# TOPOLOGICAL OPTIMIZATION IN 3D PRINTING DESIGN

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# DECLARATION

I declare that this project report entitled "Investigation On Structural Vibration Problem At MARS Building UTeM" is the result of my own work except as cited in the references

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**SUPERVISOR'S DECLARATION**

I have checked this report and the report can now be submitted to JK-PSM to be delivered back to supervisor and to the second examiner.

Signature : ...................................

Name of Supervisor : ...................................

Date : ...................................

**DEDICATION**

I would like to dedicated this dissertation to my loving parent. They have been my rock throughout this research. They have been nothing but patient and willing to give me some space. Always keeping in mind that their son is a capable person. They have been working their whole life to just finance my journey to getting my degree, never saying ‘give up’ or ‘try something else’. They would always say to finish what I started always keep an eye on my goals.

I would like to give thanks to my friends. Their negative support for always saying that it was a waste of time and keeping my will of fire burning hot and strong. Their negative encouragement also have finish my research paper to the point of always focus on my goals.

My course mate, they have given me enough information for all of us to finish and able to reduce the stress us student are commonly known to have. Their assistance have cut to work load in half so to speak.

I am grateful too for the support and advice from my faculty colleagues and the seniors. Thanks to the university to have given me this opportunities to do research and able to successfully finish it.

# ABSTRACT

In the industry sector, the demand for material even more so raw material has risen quite a lot in this coming years. The purpose of this thesis was to conduct the process of topology optimization on an object, then test it whether or it is viable to be printed using 3D printer. Afterward evaluate the data from the experimental and the theoretical data. The topological optimization process is a revolutionary process in which it reduce the use of material but still able to maintain the product mechanical characteristic and its feature. In this thesis, the part chosen was a brake pedal, it is believe that there is still room for improvement to be done. The brake pedal was then constructed into a 3D model using CAD then it was imported into the Optimization software. After the topology optimization process was completed, the final design and a number of sets of data was obtain. From the final design, it was reconstructed back using CAD software to look similar to the final optimization design. Afterward the 3D model of the final design was then printed using CubePro 3D printer. The finish product of the 3D printer was then compare with 3D model. The max value of data obtained from the analysis for the deflection value drop 86.84%, the von mises value increased about 40.06%, the pressure drastically about 90% and for the max shear stress increase 33.3%. For its exterior data obtained from using CATIA CAD is was determined that the weight was reduce up to 33.33%, the volume also reduce 15% but the area stayed the same. The data comparison between the 3D model CAD and the actual printed part is undesirable the overall aesthetic appeal was only satisfactory. The data obtained was as expected even with the CubePro because the ABS 3D printer are well known for their weakness. The aim to determine the viability of printing the topology optimize part was achieve and the result it just on the level satisfactory.

# ABSTRAK

Dalam sektor industri, keperluan bahan-bahan mentah semakin meningkat berikutan era sekarang. Tujuan tesis ini adalah untuk menjalankan proses pengoptimuman topologi terhadap sesuatu bahan, kemudian menguji sama ada bahan habis optimasi tu boleh dihasilkan menggunakan pencetak 3D. Selepas itu, data yang telah diperolehi melalui analisis akan di bandingkan dengan data eksperimen. Proses pengoptimuman topologi adalah satu proses revolusi di mana ia mengurangkan bahan mentah yg digunakan untuk menghasilkan bahan tersebut tetapi masih mengekalkan ciri-ciri mekanikal nya. Dalam tesis ini, bahagian yang dipilih adalah pedal brek, masih dipercayai ada lagi ruang untuk diperbaiki. Brek padel ini telah pon dihasilkan nya wakil 3D modal menggunkan CAD perisian dan kemudian diimportkan ke dalam perisian Optimization. Selepas proses pengoptimuman topologi telah disiapkan, reka bentuk akhir dan beberapa set data telah diperolehi. Dari reka bentuk akhir, dari situ ia telah direka bentuk semula menggunakan perisian CAD untuk kelihatan serupa dengan pengoptimuman reka bentuk akhir. Selepas itu modal 3D reka bentuk itu telah kemudian dicetak menggunakan pencetak CubePro 3D. Produk yang dihasilkan dari pencetak 3D itu kemudiannya dibandingkan dengan model 3D. Nilai max data yang diperolehi daripada analisis untuk nilai “deflection” 86,84%, nilai “von mises” meningkat kira-kira 40.06%, nilai “pressure” turun drastik kira-kira 90% dan bagi “max shear stress” meningkat 33.3%. Untuk data luaran yang diperolehi daripada menggunakan CATIA CAD telah didapati bahawa berat badan itu telah dikurangkan sebanyak 33.33%, jumlah isipadu juga mengurang 15% tetapi nilai kawasan tidak berubah. Perbandingan data antara model CAD 3D dan bahan dicetak adalah tidak diingini tarikan estetik keseluruhan hanya memuaskan. Data yang diperolehi adalah seperti yang diharapkan walaupun dengan CubePro kerana pencetak 3D ABS terkenal dengan kelemahan mereka. Antara tujuan tesis adalah untuk menentukan sama ada bahagian topologi mengoptimumkan dapat dicetak atau tidak telah pon tercapai dan hasilnya ia hanya pada tahap yang memuaskan.

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## LIST OF ABBEREVATIONS

| | |
|---|---|
| SLA | Stereo lithography apparatus |
| SLS | Selective laser sintering |
| FDM | Fuse deposition modelling |
| 3D | Three-dimension |
| CAD | Computer aided design |
| ESO | Evolutionary structural optimization |
| BESO | Bi-directional evolutionary structural optimization |
| SIMP | Solid isotropic material and penalization |
| MMA | Method of moving asymptotes |
| NA | Naturally aspiration |

# CHAPTER 1

# INTRODUCTION

## 1.1 BACKGROUND

Topological optimization is a method of effectively using material (optimize) layout for a certain design using a calculated mathematical approach. The design should have gone through rigorist analysis from load bearing analysis to stress analysis thus providing multiple parameter, within that parameter is the topological optimization will be conducted without changing any parameter. Engineer can conduct experiment or studies to find out which design is the most cost effective and optimum design structure without losing any vital function of the design.



In Topological optimization they are different field of optimization, with which of them address a different problem. Sizing, shape and topological all confront different problem. Through sizing optimization it mainly discuss around the idea that there is an optimum thickness for all design. By configuring the maximum or minimum thickness for each region of the design it can provide an effective design structure that can support the truss structure that holds the design in place. By doing so it can also preserve or not altering the physical quality of the design. For shape optimization, as the name suggest it focus on developing or finding the best design structure that can accompany the functionality of the original design. By implementing the shape optimization, engineer can innately create an optimum shape that as it was mention before can accompany the original propose without any problem. In topological optimization mainly focus on the determination of the feature of the design. These feature mainly concern the location, hole and the connectivity of all the domain that make up the design.

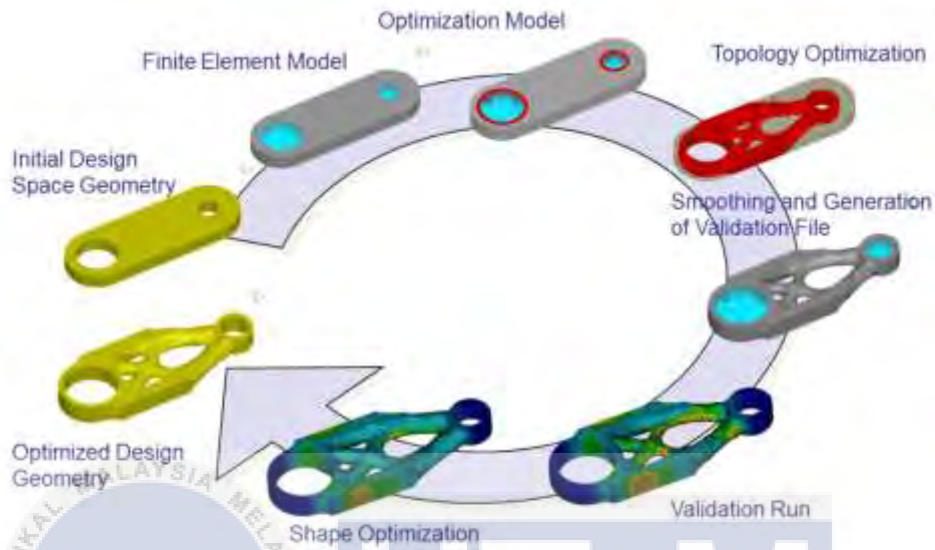



Figure 1.1: Proses of topological optimization

3D printer as an amazing one of a kind machine. The 3D printing machine's purpose is to convert CAD drawing into a 3d sculptor. The 3D printer was first develop in 1980 by an amazing Japanese innovator. At that time it was called rapid prototyping technology or in short RP tech. Its main purpose was too effectively and shorted the time of manufacturing prototype for product development for Industry Company. By 1986 the first patent 3D printer was develop. The stereo lithography apparatus (SLA) was the first patent 3D printing machine belongs to Charles Hull just exactly like figure 2. The stereo lithography apparatus or in other name optical-fabrication, photo-solidification or resin printing create or print the product by laying material on top of the previous material using photo polymerization as its bonding method. The photo polymerization process works by using light that cause a chain of molecules to link or combine together then produce polymer. After countless testing and quality control the final 3D printer was sold 1988. Not counting Charles Hull they are many other countless entrepreneurs that are within his time are doing or developing the same technology. Thus producing many other method of 3D printing for example Carl Deckard help develop the selective laser sintering (SLS) and Scott Crump ensure the future of fuse deposition modelling (FDM) which now very famous among open source 3D printer.

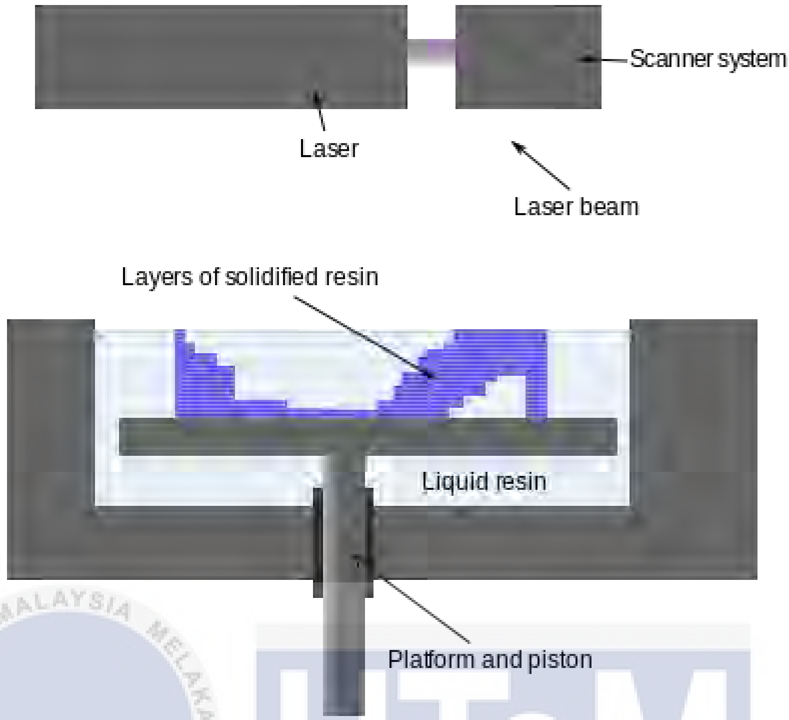



Figure 1.2: Stereo Lithography Apparatus (SLA)

By combining this two idea topological optimization 3D printing create an enormous amount of opportunity and advantage for both designer and manufacturer. 3D printing is the technology of rapid prototyping and combine with topological optimization where by optimizing its sizing, shape and topological structure without discarding its vital part and function will benefit the manufacturer in cost effectiveness greatly and also help the designer develop a master piece design and reduce the time of rapid prototype process.

## 1.2 PROBLEM STATEMENT

The problem that is responsible for this project to arise is as follows:-

i. The cost required to manufacturer the product is expansive.
ii. Material use to mass manufacturer product is too high.
iii. Waste material and capital on excessive use of it.

## 1.3 OBJECTIVE

The objective of this experiment is as follows:-

i. To perform topological optimization on product to reduce its weight or mass by using software Hyperworks.
ii. To determine whether or not is it viable to fabricate product of topological optimization using 3D printer
iii. To evaluate the theoretical data and experimental data.

## 1.4 SCOPE OF PROJECT

This thesis aim is the implement the Topological Optimization process on the Additive manufacturing technology. Using the following process:-

i. Software modelling using CAD CATIA.
    - Using CAD CATIA for 3D modelling and representation of the before and after topological optimization.
ii. Software analysis using Hyperworks.
    - After done creating the 3D model using CAD, the model is then transfer to this analysis software to be conducted different analysis such as stress analysis or static analysis.
iii. Actual fabricating the CAD model using 3D printer model Kossel.
    - The Kossel is one of the open source 3D printer provided for this project. After the analysis is done, its model is then transfer into the 3D printer database.
iv. Compared theoretical data with experimental data.
    - The theoretical data was provided by the analysis software Hyper works and the experimental data will be provided from the finish printed 3d part.

v. Report writing.

