DYNAMIC ANALYSIS FOR SELF –LOCKING TRAPEZOIDAL ORIGAMI SHELL STRUCTURE

by

Kayilass Hari Nair A/L Makentheran

23082

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

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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved by,

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(DR. DHER MOHAMMED BADRI)

UNIVERSITI TEKNOLOGI PETRONAS
BANDAR SERI ISKANDAR, PERAK

CERTIFICATION OF ORIGINALITY

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

KAYILASS HARI NAIR A/L MAKENTHERAN

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Finally, special thanks to my beloved family and friends for all their support and words of encouragement throughout my Final Year.

Abstract

This research is done based on the composite fiber used in the concept of origami. The ancient art of origami comes as a spur for the design and study of such structures. Rigid origami can be made on a human scale due to its ability to enable folding without deformation of its shape. These can be done in for applications in engineering using active origami designs for architectural, automotive industry etc. absorbing impact abilities are very sought in many applications, using in automotive industries and aviation requires this trait to increase the safety of the passengers. Therefore, using fiber reinforced composite using origami shape or design will be used as a shell structure of the vehicles, although the characteristics are light, but it has very high stiffness and low in brittle which is unfavourable for absorbing impacts. A previous study has shown the implementation of corrugation is able to increase the materials flexibility at the expense of strength. The application of origami has enabled new corrugation configurations that are beneficial for absorbing energy applications. Trapezoidal (double corrugation surface) is one of the origami designs that is used in structures that cannot change in shape. This design is chosen as the corrugation configuration and the effect of the design on the fiber reinforced composite's flexibility and strength is investigated. The corrugation design for the fiber reinforced composite is done using the AutoCAD software and fabricated via the compression moulding machine by layers of fiber reinforced composite with a stamping temperature of 200-degree celcius, 10 tons stamping pressure, 5 minutes of hold time. The resulting fiber reinforced composite's mechanical properties are tested tensile test (ASTM D882) from two different directions on the same plane.

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CHAPTER 1. INTRODUCTION

1.1 Background of Studies

Origami invented from China and was propagated in Japan. It is the art of paper folding. In Japanese, "ori" means folding and "gami" means paper. Origami can range from the super complex with realistic models to the simple models that are easier to fold, but very recognizable. In other words, it is a process of transforming a 2D sheet materials into a complex 3D shape. There are multiple variations of origami technique with different objectives; reducing surface area for deployment or to increase the mechanical strength and flexibility of a material. Corrugation is a prime example of increasing the material's flexibility or rigidity depending on how it is implemented, and it has been widely used in the fibreboard manufacturing industry. It is highly directional, which means the increase in flexibility or rigidity is highly depended on the direction of the applied stress. Quadrilateral mesh is a type of corrugation and has the advantage of producing double corrugation surfaces (DCS). Furthermore, on this design crashworthiness test are done to check on the safety of the design on field. The degree to which a vehicle will protect the occupants from the effects on an accident is called Crashworthiness. To be more subtleties, the crashworthiness is the capacity of the restriction of vitality through the controlled disappointment frameworks and modes. In this cutting-edge period, numerous explores have been directed to give a shell structure which can withstand huge effect. Aside from that, the defensive structure configuration will have the option to withstand the effect without experience straight flexible distortion. This study will focus on effects of trapezoid origami structure which is trapezoidal folded lobe shape on the tensile properties of epoxy reinforced with s-type fiberglass. In this study, there are some parameters that were controlled which are temperature, holding time and compression pressure. The bending analysis may determine the trapezoid origami structure stiffness's and the compression test will also performed to investigate their deformation behavior.

1.2 Problem Statement

To be more exact, crashworthiness is the capability of retention of energy through controlled failure modes and systems. Specifically, a trapezoidal folded lobe thermoset composite can offer high strength material with a light weight which offers a wide scope for the designer to tailor the stiffness properties to the required behaviour. Previously, a study on the composite material with trapezoidal folded mesh features for the structure to increase the energy absorption and mechanical properties. However, the corrugation design can be further improved by designing a quadrilateral mesh (double corrugation surface) and implementing it to fiber reinforced composite material. The mesh is originally used in deployable structures application where the folds enables the rigid face structures to be stored compactly by a unidirectional applied force motion. Therefore, the effect of the design on the material's flexibility and strength will be investigated and added with bending test.

