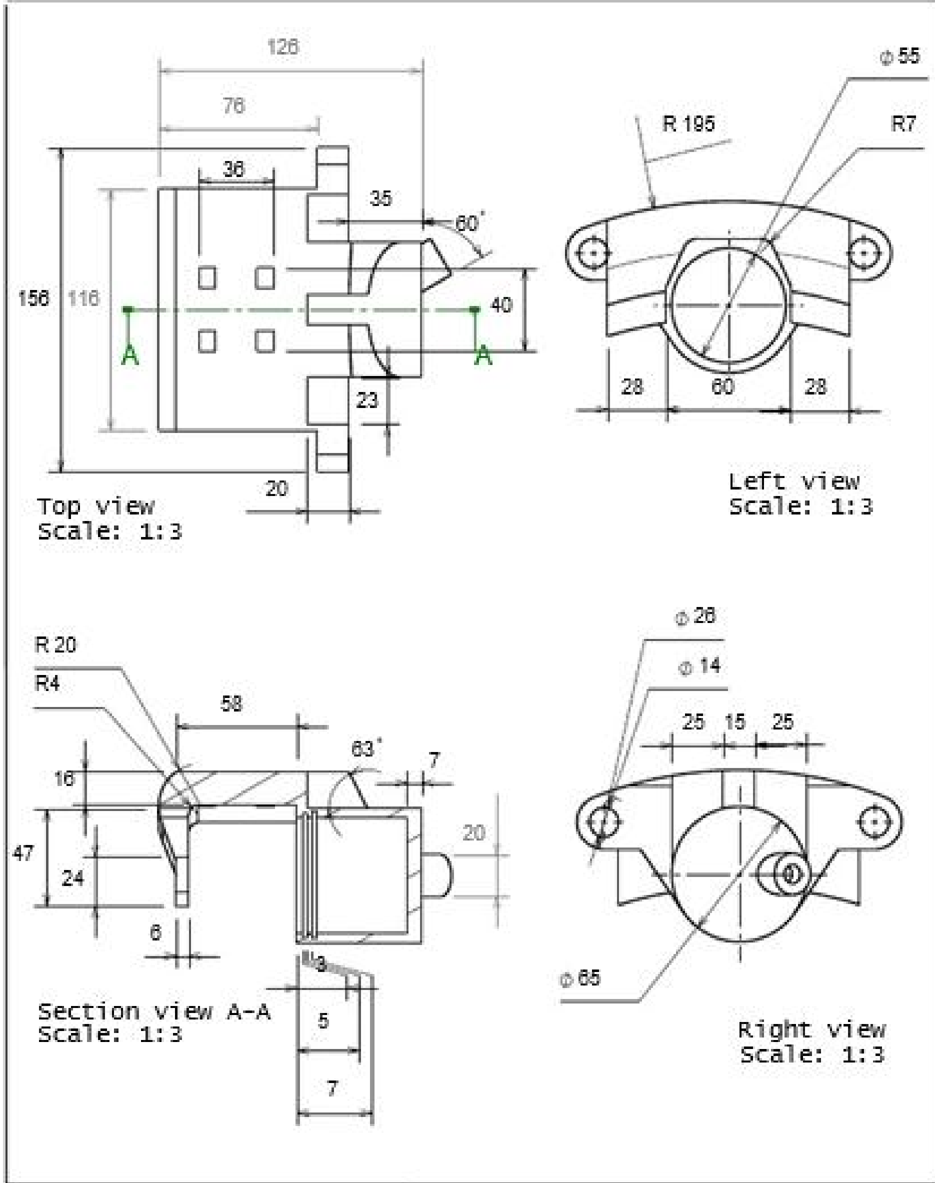


Isometric view A
Scale: 1:2

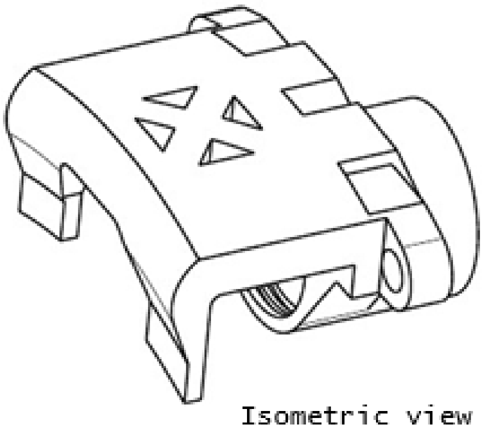


Isometric view B
Scale: 1:2

This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 1/12/2015	DRAWING TITLE: Design 3 (cross rib) Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.61980	SCALE 1:2	SHEET 7/14