- After all discussion were made and all argument is settle towards the data, a full report will be provided explaining all the work was done for this research.

## 1.5 GENERAL METHODOLOGY

These are the activities that are needed to be carried out in order to accomplish or achieve the objective of this project:-

i. Literature Review

- Journal, articles or even any reading material that are occupy the field of studies of this project are reviewed.

ii. 3D Representation

- Draw the full 3D design using computer aided design Catia to inspect any flaws before start to print and are able to modify to implement the topological optimization concept on it.

iii. Analysis and Propose Solution

- Analysis will be conducted before moving on to the 3D printing, the analysis will be done using the software hyper works. Hyper works is a software specifically design to be an analysis software. The analysis will continue until the modification on the product is stable and no change in appearance or its micro structure.

iv. Producing product through 3D printing

- After analysis process is successful, the 3D representation of the product will be transfer into another software called slicer where it will be reconstructed into a format that the 3D printer can read then print.

v. Conduct a string of experiment to determine the mechanical properties
    - The product produce by the 3D printer will be then submitted to countless experiment to test its mechanical properties and gather experimental data at the same time.

vi. Comparison between the experimental data and the theoretical data
    - The experimental data gather through the experiment and the data gather by the analysis software will be compare to create a viable hypothesis of the properties of the 3D model.

vii. Report writing
    - Report writing on this project will be done at the end of this project.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 3D MODELLING

In the late 1980's, the need of engineer to hand drawn design, schematic or plan for a project had been greatly reduced (Hazrat Ali, Katsuki, Kurokawa and Sajima 2013). This is because virtual 3D modelling was introduce into the world. At the time of exposure, small and medium size company have already incorporated this revolutionary idea into their ranks. They are easy to access and even more compatible with personal computer making it easier for engineer to perform 3D modelling outside of work. This also means that company are able to cut cost by reducing obsolete department.

This does not only effect the industrial world. On this present time, almost all university or higher learning institute have completely abolish the need to expose student to manual drafting or hand drawing (technical drawing by hand). Student are no longer have the need to use any drawing tool such as protractor, compasses and etc. Student are to focus using computer aided design CAD. Computer aided design or CAD are a complex intricate design software that have greatly benefit not just for students to learn but also for engineer, designer and even scientist. As can be observe in Figure 2.1 an example of intricate 3D model.

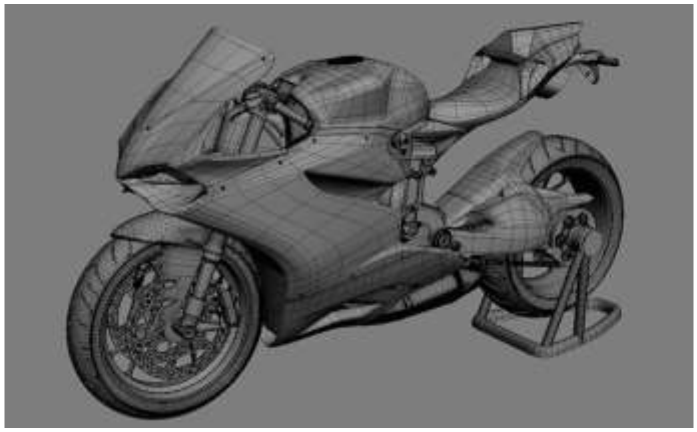


Figure 2.1: Example of 3d model using CAD

3D modelling is define as producing three-dimensional object or surface into a mathematical representation using specialize software either its automatic or manual. These CAD produce such amazing 3D model by first using the available or already drawn 2D design and put it through a process call 3D rendering and use computer simulation. 3D model can also be seen as combine line, shapes and curve surface, than are also form because of combination of point present in 3D space.



## 2.2 METHOD OF ANALYSIS

Topological optimization is a study of optimizing a certain structure design of its geometrical layout while still under the prescribe targeted performance level (X.F.SUN, J.YANG, Y.M.XIE, X.HUANG, Z.H.ZUO 2011). Various optimizing method were discovered throughout the years. Solid isotropic material with penalization SIMP (Bendsoe 1989) and the evolutionary structural optimization ESO. The evolutionary structural optimization ESO method focus by obtaining the best shape and topology of continuum structure whiles slowly material that are not in use will be remove from the structural domain. BESO is bi-directional evolutionary structural optimization and is an extension of the early evolutionary structural optimization ESO.

The optimization employed by BESO is similar to ESO, but at the same time it can also add material that it think it can be beneficial or effective to the structure. It is a more robust method compared to evolutionary structural optimization ESO. Level set method is an applied method of changing the whereabouts of boundary in other word moving boundaries. In some condition, these moving boundaries will come in contact and are join together and a new hole is created (S.Shgaee, M.Mohammadian 2012).

In the early year, structural optimization had to only rely on integer values to use as design variable. Bendsoe (1989) was able to come up with brilliant idea, Bendsoe propose a method that will result in a non-discrete solution by varying the design variables in a loop. In pursuing to achieve a non-discrete solution that can come close to a discrete solution method of analysis (mathematical model) used was change to provide a less influence to the intermediate value of the variable. This method was later name as solid isotropic material with penalization (SIMP) (Philip Anthony Browne 2013, D.Brackett, I.Ashcroff and R.Hague 2011).

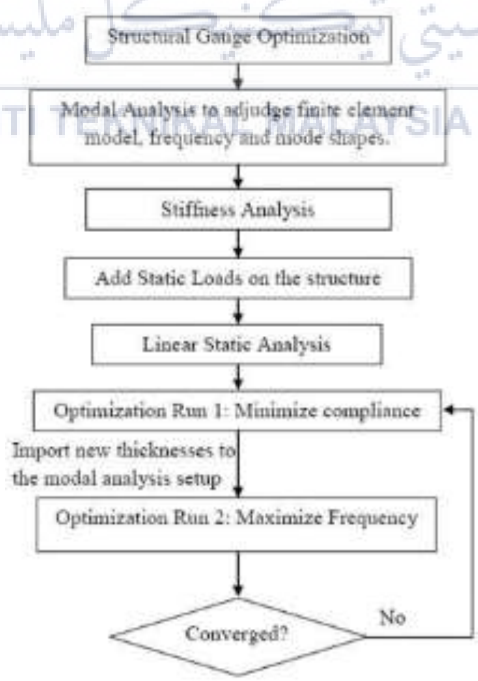



Figure 2.2: Flow chart for solid isotropic material with penalization

In later years, many have use this method couple with other method to solve optimization design problem. Krister Svanberg (1987) propose to used solid isotropic material with penalization SIMP couple with Method of Moving Asymptotes (MMA) but reduce the number of objective function of a non-linear structure that was subjected to volume constraints. In 2001 Rozvany (2001) prepare a historical article about the advantage of solid isotropic material with penalization SIMP to solve topology optimization problem compare to other method. Figure below illustrate the differences change by each iteration.

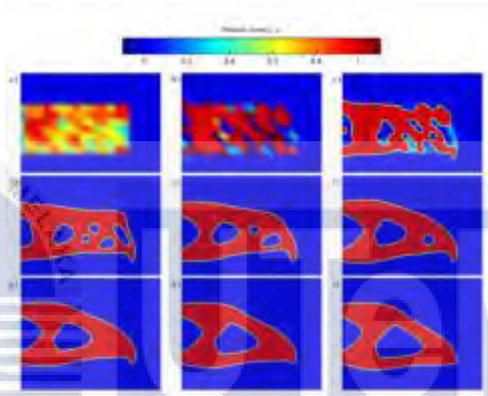


Figure 2.3: The differences in structure for each iteration



## 2.3 TOPOLOGICAL OPTIMIZATION

Topological optimization is a method of optimizing the material layout of a structure by using a calculated approach without changing the initial condition act upon the structure or any other boundary condition while not changing its purpose or its functionality. According to Christiansen et al (2015), topological optimization is a method of investigating the best design and topology of a structure, while Mohammad Rouhi (2009) implied that topological optimization is the distribution on volume or mass inside a specific design domain or structural universe. Other concept can also be taken as definition of topological optimization as well, such as investigating the optimum load path between the load bearing position and the support point which will be identified as a ground element.

This outlook is suited for truss structure formation. The concept of optimization revolves around the fact of determining the optimum or the most suited idea, shape or even topology of a structure. Topological optimization can be divide into two branch, continuum and truss. These division are mainly because to divide topological optimization base of different structure formation, for each of those structure requires different method on implementing topological optimization on them. They're many other method of optimization, the optimization approach for structure size, design or topology of the structure have been discovered and developed thus been wide spread throughout the engineering field (Liang Xia 2016), but regardless of the different type of optimization, each of them approach the structural design problem differently (Bendsoe and Sigmund 2004).

The idea of topological optimization have been proven countless time that it is a revolutionary idea, using this idea can help cut back on almost everything concerning manufacturing of a product. It does not only help reduce in expenses but also help with solving problem arising from design flaws even more so when it comes to complex design such as automobile, houses and as small as a computer chip (Christiansen et al 2015).

When talking about topological optimization, it can be sure that the structure or product that is implemented onto has reduce the amount of compliance greatly. Logic dictate that with low level of compliance come with high level of stiffness, that is an acceptable result. Plus with topological optimization the optimum design is sought out by the removal of inessential material from the product causing the weight to reduce significantly. The characteristic of the product being low level of compliance, high level of stiffness and light weight is quite an amazing result. As mention previously, topological optimization is the distribution of volume or mass throughout a specific design domain (Mohammad Rouhi 2009).

The best course of action would be on investigating the optimum distribution of material on a set of design domain. Optimum distribution of material insure of better use of material or no inefficient used of material while designing the product. The optimization of distribution of material should reveal a higher level of stiffness. The better the distribution of material, the higher the level of stiffness will be. The benefit of topological optimization are seemingly endless.

Designer and engineer when producing an idea can come up with amazing idea with complex design, but later it was determine it cost too much to manufacturer it but with topological optimization designer and engineer are able to design a product with similar function but at an optimum shape and size by removing unwanted material (Christiansen et al 2015).

As mention previously, topological optimization is a study of finding the optimum shape, size or structure of a product without changing any parameter or boundary affiliated with it whiles maintaining its function. The only known qualities too difficult to maintain are the applied load, support condition, volume and possibly design restriction (Bendsoe and Sigmund 2004). It's fairly important as well to know that with topological optimization, the modification of the interior configuration and the exterior shape can be change simultaneously without any difficulty (Mohammad Rouhi 2009).

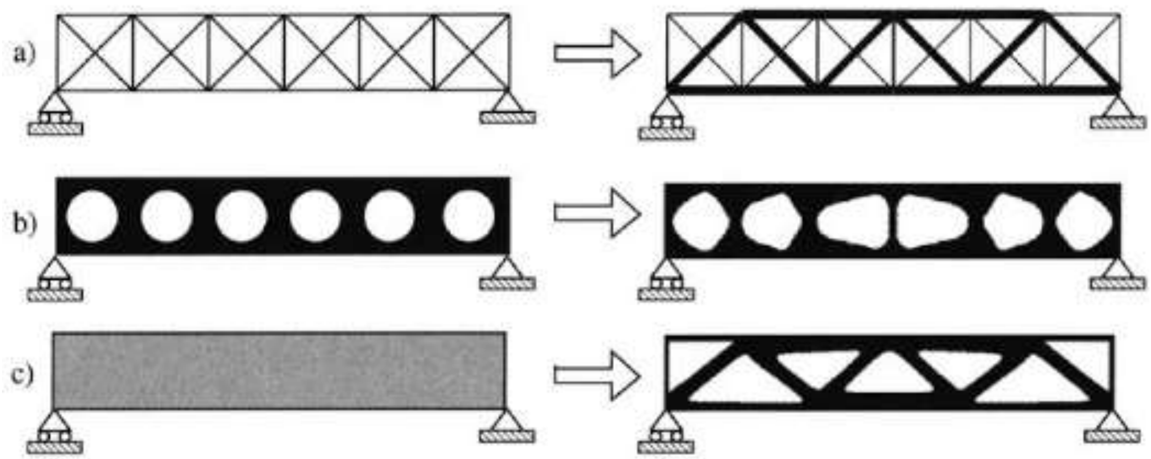



Figure 2.4: Categories of structural optimization

a) Sizing optimization
b) Shape optimization
c) Topological optimization.