1.3 Objective

The aim of this project is to study on trapezoidal double corrugated shell which is to be produced. The main objectives from this study is as below:

- To fabricate corrugated thermoset composite sheets with respect to the selected profile which is trapezoidal folded lobe by using stamping process
- To study on the deformation of the corrugated trapezoidal structure when exerted by high force
- To determine the behavior of the trapezoidal structure on tensile strengths and other mechanical properties

1.4 Scope of Study

This project will be focused on the crashworthiness design for Trapezoid Origami crash structure by using composite material that is formed using stamping process the scope of study for this project are:

- Suitable composite material that can be used for stamping process.
- The behaviour of the composite material on stamping process.
- Mechanical properties of the Trapezoid Origami shape sample.

CHAPTER 2. LITERATURE REVIEW

2.1 Origami Fundamentals

Origami form plays an important role in improving engineering theory to produce unique architectural design structures and self-fold mechanism which can be compacted into smaller object and open up when arrived to its destination such as the 'Eyeglass' telescope by Lawrence Nevermore National Lab and Heart Stent by Zhong You. After the origami technique had widespread during the modern era, many researchers and mathematician had studied the technique and produced some theorems.

Based on Fei and Sujan , the common origami folding are Mountain Fold (fold from behind), Valley Fold (fold to the front), Crease (a line produced from unfolded paper) X-ray line (hidden edge/crease)and Crease Pattern (all crease lines) [1].

Other than that, based on Tachi , when adding enough amount of foldlines to origami quadrangles form will result in smooth bending behaviour. This model represented as unstable truss mechanism which each edge is rigid bar. Its degree of freedom depends on the formula n_o**-3** where n_o **is** the number of edges on the boundary of mesh on topological disk structure. The form is stabilized by equilibrium of the force from elastic bending of each panel which is assumed to be angular springs at the edge with triangulate panels. The equilibrium of bending and the axial force is very trivial condition for the structure to be in valid configuration. These are called the Bending theorem.[2]

Apart from using the quadrangles origami form like Miura-ori to interactively simulate the shape, Tachi also introduced Kinematic Tessellated surface and Uncreased surfaced design. The Kinematic Tessellated surface use design system to freely produce a 3D surface form in the system and manipulated by its positions of the support or called as support pins. On the other hand, the Uncreased surface manipulate the bending based on the uncreased lines on the meshed surface along the ruling of bent surface. This design effectively captures the behaviour of bending of uncreased sheet[2].

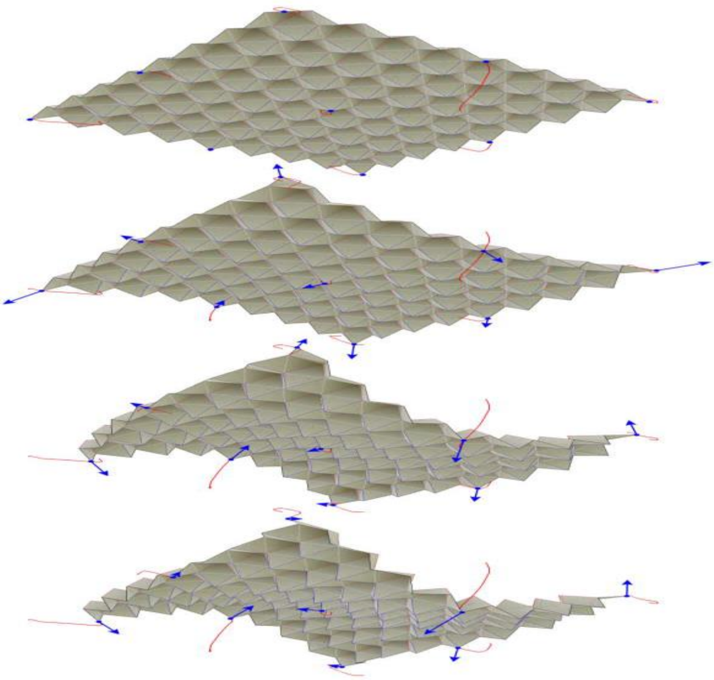


Figure 1: Kinematic surface controlled via the positions of 9 points.