This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang			
DRAWN BY CHIA	DATE 1/12/2015	DRAWING TITLE: Design 3 (cross rib) Floating Brake Calliper			
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.61980	SCALE 1:3	SHEET 8/14	



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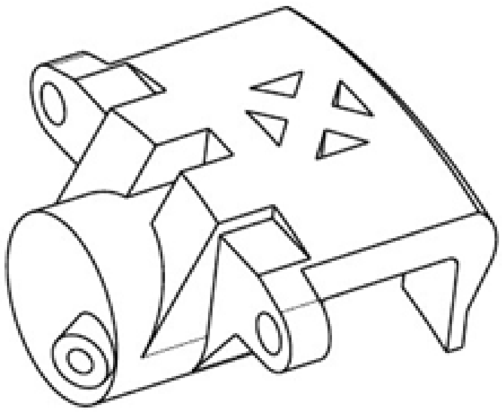
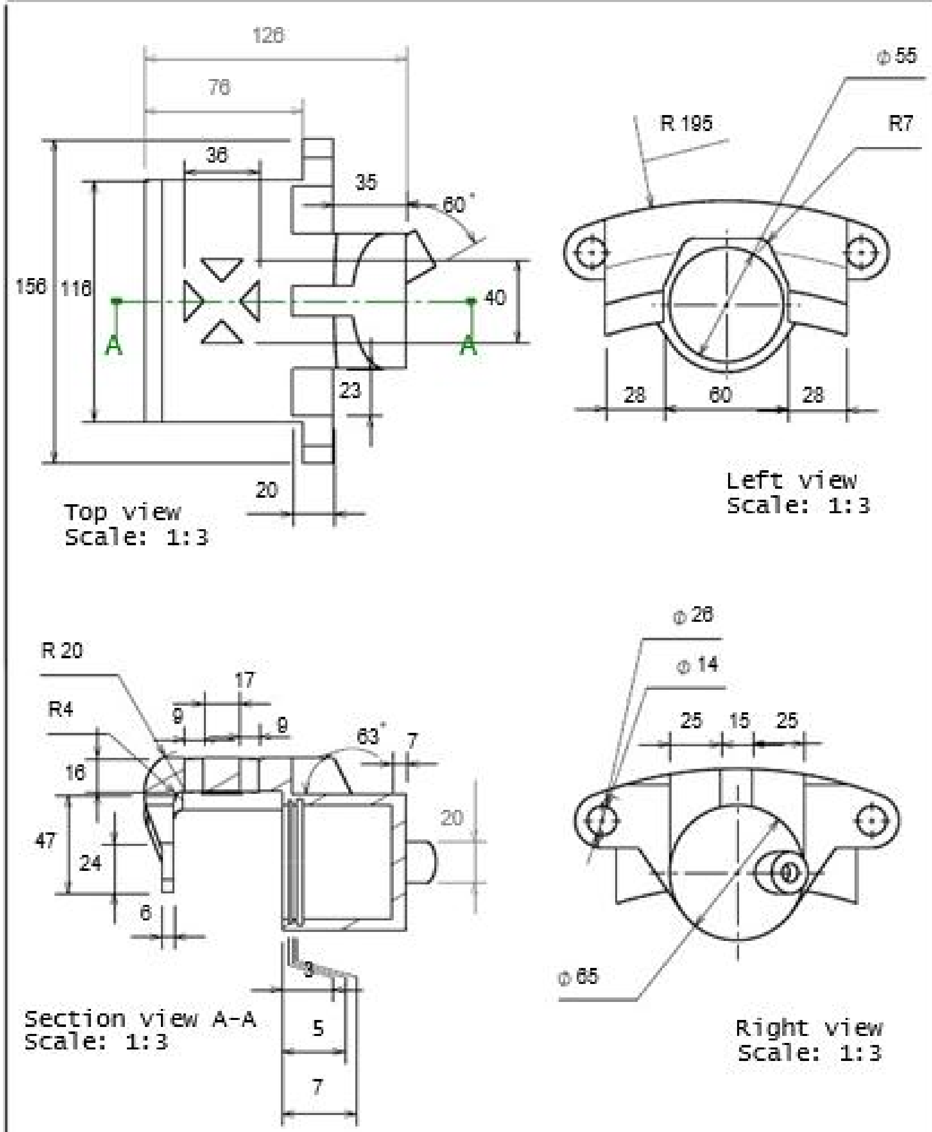
Scale: 1:2