In Figure 2.4 shows the different type of optimization, even though for this dissertation focus on topological optimization, a brief explanation should be present here. The differences between these three structure optimization are how their design variable are define. As you can observe in Figure 2.4, a) is sizing optimization, the problem facing sizing optimization is that the layout of how the structure should look like was already present or prescribe beforehand. Sizing optimization can also influence the cross section of a structure, given the structure changing the thickness either increasing it or decreasing it will affect its performance (Henrique A. Almelda, Paulo J. Bartolo 2013). For b) shape optimization problems are that both interior configuration and exterior shape are both considered as design variable. Aside from the truss structure, other example of shape optimization are by changing used component with other with similar function but different shape hence increasing the desire variable within a design domain. C) represent topology optimization, the design problem facing topology optimization are not like the two optimization previous mention above, it has a wide free range of motion because it is not confine to a prescribe design and it recognize the exterior shape and the connectivity as a design variable. Topology optimization also provide the first design concept of a structure.

By pursuing the goal for minimization of compliance while still within the remain volume constraint. A structure compliances level is double the amount of the strain energy. By minimizing the amount of compliance also means the reduction of strain energy (Henrique A. Almelda, Paulo J. Bartolo 2013). Topology optimization also focus on the elimination of ineffective material, by doing so it makes sure that the material are use at its best thus aiming for maximum stiffness design. To do so it requires no parameter.

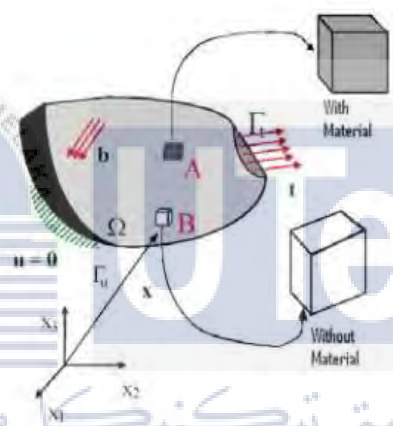



Figure 2.5: An illustration on topological optimization



It should also be of concern that topological optimization can be applied in different area design problem. Some other design problem that can also be solve by implementing topology optimization is composite heat transfer problem, acoustic, electromagnetism and fiber optic (Mohammad Rouhi 2009).

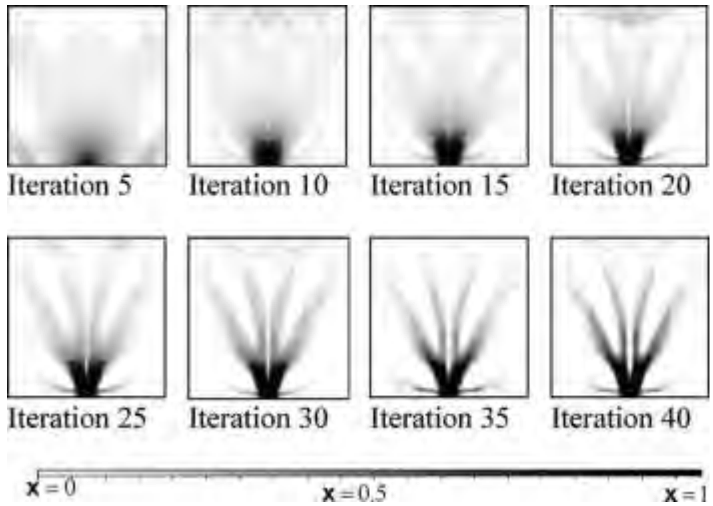



Figure 2.6: The change of heat transfer flow.

In Figure 2.6 shows that the differences of heat flow through solid object for each iteration. Each iteration present a modification on the topological aspect of the solid boundary, proving a better more optimum flow path for the heat to travel whiles minimizing the heat loss through heat conduction.

Heat transfer problem directly correlate with the structure design of the domain where the heat is travelling. By using topology optimization the detection of optimum direction of flow of conduction (type of heat transfer) is possible. Sound wave can be influence by the terrain of which it travel on, by adjusting the geographic terrain using topology optimization, it is possible to either tune the sound wave into other note through the vibration bouncing back from the terrain or propel the sound to travel further than before. How magnetism is effected by design problem? No, it does not. A magnet has a fix magnetic field that it produce, but an electromagnet can be effected by design problem. The magnetic field produce by an electromagnet is directly proportional to how the design of the electromagnet is. Those are just of the bat problem statement with an easy solution, but with further investigation in time, a better solution can be found.

## 2.4 3D PRINTING

3D printing is basically producing a 3D object from a 3D representation of it computer drawing. By drawing a 3D model of the object, the 3D printer can manufacturer that 3D model by over lapping material on top of one another until the desired product is finish. In the coming years, rapid prototyping has becoming more widely spread than it was estimated, with that being said, the ingenuity surrounding 3D printing will have people come bringing new idea concerning it, Long Yang et al (2016) state that of the coming years, rapid prototyping technology has been couple with digital orthopedic technology, because of that, the applicability surrounding it has been greatly expanding from the industrial field all the way to the orthopedic field of study.

The reason that 3D printing or rapid prototyping technology is believe to be a revolutionary idea, is because the fundamental idea that develop around it. The 3D printing literally took about most of the process of producing a prototype away from the industrial company, now it can be used by the common people.

According to Zhen Chen (2016) scholars and industrialist have predicted with the rising of the development of 3D printing, it can change the rule set by the first industrial revolution in production manufacturing, any and all type of digital production will cause or promote the coming third industrial revolution all together. Muller and wings (2016) suggested it that an on demand and production on site has a higher probability rate now that the existence of 3D printing or additive manufacturing have come. Figure below shows an example of an open source 3D printer.

Figure 2.7: Example of a 3D metal printing

# CHAPTER 3

# METHODOLOGY



## 3.1 INTRODUCTION

This chapter provide a detail description of its methodology or how this whole project will proceed. This chapter also focus on what kind of method being use to obtain the necessary data for the topological optimization process. As can be observe in the flow chart provided in figure 3.1, the flow chart show the step required to successfully obtain this data are by studying the object choose to be optimize which is this case is the “ connecting rode “ of a piston from a combustion cylinder in engine.

The connecting rod is a fully solid metallic object, a 3D modelling representation of the connecting rod will be create. After victoriously created the 3D model of the connecting rod, the 3D model will be then transferred into an analysis software, where there it will be given a full diagnose Stress analysis which is similar to the real connecting rod will be experience inside an engine. Afterward the analysis is done, the vital data can be gathered and topology optimization can be preform on the connecting rod.

When the topological optimization process is done, a new connecting rod will be produce in a form of 3D model. The new 3D model will be slightly different than it was before undergoing the topology optimization process. The 3D model will be then transfer into a 3D printing machine, where it will be produce. The full product that was produce by the 3D printer will be undergoing countless experiment design to test its mechanical characteristic. Finally the theoretical data obtain from the analysis software will be compare to the experimental data gather from the conducted experiment.

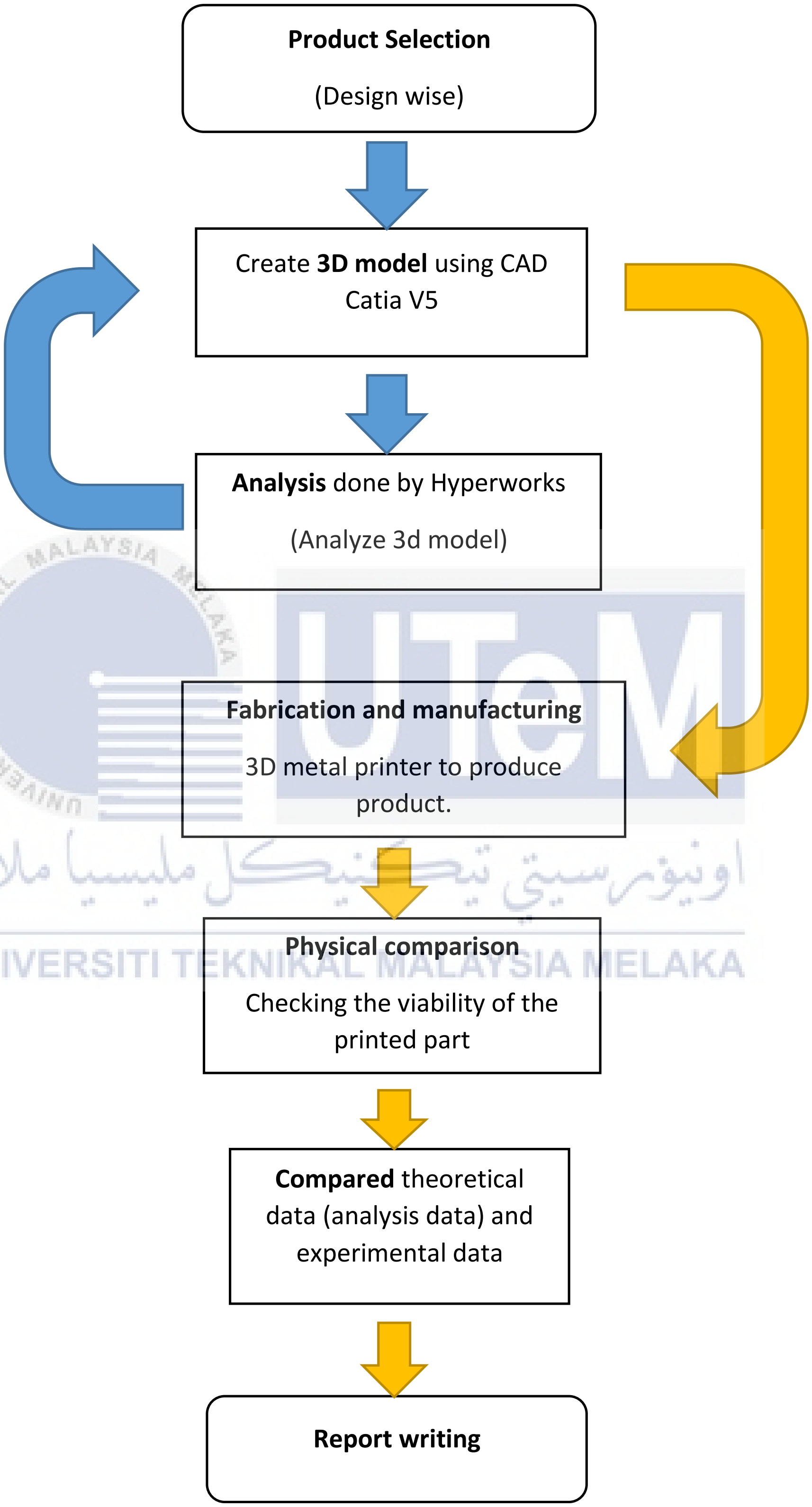



Figure 3.1: Flow chart of the whole project

### 3.2 LITERATURE REVIEW

A literature research was conducted by studying past journal published by other regarding the matter of topological optimization of 3D printing product. In the previous chapter these literature research was done in accordance to familiarize oneself with the topic at hand. The topic of this whole thesis is to implement the concept of topological optimization on 3d printing product, thus the literature research was carried out by dividing it into 5 subtopic. The first sub topic discuss or explain in detail what is topological optimization (with in mind every material is obtain from other research journal). Discussing the different type of optimization and what are the differences between the other optimization method and topological optimization.

The second subtopic explores area about 3D printing, this area explain, and what is 3D printing? From the first 3D printer to the comparison application difference between when it was first debut and how 3D printer are use now. How the 3D printer are able to effect the industrial company from all sort of back ground. The third subtopic hover around 3D modelling. In the olden days, all draft design was done by hand, every prototype draft drawing was done by hand. The transfer of information between the marketing department and the design engineering department was considered acceptable at that time, but later the advancement of computer took over the world. Information was then turn to data stream consist of binary code, but information of drawing are still represented as drawing by hand. 3D modelling has help these department and help the transfer of information between department increases exponentially. This also help with communication with costumer. 3D modelling aren't just for representation in computer form, but it also provide a way for computer to do many other operation with it such analysis or modification.

The following subtopic discuss analysis method. The fourth subtopic talks about the analysis method, it entail the discussion of many different type of optimization method. Whereas the fifth subtopic tells about the topological optimization in 3D printing. The fifth literature research subtopic focus more on the combination of the first and the second subtopic. Discussing the idea that to two concept can be combine. With rapid prototyping combine with topological optimization can help with furthering the advancement of manufacturing in many ways.

**3.3 3D MODELLING**

After all the possible research was done, data was needed. Every experiment needs data to be interpreted, is this case to obtain any data what so ever a 3D model of the object is needed. The 3D model of the data will construct by using computer aided drawing CAD software Catia V5. Catia V5 is a sophisticated software mainly use to create 3D model representation of an existing object of a prototype. For this project, the 3D model that is needed to be constructed is the connecting rod for piston engine. The connecting rod that was choose is taken from a standard Naturally Aspirated engine.



Figure 3.2: Example NA engine

### 3.4 ANALYSIS

After the finishing the 3D model of the connecting rod, the model will go through analysis. Software used can either be Catia or Hyperworks. The aims of this analysis is to produce theoretical data. Base on that theoretical data obtain from the analysis, then the experiment that will be carried on the produce model can create a platform of which will be used to obtain the experimental data.