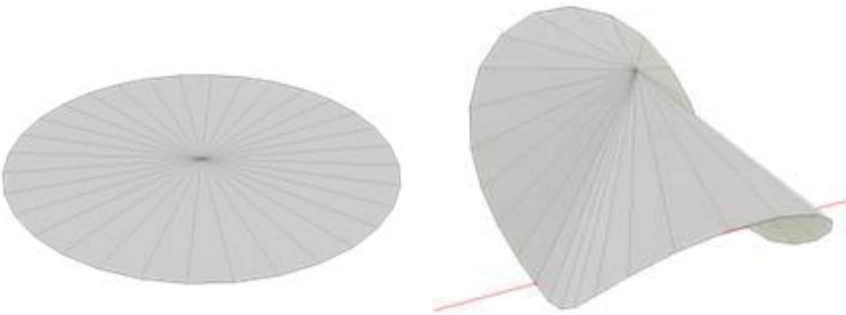


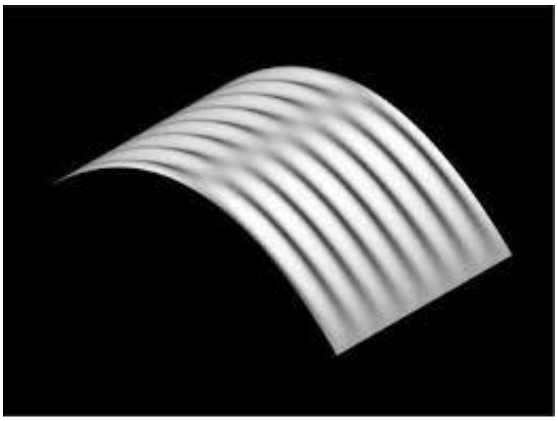
Figure 2 : Bending of uncreased surface with a center crease point.

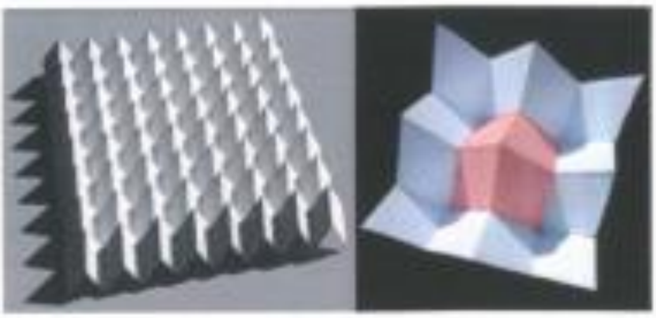
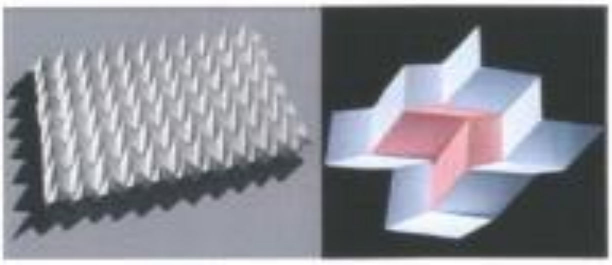
2.2 Composite material

Composite materials can be defined as a combination of two or more materials to obtain better properties of the constituent material when standing alone. As with metal alloys, the composite material in this composite retains chemical, physical, and mechanical properties with each other[3]. Composite material is a macro composite material defined as a material system composed of mixtures or combinations of two or more main elements which are macro distinct in form and or inseparable material composition [4]. By combining two or more different materials, it can be improved and developed the mechanical and physical properties of such materials such as:

- Thermal Conductivity
- Fatigue Resistance
- Strength
- Display
- Stiffness
- Corrosion Resistance
- Friction Resistance
- Electrical Insulation
- Weight
- Heat Insulation

2.3 Types of Corrugated Form

TYPES	CHARACTERISTICS
Curved Corrugated form  Figure 3: Curved Corrugated Shell	The curved corrugated form is a cylindrical form shell where its structure is tightly coiled if pulled and pushed. Moreover, positive and negative Gaussian curvature based on transverse bending direction can be applied in this form. This structure can be formed by joining together some curved strips along the edges.