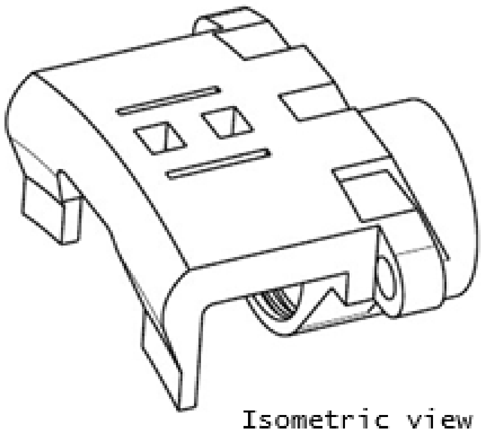


Isometric view B
Scale: 1:2

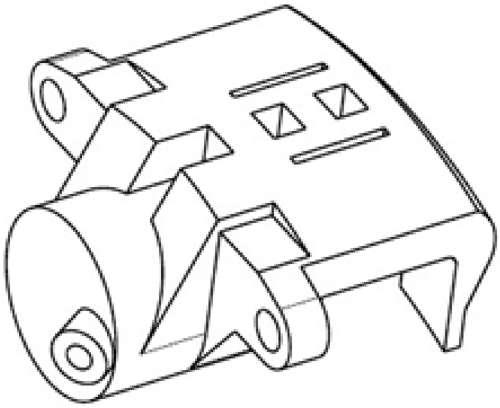
This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 2/12/2015	DRAWING TITLE: Design 4 (X-rib) Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.61722	SCALE 1:2	SHEET 9/14



This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 2/12/2015	DRAWING TITLE: Design 4 (X-rib) Floating Brake Calliper		
CHECKED BY DR. NANANG	DATE	MASS (kg) 0.61722	SCALE 1:3	SHEET 10/14