Catia's CAE program mainly use finite element analysis FEA but Hyperworks focus on solid isotropic material and penalization SIMP. It would be better to use Hyperworks to assist on the analysis, because it has a wider range on test and it is a suitable analysis program corresponding to the latter tensile testing.

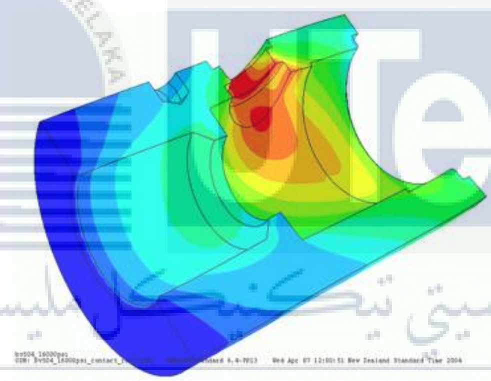




Figure 3.3: Example of 3d model undergoing finite element analysis FEA

### 3.5 PRODUCTION & FABRICATION MODEL 3D

The production or fabrication of the 3D model will be carried out by a 3D metal printer. Why metal? Because the material use for the connecting rod. The common material for a connecting rod is forge steel, that means additive manufacturing using filament are not acceptable because its mechanical characteristic are far from the steel, After the 3D model has gone through topological optimization process and a new 3D model is produce, that new 3D model will be transfer into the 3D printer software. There the 3D model will careful adjusted and modify to fit the parameter of the 3D printer. The software will use a splicer technique to show operator what will come of the product when finish fabricate.

Figure 3.4: Example of a product 3D metal printing.



### 3.6 PHYSICAL EXPERIMENT

When the physical representation of the object is present, the opportunity to conduct a number of experiment that will test its mechanical characteristic is achievable. The experiment carried out will be precisely to test and gather data of its mechanical characteristic. The experiment that will be conducted on the connecting rod is tensile test.

Connecting rod usually crack before of its inability to fully transfer gas and inertia force from the piston to the crankshaft. The connecting rod that could not transfer the inertia force usually crack where to force most heavily concentrated. That is why tensile test is the most optimum test, it assess the mechanical characteristic the material of the product. The usually test subject are confine to a certain shape which the common dog bone shape but because of the connecting rod has a very different shape compared to the dog bone shape, there is a high probability that the result gather will be different even if they are using the same material.

Tensile testing also previously known as tension testing, as the name suggest that it inflict tension on the subject. A control tension is inflicted on the subject, slowly increasing the tension act upon it until it crack or failure. Tensile testing are usually use to determine the application of a material, quality control and to use the data gathered to determine what will happen to structure on different sizes with the same material with different force act upon it will happen (prediction). Base on that raw data, operator will be able to determine the material Young's modulus, Poisson ratio, yield strength and strain hardening.

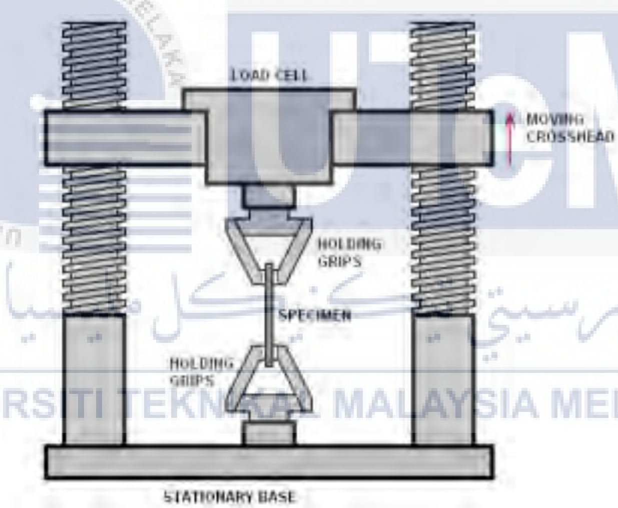



Figure 3.5: Diagram of tensile testing

## 3.7 COMPARE THEORETICAL AND EXPERIMENTAL DATA

After successfully gather all the data from the experiment and the analysis, the comparison will commences. The purpose of comparing the experimental data and the theoretical data is to evaluate the percentage error between them. If the percentage error has a large value then it could mean that somewhere somehow when conducting the experiment an error occurred without the operator knowing. This also means that the topological optimization applied on the 3D printing product was a failure vice versa.

## 3.8 REPORT WRITING

After every aspect of this thesis is finish, all the data gather were satisfactory and the comparison done between the experimental data and theoretical data are at acceptable range then proceed with documentation. Report writing function is to document everything that was done from the start to the end of the whole process. All data concerning the analysis and physical experiment will be tabulated and discuss thoroughly.

# CHAPTER 4

# RESULTS

## 4.1 MAXIMUM DEFLECTION AND VON MISSES STRESS RESULT

Base on the analysis carried out through Hyperworks Optistruct 14.0, the result for the maximum and minimum for the deflection and von misses result was extracted from it. The maximum reading is divided to before and after the optimization process. The before reading indicate that the maximum and minimum deflection result is 22.987 at grid 518 and 0for the minimum deflection, the negative value signify it downward direction. As it can be observe in figure 4.1.1 and figure 4.1.2 show the maximum and minimum deflection result.

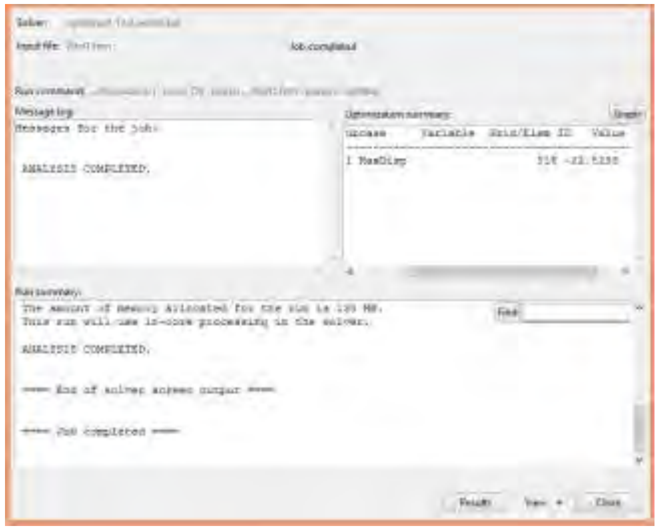



Figure 4.1.1: Command prop provided with max deflection value



Figure 4.1.2: Visual conformation on the minimum deflection value

The maximum and minimum value of deflection after going through optimization process is 3.095 at grid 569 and still zero for the minimum value of deflection.

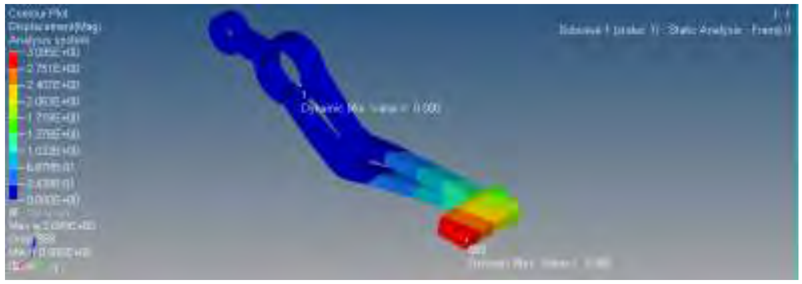


Figure 4.1.3: The maximum and minimum value of deflection after optimization

Table4.1.1: The comparison of degree of deflection between before and after optimization

| DEFLECTION | BEFORE | AFTER | DIFFERENT | % |
|---|---|---|---|---|
| **MAXIMUM** | 22.987 | 3.095 | 19.892 | -86.84 |
| **MINIMUM** | 0 | 0 | 0 | 0 |

The force introduce to the brake pedal was from the z-axis going downward direction. The maximum or biggest result gathered for deflection is of course the Z-axis but they are seems to be deflection occur on X and Y axis. The X-axis show the maximum and minimum deflection occur at that axis is 0.016 at grid 154 and -22.526 at grid 518. The Figure 4.1.4 shows exactly the result through analysis.



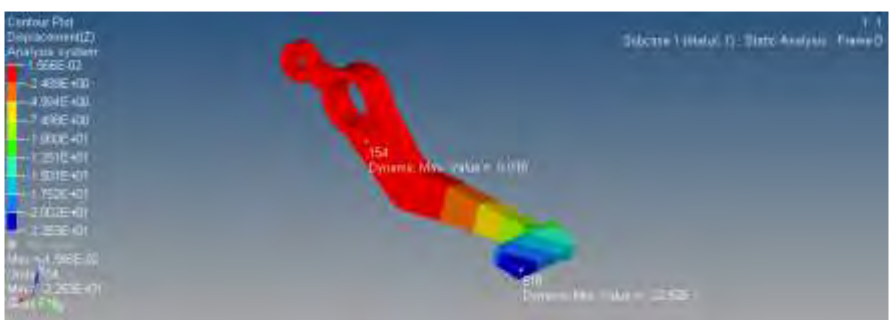


Figure 4.1.4: Deflection before optimization occurred on the Z-axis plane

The maximum and minimum value gathered from the deflection on the Z-axis is for after optimization process is 0.005 at grid 503 and -3.038 at grid 569.

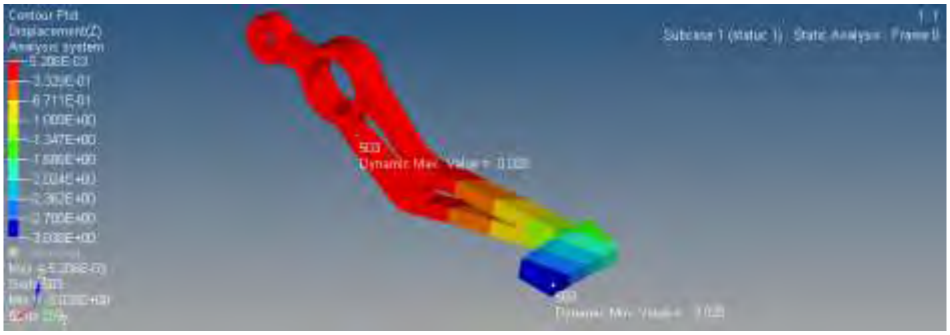



Figure 4.1.5: Deflection after optimization occurred on the Z-axis plane

For the maximum and minimum value for Von misses obtain through the analysis before optimization is 3796.338 at grid 365 and 0.025 at grid 23. The maximum and minimum value for Von misses after going through the optimization process is 5317.273 at grid 504 and 0.022 at grid 177. Figure 4.1.6 and 4.1.7 shows the result for the Von misses.



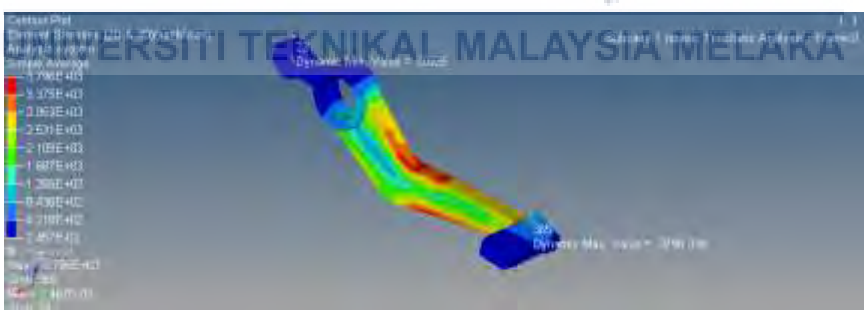



Figure 4.1.6: Result for Von misses before optimization

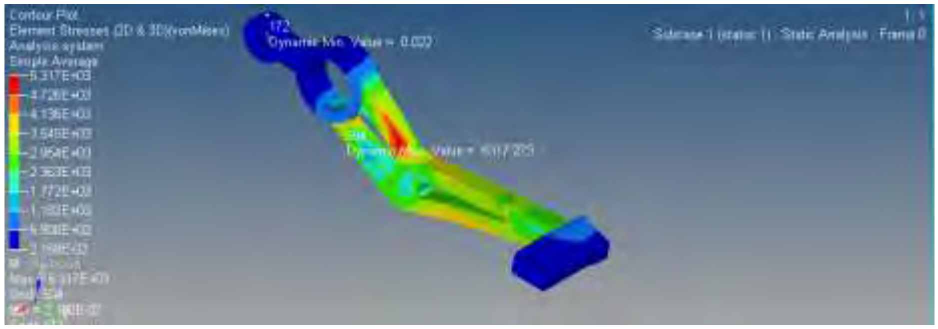


Figure 4.1.7: Result for Von misses after optimization

Table 4.1.2: The comparison of Von misses between before and after optimization

| VON MISSES | BEFORE | AFTER | DIFFERENT | % |
|---|---|---|---|---|
| **MAXIMUM** | 3796.338 | 5317.273 | 1520.935 | +40.06 |
| **MINIMUM** | 0.025 | 0.022 | 0.003 | -12 |

` For the maximum and minimum value for Tresca obtain through the analysis before optimization is 4183.253 at grid 365 and 0.027 at grid 23. The maximum and minimum value for Tresca after going through the optimization process is 5598.509 at grid 0.024 ay grid 172. Figure 4.1.8 and 4.1.9 shows the result for the Tresca.