Eggbox Form  Figure 4: Eggbox form	The eggbox form is developed from orthogonal sets of overlapping hinge lines and compliant at parallel direction to hinge lines. Also, the modes are coupled. It will expands and contracts in opposite direction when it is in-plane compression and stretched. This form has positive Poisson's ratio due to its effectiveness where it can resist shear deformation along the hinge lines which caused by some interference of the hinge lines.
Miura –Ori Form  Figure 5: Miura-Ori form	The Miura –Ori form which was created by Miura himself has intersecting hinge lines which similar to zigzags line. Compared to the eggbox structure, it has crooked and typical corrugating pattern as indicated. This form has negative Poisson's ratio as the sheet can expands in all directions when pulled inversely or vice versa makes it notable as flexible and bendable form.
Corrugated Flat Sheet	This form has many geometric effects which constrained some significant residual stresses in any configuration that makes it more stable. It has two types of curvature which are 'global' and 'local' curvature. These curvatures are assume to be uniformly curved upwards and

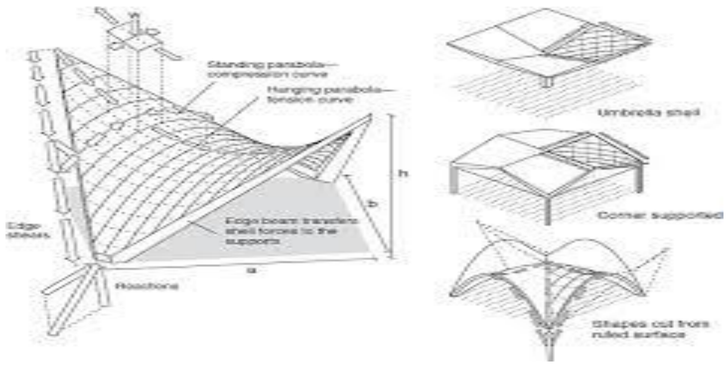
<table>
<tr>
<td>
Figure 6: Corrugated Flat Sheet</td>
<td>downwards. It will also tend to have local with double curvature due to interaction of both curvatures. This will result in significant stretching and bending strain during deformation. Also, this form is the most basic corrugated form.</td>
</tr>
<tr>
<td>Hyperbolic Parabolic form


Figure 7: Hyperbolic Parabolic</td>
<td>The hyperbolic parabolic form has doubly-curved surface which quite resembles he shape of a saddle. It is basically a convex form along one axis and concave shape on along the other axis. As the angle of curvature is increased on either axis the hinge lines will moves closer to each other together while rotating out of the plane. In other words, the form will be twisted around if pushed from two opposing points. Hence, this form is very flexible and has high bending capability.</td>
</tr>
</table>

Table 1 : Types of Corrugated design

2.3 Compression Moulding Process

Compression moulding a typical procedure utilized for both thermoplastic and thermoset materials. Compression moulding is practiced by putting the plastic or composite material (can be in small chip or sheets structure) in a shape hole to be framed by warmth and weight. The warmth and weight compel the materials into all regions of the form. The warmth and weight cycle of the procedure will solidify the material and after that it very well may be evacuated.

It ordinarily utilizes a coordinated metal device in a warmed (regularly hydraulic) press to solidify sheet materials or moulding mixes at generally high weights. Instances of composites that are ordinarily handled by compression moulding incorporate thermosetting prepregs, fibre-fortified thermoplastic "organosheets", moulding mixes, for example, sheet moulding compound (SMC) and slashed thermoplastic tapes. It is likewise broadly used to create sandwich structures that consolidate a centre material, for example, a honeycomb or polymer froth, although care must be taken not to utilize unreasonable weight that may pound the centre.