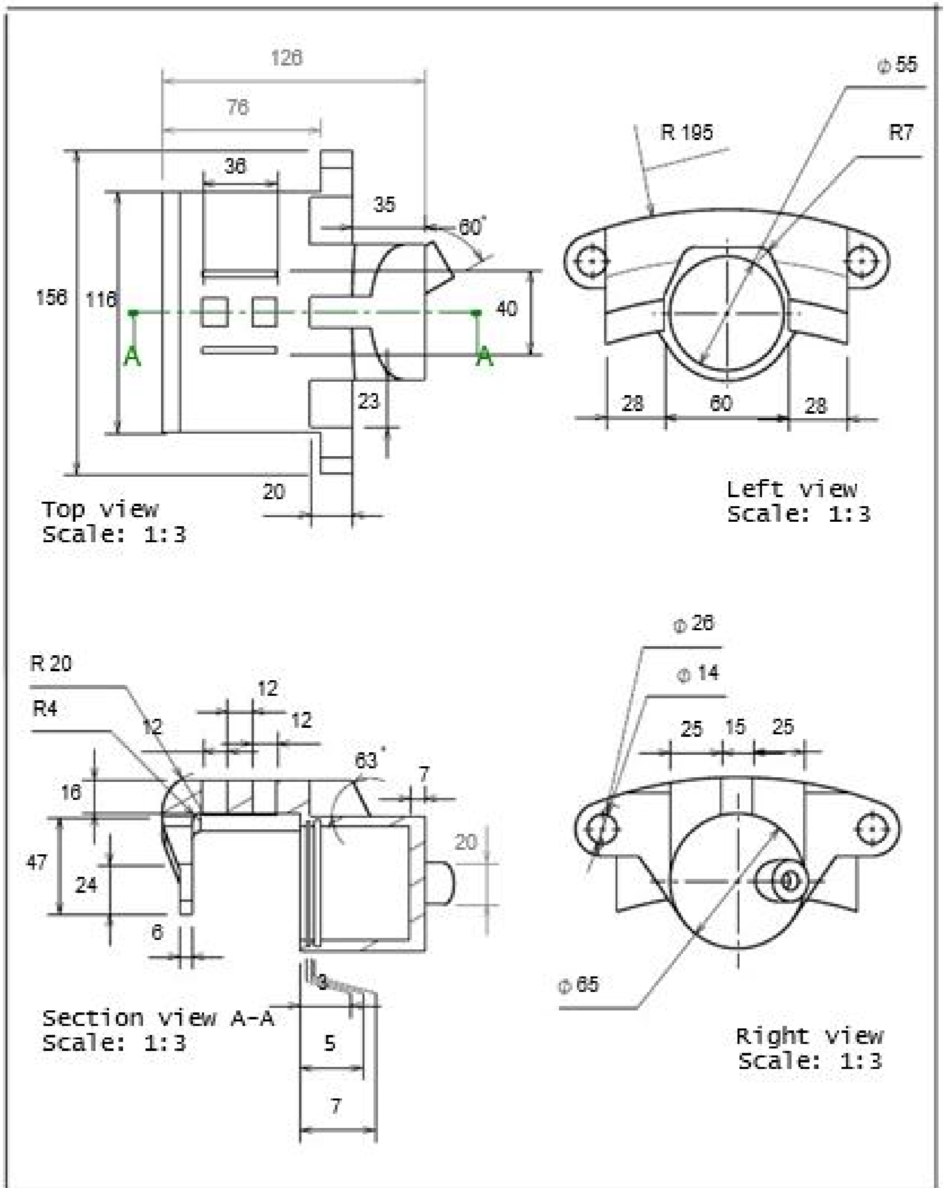


Isometric view A
Scale: 1:2

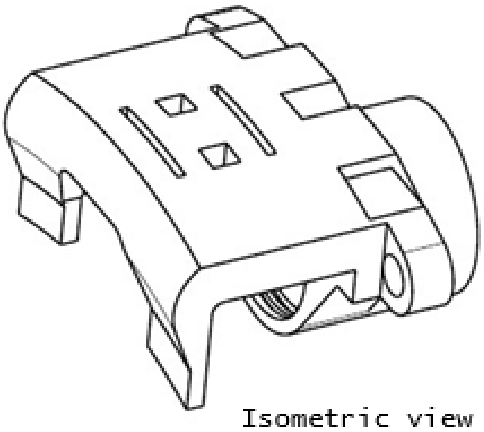


Isometric view B
Scale: 1:2

This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 5/12/2015	DRAWING TITLE: Design 5 (I-rib) Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.61240	SCALE 1:2	SHEET 11/14



This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 5/12/2015	DRAWING TITLE: Design 5 (I-rib) Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.61240	SCALE 1:3	SHEET 12/14