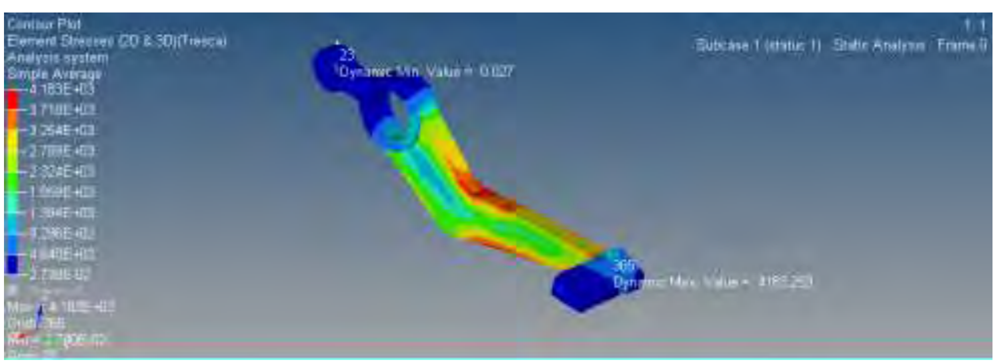


Figure 4.1.8: Result for Tresca before optimization

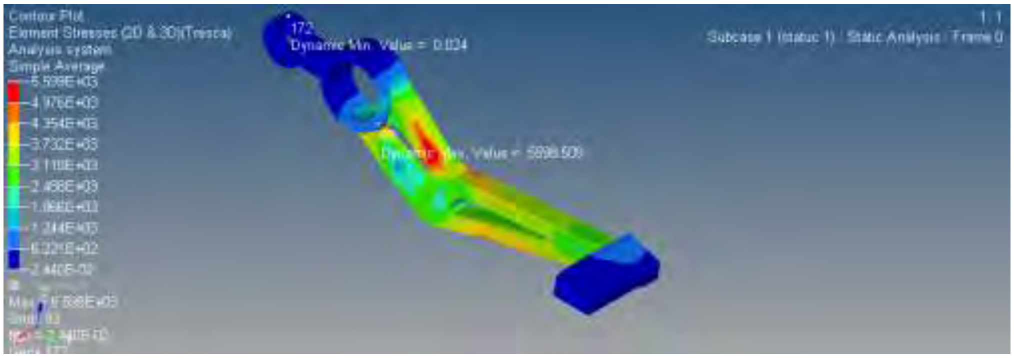



Figure 4.1.9: Result for Tresca after optimization

Table 4.1.3: The comparison of Tresca between before and after optimization

| TRESCA | BEFORE | AFTER | DIFFERENT | % |
|---|---|---|---|---|
| **MAXIMUM** | 4183.253 | 5598.509 | 1415.256 | +133.83 |
| **MINIMUM** | 0.027 | 0.024 | 0.003 | 11.11 |

The force exerted on the brake pedal has significant side effect, but from the data gathered before and after optimization occurred the pressure experience by the brake pedal is quite different. The maximum and minimum value for pressure experience by the brake pedal is 2342.253 at grid 365 and -1526.034 at grid 316. The maximum and minimum value gathered for pressure experience by the brake pedal after going through the optimization process is 2374.375 at grid 513 and -4885.137 at grid 95. The result for pressure experience by the brake pedal before and after the optimization process can be seen in Figure 4.1.10 and 4.1.11.

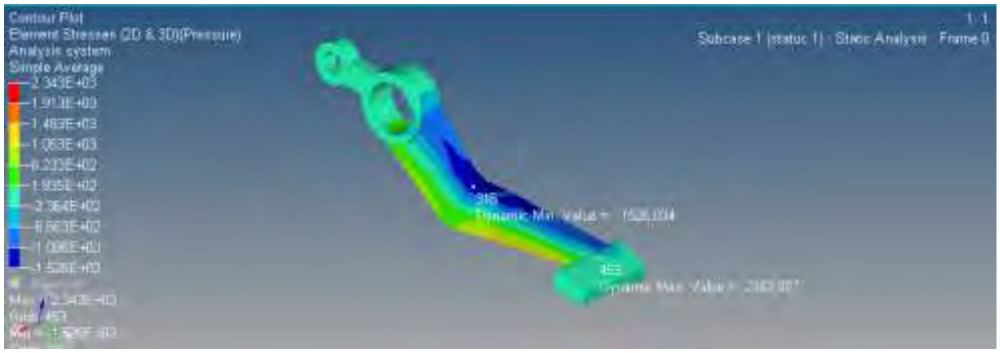



Figure 4.1.10: Result for pressure before optimization


Figure 4.1.11: Result for pressure after optimization



Table 4.1.4: The comparison of pressure between before and after optimization

| PRESSURE | BEFORE | AFTER | DIFFERENT | % |
|---|---|---|---|---|
| **MAXIMUM** | 5.800e+062342.827 | 2374.375 | 313548 | -99.9 |
| **MINIMUM** | -1526.34 | -4885.137 | 3359.183 | +220 |

The maximum and minimum value for max shear stress experience by the brake pedal is 2091.626 at grid 365 and 0.014 at grid. The maximum and minimum value gathered for max shear stress experience by the brake pedal after going through the optimization process is 2799.255 at grid 93 and 0.012 at grid 172. The result for max shear stress experience by the brake pedal before and after the optimization process can be seen in Figure 4.1.12 and 4.1.13.

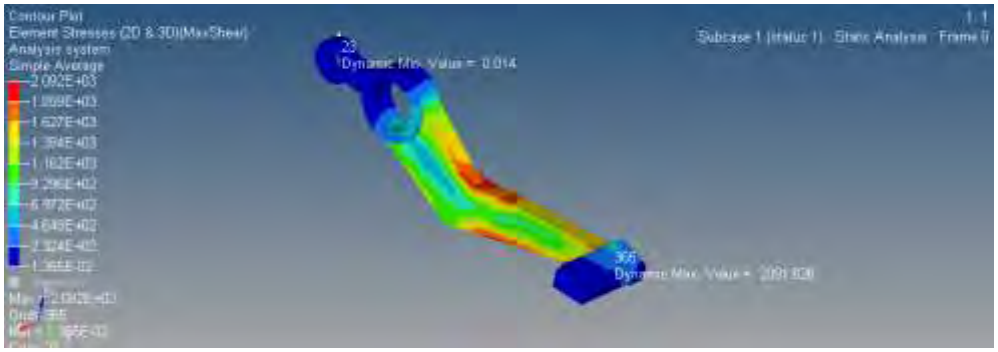



Figure 4.1.12: Result for max shear stress before optimization process

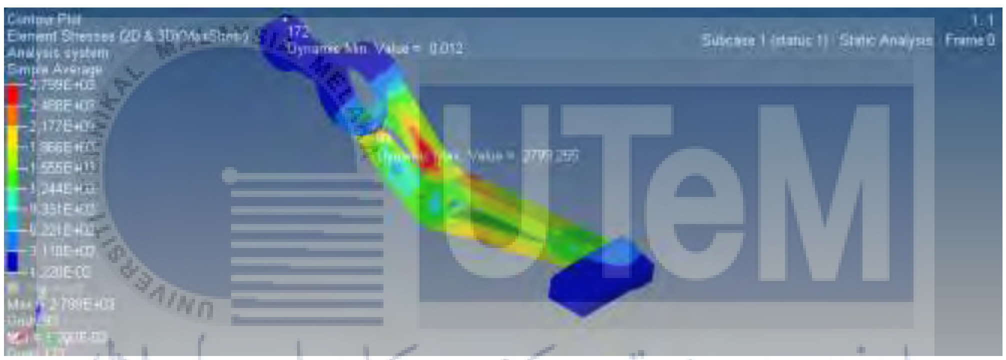



Figure 4.1.13: Result for max shear stress after optimization process



Table 4.1.5: The comparison of max shear stress between before and after optimization

| MAX SHEAR | BEFORE | AFTER | DIFFERENT | % |
|---|---|---|---|---|
| **MAXIMUM** | 2091.626 | 2799.255 | 707.629 | +33.8 |
| **MINIMUM** | 0.014 | 0.012 | 0.002 | 14.3 |

## 4.2 TOPOLOGY OPTIMIZATION RESULT

Using Hyperworks Optistruct 14.0 after following through with the topological optimization process, the suggest new design of the brake pedal can be observe in figure 4.2.1. In the figure is the final design of which the 7$^{th}$ iteration.

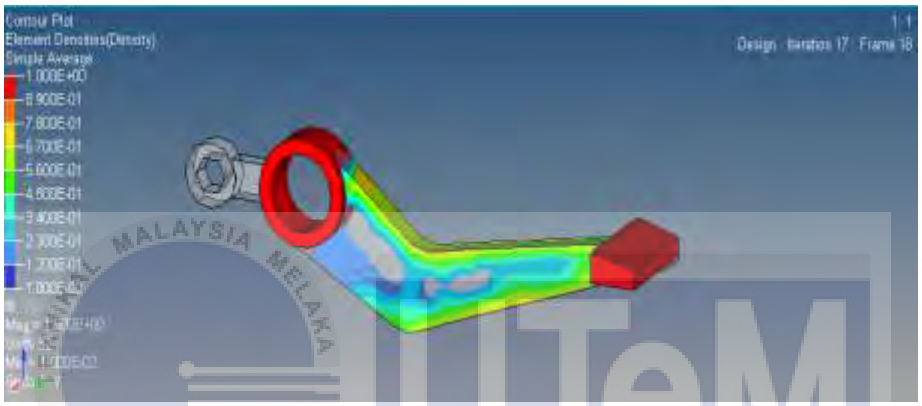



Figure 4.2.1: The suggested final design for topology optimization

The suggested final design from Hyperworks Optistruct 14.0 was then converted into an IGES or any file that is compatible with Solidwork or CATIA CAD format. The whole final design was also converted into a tetramesh format. The figure below will show the final design in tetramesh form.

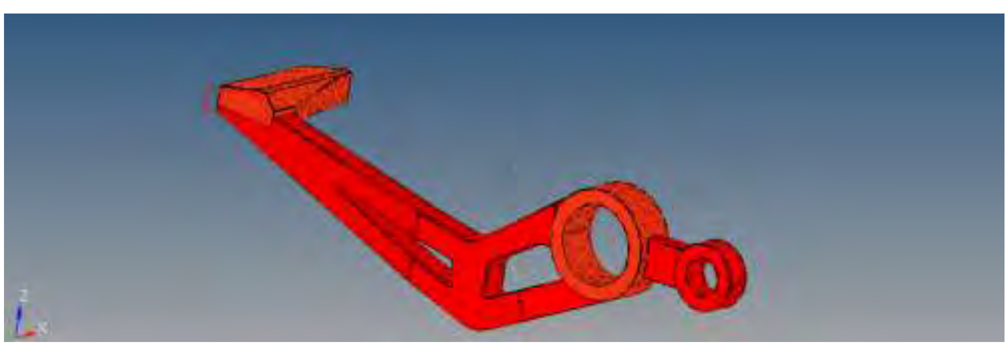


Figure 4.2.2: The final optimize design in tetramesh form

## 4.3 DISCUSSION ON PROPOSED DESIGN FROM TOPOLOGY RESULT

Base on the result gathered on the topology optimization of the brake pedal, the result was significant through software analysis but to implement it on 3D printer is another story. The product of a 3D printer composite material structure are different compare to product produce by conventional method. The conventional method focus on the quality of the product as much as it focus on its aesthetic but when compare to a 3D printer product which focus on rapid manufacturing it does not focus on the structural integrity of its product. The only way to know is to print the final design using a 3D metal printer. By doing that it may probably shows that a 3D printer can accommodate topology optimization concept.

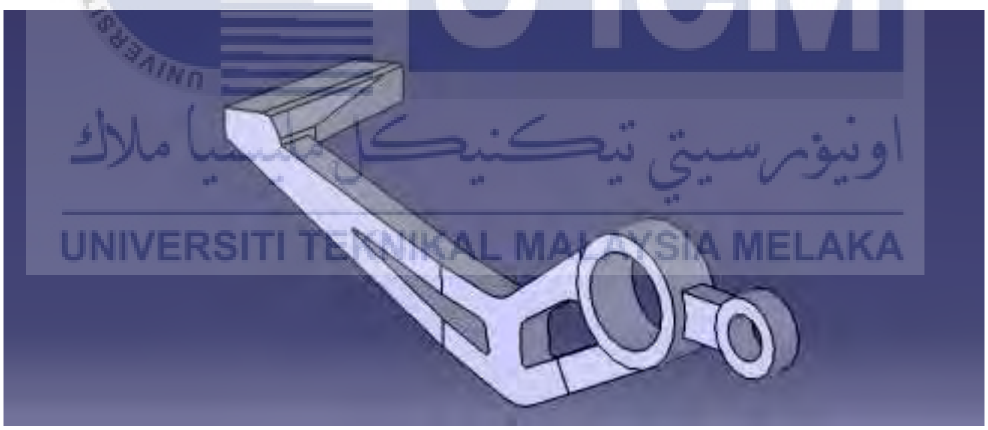


Figure 4.3.1: Final design after topology optimization

## 4.4 RATIO

The initial mass of the brake pedal before going through topology optimization is 0.03kg but after Hyperworks Optistruct 14.0 has perform optimization on it the final mass is 0.02kg.