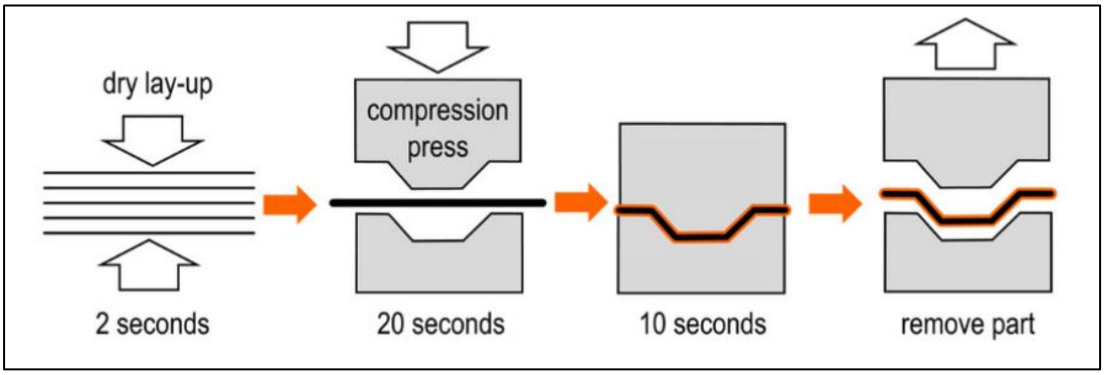


Figure 8: Compression Moulding Process

Compression moulding process has advantages and disadvantages that can be considered in this research.

No	Advantages	Disadvantages
1	Low labour cost and shorter lead time	Lack of simulation facilities for the process
2	Holes, flanges, non-uniform thickness can be created in the part thereby reducing additional processes like welding and drilling	High initial investment in the form of mould is needed, but a high-volume part can compensate this investment
3	Produces near net shape parts eliminating secondary operations	Knowledge about the process and controlling parameters

Table 2: Compression moulding advantages and disadvantage

2.4 Geometry of Trapezoid Origami Structure

Figure 2 shows the origami pattern of a module which includes the width, length and height are b - c_1,1 and h, respectively. The dashed line and solid lines which can be seen in Figure 1 (a) represents valley and hill creases. Each module of trapezoid origami structure has the same dimension, and thus the trapezoid origami structure can consist of one module or several modules by aligning the together.

Zhou, Zhou and Wang (2017) have done their research on energy absorption based on the shape of trapezoid origami crash box where the origami pattern on one module is composed by sixteen isosceles trapezoids [5]. From their research, each corner consists of two trapezoids which also knows as trapezoid folded lobe as shown in Figure 2. The trapezoidal folded lobe is highlighted by dashed line. According to Zhou, Zhou and Wang (2017), the trapezoid folded lobe is intended to achieve two desired functions which are geometric imperfections and collapse mode inducer [5]. Figure 3 shows a quarter pattern of Figure 2 which have the length of trapezoidal folded lobe bases consist of c_1 and c_2 at an intermediate stage in folding process.

Zhou, Zhou and Wang (2017) also state that there is a relationship between dihedral angle θ, and the corner angle Ψ based on geometric compatibility condition which can be illustrated in Eq. (1) [5].

$$\boldsymbol{\Psi = \pi - 4\tan^{-1}\{[l/(c_2 - c_1)]\cos(\theta/2)\}} \tag{1}$$

At the initial folding stage, the sheet is completely flat. Hence, both θ and Ψ are equal to π. At the end of folding stage, the corner angle Ψ reaches $\pi/2$. Thus, the folded quarter of the pattern forms a corner of a tube and consequently, Eq. (1) reduces to Eq. (2)

$$\boldsymbol{\theta = 2\cos^{-1}[(-1)(c_2 - c_1)/l]} \tag{2}$$

Based on the analysis by Zhou, Zhou and Wang (2017), it can be concluded that a trapezoid origami crash box can be folded from a flat sheet [5]. This character lead to simpler manufacturing process and reduce the manufacture costs of the trapezoid origami crash boxes. The geometry constraint $c_1 < c_2$ is enforced towards the design.