Isometric view A
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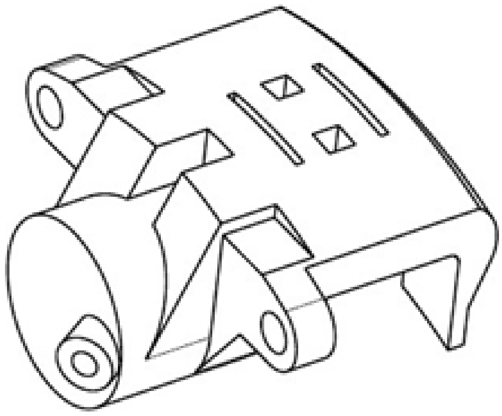
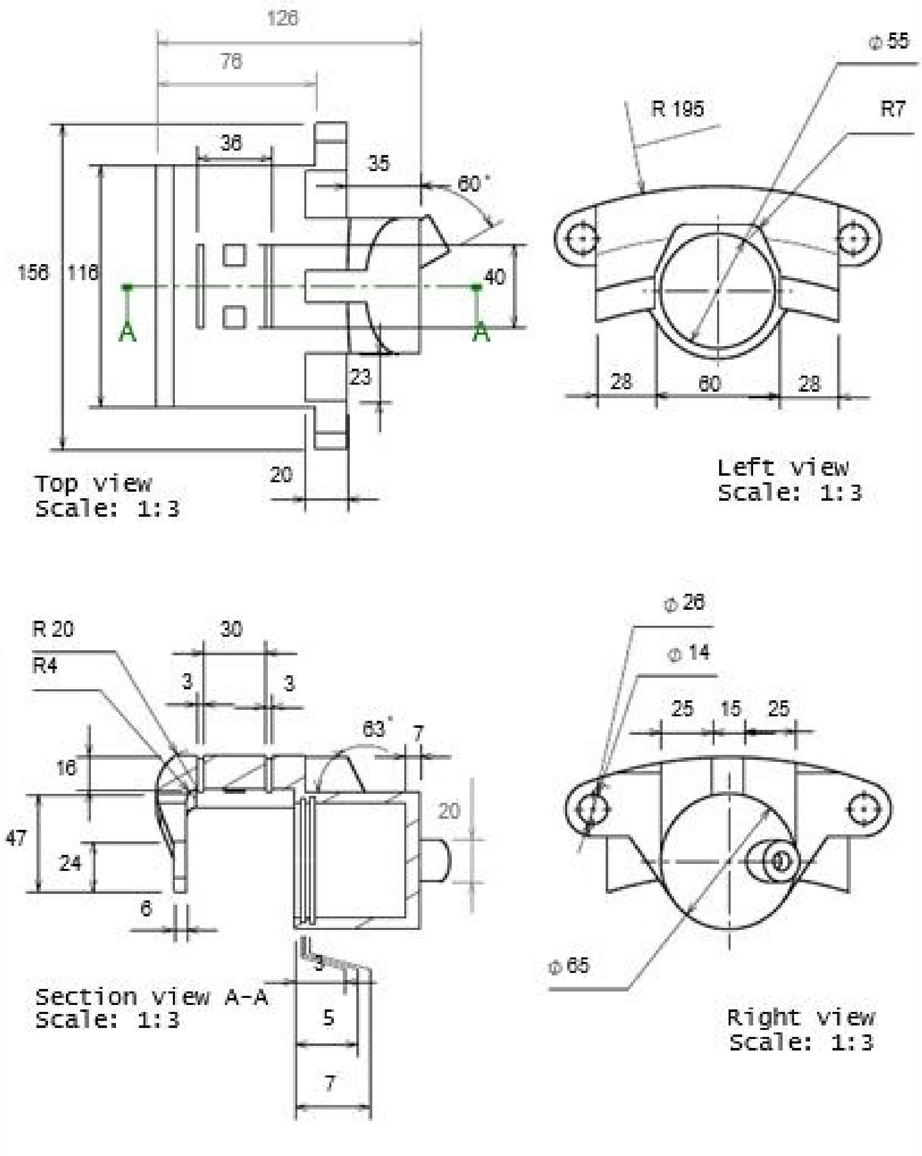


Isometric view B
Scale: 1:2

This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 10/12/2015	DRAWING TITLE: Design 6 (H-rib) Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.61597	SCALE 1:2	SHEET 13/14



This drawing is our property. It can't be reproduced or communicated without our written agreement.		University Malaysia Pahang		
DRAWN BY CHIA	DATE 10/12/2015	DRAWING TITLE: Design 6 (H-rib) Floating Brake Calliper		
CHECKED BY DR.NANANG	DATE	MASS(kg) 0.61597	SCALE 1:3	SHEET 14/14