Mass ratio [(Initial mass – Final mass)/Initial mass] x 100%

[(0.03kg – 0.02kg)/0.03kg] x 100%

= 33.33%

The mass reduction experience by the 3D printed part is about 30%

The initial area of the brake pedal before going through topology optimization is 0.012m$^2$ but after Hyperworks Optistruct 14.0 has perform optimization on it the final area is 0.012m$^2$.

Area ratio [(Initial area – Final area)/Initial area] x 100%

[(0.012m$^2$– 0.012m$^2$)/ 0.012m$^{2]}$ x 100%

= 0%

The area reduction experience by the 3D printed part is about 0%, but that does not mean that the 3D printed part did not change. It simply means that the original surface area and the after optimization surface area is accidentally the same(the part of the 3D printed part that was remove has the same surface area as the new surface area that will replace it afterward )

The initial volume of the brake pedal before going through topology optimization is 2.828e-05m$^3$ but after Hyperworks Optistruct 14.0 has perform optimization on it the final volume is 2.404e-05m$^3$.

Volume ratio [(Initial volume – Final volume)/Initial volume] x 100%

[(2.828e-05m$^3$ – 2.404e-05m$^3$)/ 2.828e-05m$^{3]}$ x 100%

= 14.99%

The volume reduction experience by the 3D printed part is about 15%

## 4.5 JUSTIFICATION RESULT

The original design of the brake pedal was supposedly should have had the foot pad, the place where drive place their feet but for this case by removing the foot pad the end result was no different. Also base on reading gathered after topology optimization was taken place, it can be assume that the product later on produce by 3d printer will prove to be not much different with its CAD counterpart. The below figure show that the final design of the brake pedal in going through analysis.

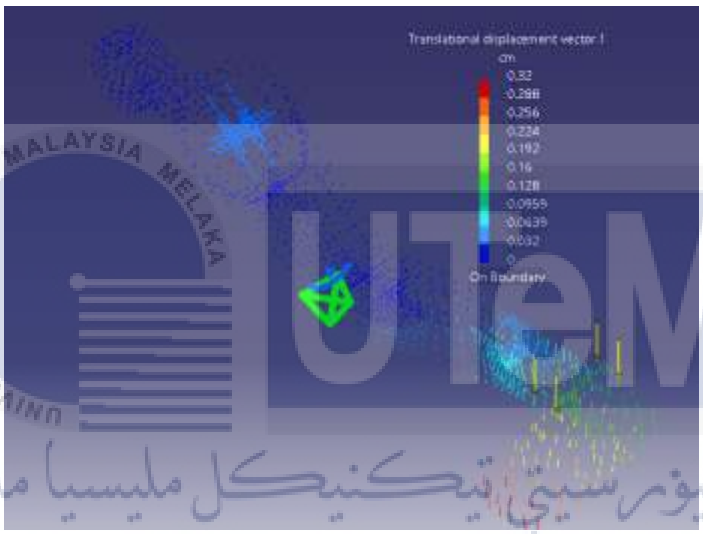





Figure 4.5.1: Result of the final design for displacement

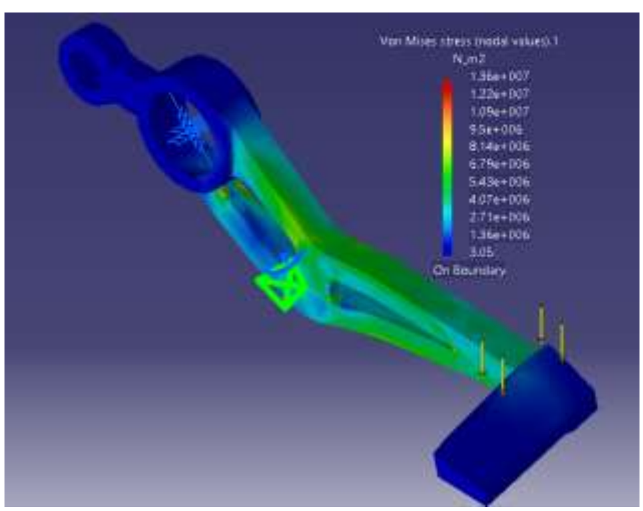



Figure 4.5.2: Result of the final design for Von misses

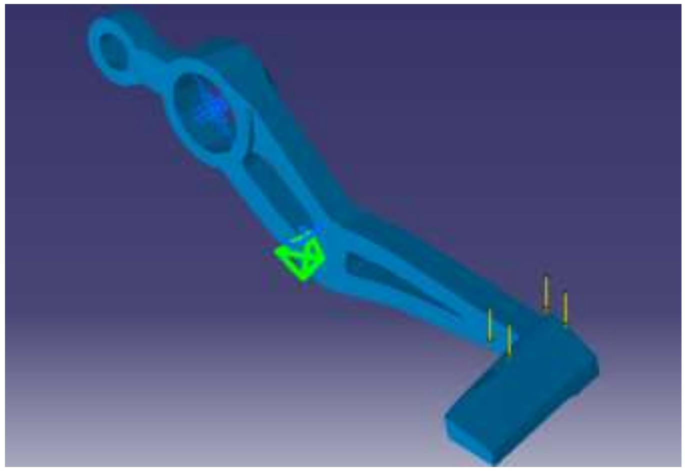


Figure 4.5.3: Result for the final design for deformation

Table 4.5.1: Summarize result

| TOPOLOGY OPTIMIZARION | VON MISSES | WEIGHT (kg) | AREA ($m^2$) | VOLUME ($m^3$) |
|---|---|---|---|---|
| **BEFORE** | 6.05e+06 | 0.03 | 0.012 | 2.828e-005 |
| **AFTER** | 1.3573e+007 | 0.02 | 0.012 | 2.404e-005 |
| **PERCENTAGE** | +124.34 | 33.33 | 0 | 15 |

# CHAPTER 5

# DISCUSSION

## 5.1 STRUCTURAL EXPLANATION



Base on the analysis preform on the final design of the brake pedal, the integrity or the mechanical characteristic of it still does not stray far from the original design. The original mass of the brake pedal in 0.176kg and the final optimize design mass was 0.149kg, and from data collected from the analysis both before and after the optimization of the brake pedal has not much different in them. This could mean that the final design of the brake pedal could withstand the properties or the force exerted on the original design without much different, but because the manufacturing process for this thesis needs to use 3D printing it does not insure much confident on product it will produce. The value of the Von misses for the final optimize design decrease significantly, that shows from the analysis on the original design that by removing certain part of the brake pedal that was not influence much by the force won't make much difference. The value for Von misses for before and after is 3796.338 and 5317.273. The increase in Von misses shows that by removing material strategically it can increase the amount of stress the structure can withstand. Thus reduce the use of material but still maintaining the mechanical characteristic of the whole object and in some cases increase its characteristic.

## 5.2 FORCE INFLICTED

The force inflicted on the brake pedal for the analysis must be as close to the real thing as possible. The average amount of force use by human daily need to be determine to make the analysis of the brake pedal be as close the real thing so that when it comes to the point of manufacturing the object and running simulated test on them it has to be as accurate as it can be. The chosen force use on the brake pedal is -25N (negative represent the direction of the force, which is downward).

## 5.3 COMPARISON DATA BETWEEN BEFORE AND AFTER TOPOLOGY OPTIMIZATION

The result gathered form the analysis for both before and after was tabulate in Chapter 4. The Von misses for before and after is 3796.338 and 5317.273. The little difference between them are assuring. The reduction of the Von misses result after going through the optimization process shows that the final design is viable. The recorded pressure for both of them are also is good condition, the before value is 2342.827Nm$^2$ and the after pressure is 2374.375Nm$^2$. the increase of pressure can indicate that the pressure that is experiences by the 3D printed part will be more after going through the Topological Optimization process, but because the increase of pressure is at a low and even noticeable stage, in can be neglected. The same can also be said about the deflection or deformation occur through the analysis, the result gathered before and after are 22.987mm and 3.095mm. The result the shows a reduction of the deflection by the brake pedal. The differences between the before and after optimization process for the deflection can be consider risky, the gap between the two has not expected but through the analysis process it was determine that the brake pedal will and can perform just as the same as its counterpart.

Through the experimental data gathered later will be able to determine weather the large gap in deflection after the optimization process is viable or not. By using this theoretical data, in hopes that when it comes to actually preforming the test on the real product it will yield the same result.

Table 5.3.1: observation analysis of the printed part.

| CHARACTERISTIC | LEVEL OF SATISFACTION |
|---|---|
| Detail design | 2 |
| Aesthetics | 2 |
| Structural Integrity | 1 |
| Overall | 2 |

( 5 = Very Good , 4 = Good , 3 = Medium , 2 = Satisfy , 1 = Bad )

## 5.4 3D PRINTED PRODUCT COMPARED TO ACTUAL PRODUCT

The product that was chosen due to its criteria falls under the parameter set at the beginning of this research. The product in question is a rear brake pedal of a Bajaj Pulsar 180cc. The actual product can see at the figure below.

Figure 5.4.1: CBR 1000cc motorcycle

The decision to choose this motorcycle other than its part fit the criteria set at the beginning of this research, but it is a very popular motorcycle at the present time. By implementing this research onto a popular mode of transportation, it is believe that it can make a bigger leap in topological optimization in everyday life.

Figure 5.4.2: Actual rear brake pedal of CBR 1000cc

The figure above is the actual rear brake pedal, the CAD drawing is model base on this rear brake pedal.  But some of the not essential criteria was not put into the CAD drawing because it is believe it will not influence much of the result of the analysis. The actual rear brake pedal is made out of standard steel, but because this research focus on the application of topological optimization on  3D printed part, the analysis was not set to standard steel but was change into a more suitable  material which is ABS (Acrylonitrile-Butadiene-Styrene). The Acrylonitrile-Butadiene-Styrene is nowhere close to the actual material use to forge the rear brake pedal but by using this, it can be determine the viability of implementing the concept of topology optimization on 3D printed parts

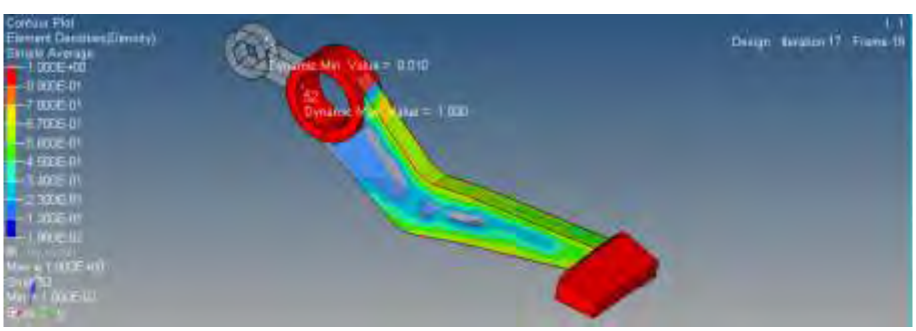



Figure 5.4.3: Topological optimization, the final design propose by Hyperworks.

Base on the figure above, it is the final design of the rear brake pedal propose by HyperWorks. After 17 iteration done by the software, the final design was compile, but from an engineer stand point, the design propose by the software cannot be manufacture by normal means. If to manufacture the final design requires a sophisticated machinery tool to produce just of these final design would cost more than the idea of cost saving using topological optimization through removing unwanted material of product. Thus, this has to be taken into CAD software to be redesign or modified so that it would be more production friendly meaning that to produce such a part would coz time and more money. By importing the final design propose by the software, then it was smoothen the rough edges and flatten any uneven terrain. Thus producing the final design that was deem viable for the 3D printer to print.

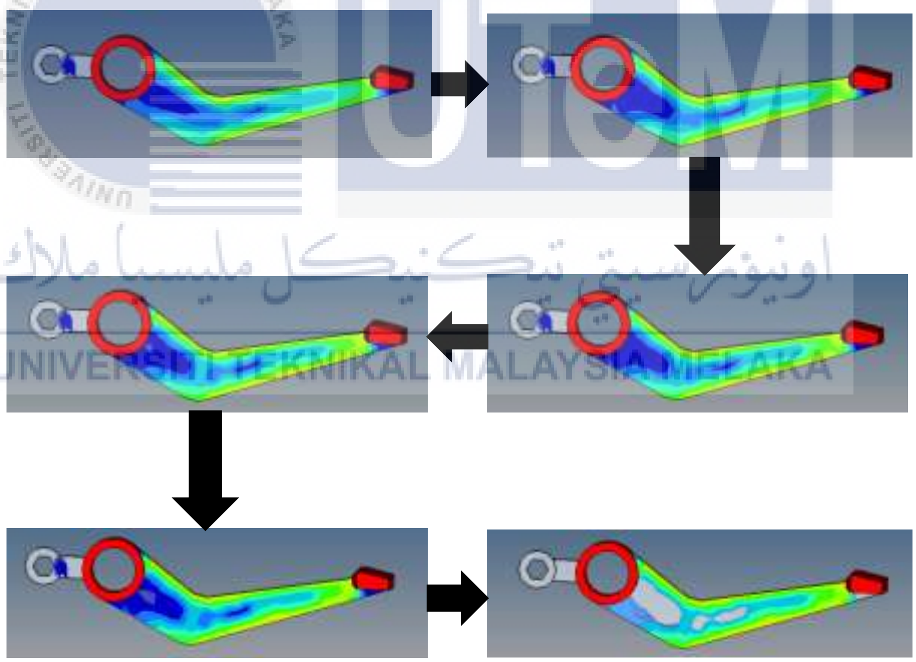




Figure 5.4.4: Simplify cycle of iteration done

Each of the iteration that can be seen is the simplify cycle of iteration. The total iteration done is 17. Each iteration the software calculated based on the variable and the parameter then remove pieces or bit by bit of the material until the optimum structural or topology optimize was complete which was at the 17$^{th}$ iteration. As it can be observe, that each of the iteration done the design produce has the similarity or at least has a natural look to it. From the first to the last design, each were calculated to be like that. As was mention before, the problem arises when product start, yes, a high end 3D printer can absolutely print the final design with ease but if this design were to be put into mass production, it would quite a difficult process. The uneven terrain has make it hard and in need of use more than one tool. Because of that, the intervene of the engineer or CAD operator is important. The engineer or CAD operator can adjust the final design without making too much changes on it, but enough so that the ability to be produce it without any hustle or problem increases.

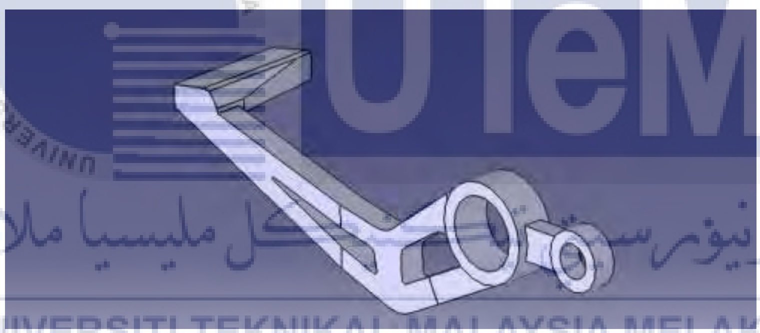




Figure 5.4.5: Final design for production

There are limitation to actually printing a product. The 3D printer that is being used for this research is the CubePro 3D printer. The CubePro is an approximately around 50cm x 50cm x 50cm.  The limitation for CubePro is the size of what it can print out. Also, medium end 3D printer has a couple of disadvantage compared to the high end ones. CubePro accuracy is a bit lacking, each 3D printer are able to adjust their setting depending on the accessibility and the affordability of the part for adjustment. The accuracy problem for CubePro can be easily solve but the accessibility to the part have made it much harder to adjust.  Because of that the end product of the 3D printer is quite lacking in its accuracy. That could spell disaster for the result.

# CHAPTER 6

# CONCLUSION AND RECOMMENDATION

To conclude this thesis, the data gathered for Von misses, deflection or deformation, tresca, pressure, max shear stress, mass, area and volume through analysis help determine that the process of optimization of its material structure is viable. The data were all good and supportive result. This will help for future of optimization, but the problem arise when manufacturing using 3D printing. 3D printer is not like any other manufacturing process, it is call rapid manufacturing process. When rapid manufacturing process comes in mind the idea of the structural integrity went out of the window. The process for which 3D printing us cannot be compare with the conventional method. By using 3D printing will prove to be a challenge for which only the ABS type 3D printer are allow for the time being. To further explore and discover or to be able to determine the answer for, is it viable to use topological optimization on 3D printer product? Because of that, it was decided that the manufacturing process and the testing of the manufacture product will be suspended for the time being, until the arrival of the metal 3D printer. The metal 3D printer has a different method of manufacturing, the mechanical characteristic of the product of the metal 3D printer is presumably much greater than the ABS type.

## REFERENCE


A.T. Gaynor. *TOPOLOGY OPTIMIZATION ALGORITHMS FOR ADDITIVE MANUFACTURING*. (2015)

Bendsøe MP, I.N. Rozvany. *Optimal shape design as a material distribution problem*. Topology optimization in structural mechanics. Structural and Multidisciplinary Optimization. (2001)

Christiansen, Nyman. A, Bentsen, Andreas. J, Nobel-Jorgensen. Technical University of Denmark. *Combined shape and topology optimization of 3D structures*. (2014)

D. Brackett, I. Ashcroft, R. Hague. *TOPOLOGY OPTIMIZATION FOR ADDITIVE MANUFACTURING*. (2011)

Dreyer. T, Maar. B, Schulz. V. *Multigrid optimization in applications*.
(15 December 1999)

G.I.N Rozvany. *Structural and Multidisciplinary Optimization* (April 2001)

H.A Almeida, P.J Bártolo . *Topological Optimization of Scaffolds for Tissue Engineering*. (2013)

Mohd Nizam Sudin, Musthafah Mohd Tahir, Faiz Redza Ramli. *Topology Optimization in Automotive Brake Pedal Redesign*. (2014)

M. P. Bendsø. *Structural optimization* (December 1989)

MD. Hazrat ALI, KATSUKI. A, KUROKAWA. S, SAJIMA.T. *Design of Mechanical Actuator in 3D CAD Software*. (2013)

Mohammad Rouhi. *TOPOLOGY OPTIMIZATION OF CONTINUUM STRUCTURES USING ELEMENT EXCHANGE METHOD***. (**May 2009)

P.A. Browne. *Topology Optimization of Linear Elastic Structures* submitted by for the degree of Doctor of Philosophy of the University of Bath Department of Mathematical Sciences. (2013)

R. Jain, P. Tandon, M. Vasantha Kumar. *Optimization methodology for beam gauges of the bus body for weight reduction*. (2014)

S. Shojaee, M. Mohammadian. *Structural topology optimization using an enhanced level set method*. (25 June 2012)

Svanberg. K . The Method of Moving Asymptotes - *A New Method for Structural Optimization*. International Journal for Numerical Methods in Engineering. (1987)

X. F. SUN, J. YANG, Y. M. XIE, X. HUANG. *Topology Optimization of Composite Structure Using Bi-directional Evolutionary Structural Optimization Method*. (2011)

Zhu. B, Zhang. X, Fatikow. S. *Structural topology and shape optimization using a level set method with distance-suppression scheme*. (16 August 2014)

## APPENDIX

Figure A1: Equipment for 3D printing

Figure A2: Filament going into the CubePro



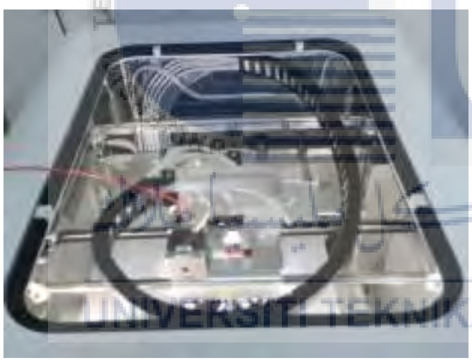


Figure A3: Top view of the CubePro

Figure A4: 3D printing in process

Figure A5: Side view

Figure A6: Slicing in process

Figure A7: CubePro

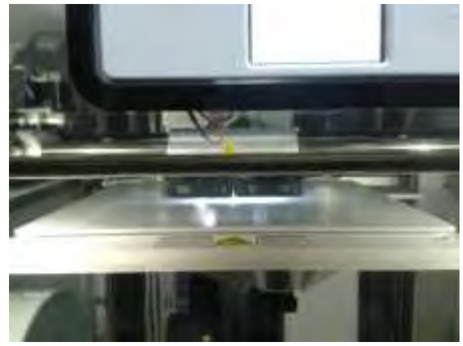
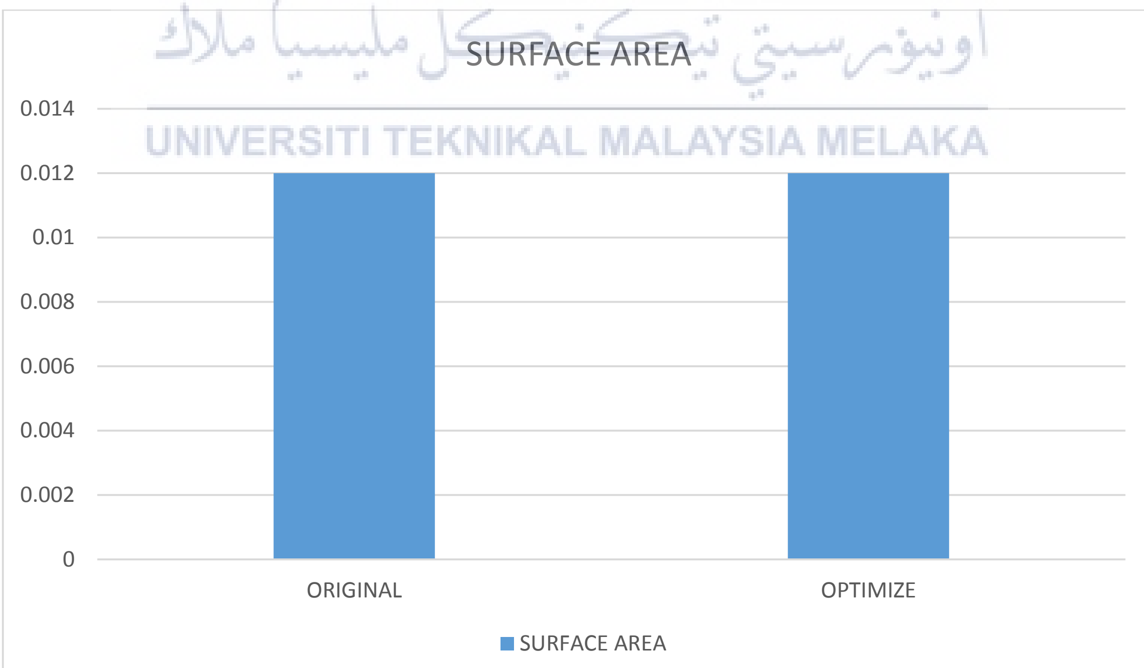


Figure A8: 3D printing in process

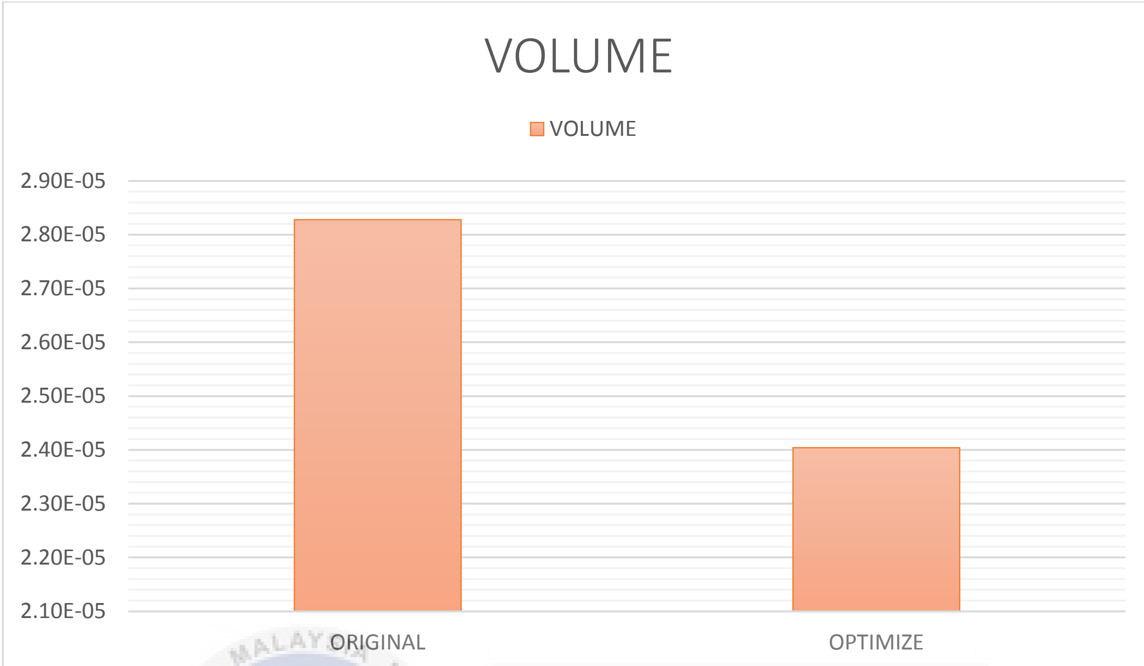
Figure A9: Hanging defect (3D printing)

Figure A10: Rough surface



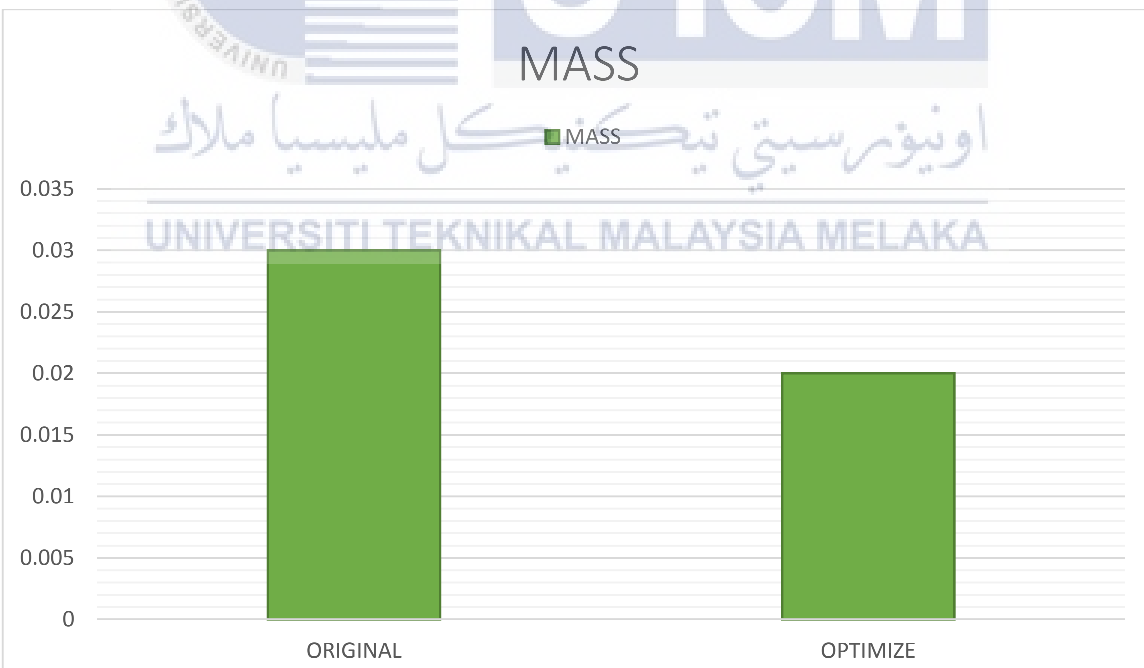



Graph 1: Differences between original and optimize value of surface area

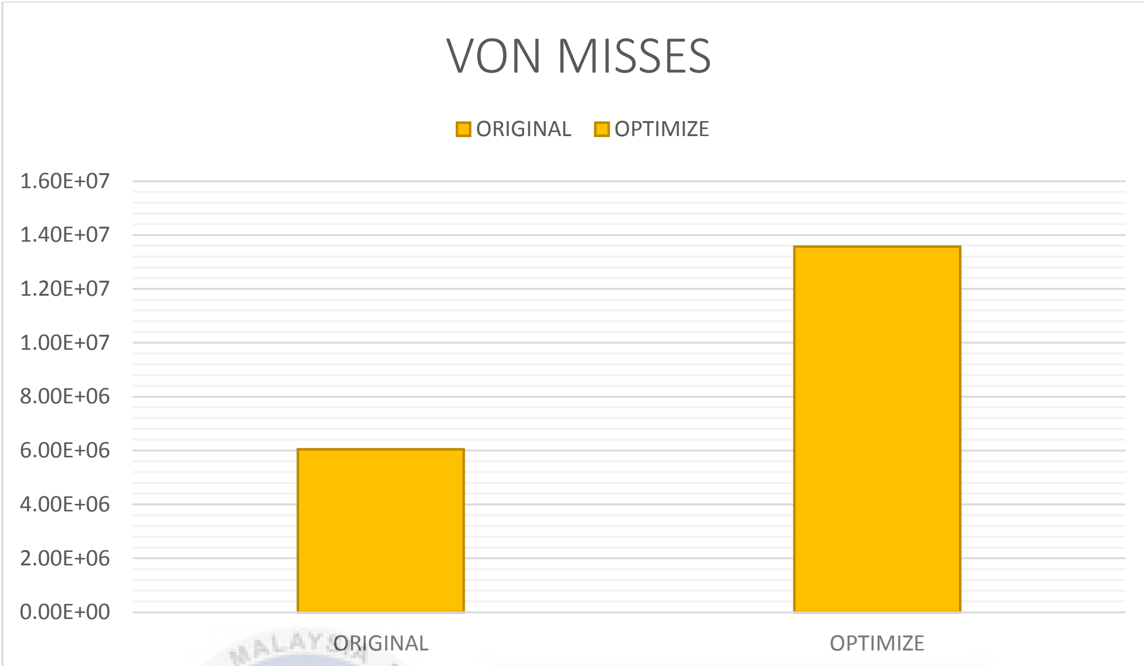



Graph 2: Differences between original and optimize value of volume

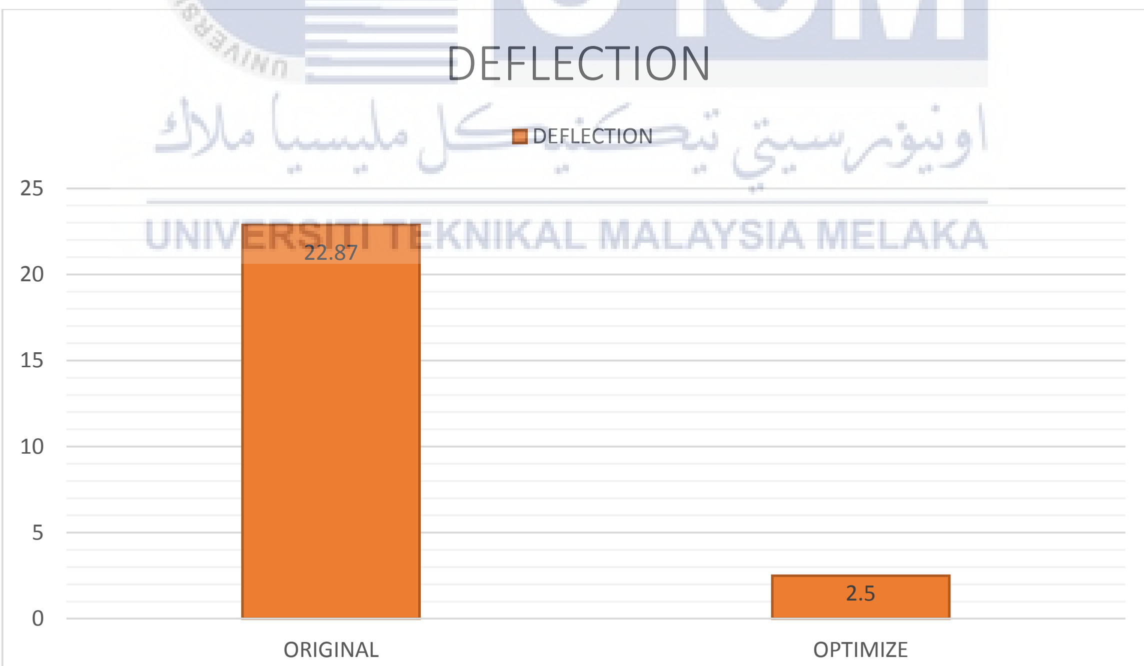




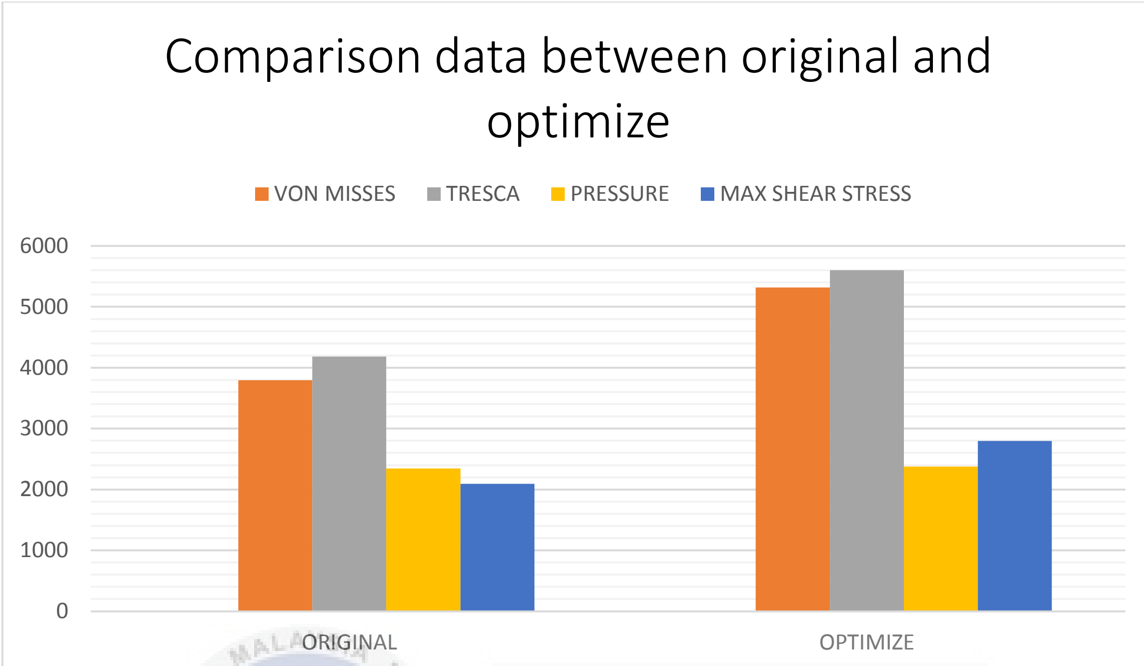

Graph 3: Differences between original and optimize value of mass



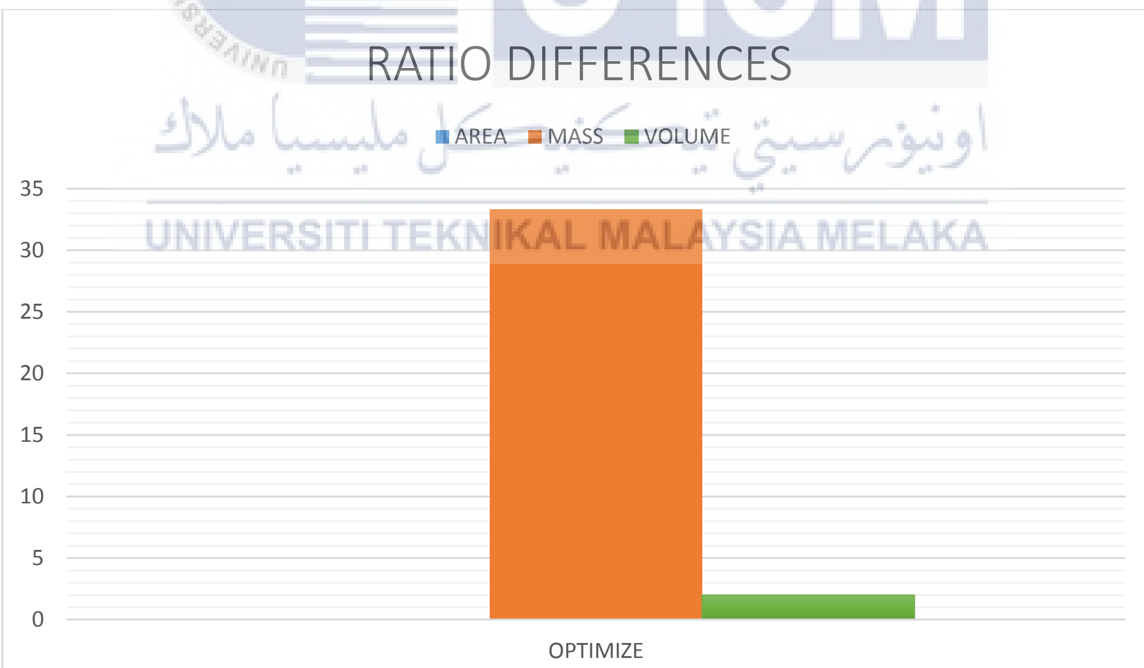

Graph 4: Differences between original and optimize value of von misses




Graph 5: Differences between original and optimize value of deflection




Graph 6: Differences between original and optimize value of Hyperworks result




Graph 7: Ratio differences between mass, area and volume