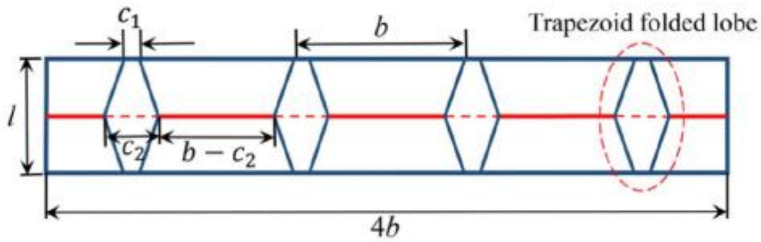


Figure 9 :The origami crease pattern

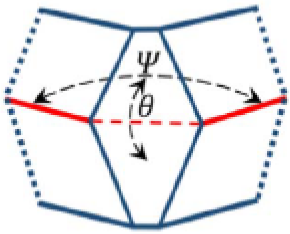


Figure 10: A quarter of the origami pattern partially folded

Source: Zhou, Zhou and Wang (2017) [5]

2.5 Origami Engineering

The word Origami comes from two Japanese words that are ori that means folded and kami that means paper, but in the engineering applications proposed in the following paragraph paper is not used. However, it is very useful to utilize paper model in order to understand the way of folding and then apply these results in engineering purposes.

First, it's necessary to introduce some fundamental parameters like a crease that is a fold and can be convex or concave and it's called respectively mountain and valley. Where two or more creases join each other, a vertex is generated and all the creases make up a pattern. The key concept of origami engineering is understanding how the folding crease involves rigidity to the structure.

Origami has also an application in optics where there is the necessity of folding long focal length into small spaces. This technique creates high resolution using small mirrors that reflect light many times and find some application for the telescopes or for cell phones construction. Recently some researchers tried to use the potentialities of this theory applying on the design of crash box or other structures responsible for the energy absorption in automotive applications.

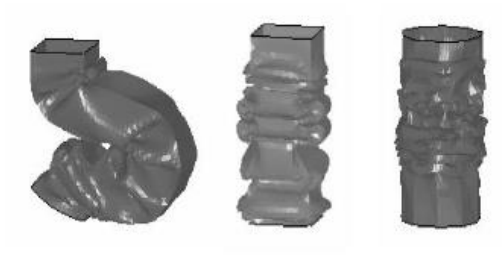


Figure 11: Tube vs Origami beam comparison

Source: Zhao, Hu, Hagiwara (2011) [6].

To evaluate the results and the potential of the origami beam, Zhao, Hu, Hagiwara (2011) made a comparison with two straight tube, (1) that bends during the crash and another tube (2) that deforms correctly in axial direction [6]. In the *Table 1* is possible to see the high increase of energy absorption and also a small decrease of first peak load.

	Original case (1)	Original case (2)	Optimal structure
Absorbed energy (Nmm)	4450601	6176092	8484763
First peak load (N)	53661.11	53652.85	52450.43
Structure mass (kg)	0.532575	0.532575	0.532575

Table 3:Energy and load comparison

Source: Zhao, Hu, Hagiwara (2011) [6].

2.6 Prepreg of Epoxy-Fiberglass Composite

Prepreg is a common term for a reinforcing fabric which has been pre-impregnated with a resin system which is typically epoxy and already included with the proper curing agent. This will make the prepreg ready to lay into the mould without the addition of any resin. It is necessary to use heat and pressure in order for the prepreg to cure. According to Chen et.al (2017), the glass fiber laminate composite can be made from different glass fiber reinforcement in the forms of woven, multiaxial, unidirectional and chopped strand mat in various matrices which consist of phenolic, polyester or epoxy [7].

One of the glass fiber laminate materials which is thermo-laminated woven fiberglass is made from woven glass fiber fabric impregnated with epoxy resin binder. According to Chen et.al (2017), the glass fiber laminate has high mechanical strength, humidity resistance, sound flame resistance and good corrosion resistance [7]. Chen et.al (2017) also state that this type of laminate composite is suitable to use in variety of industry and application which includes insulating structural parts in electrical equipment, vehicle structure, pressure vessel, and gas pipe [7].

. Based on the research done by Chen et.al (2017) on the tensile properties of fiberglass laminate sheet, the fiberglass has increasing tensile strength at increasing strain rate [7]. The results show that the tensile strength of the fiberglass is high which can be up to 423.4 MPa. Furthermore, increase of tensile strength is heavily affected by the damage modes where more damages such as delamination and diagonal cracks were extended to a larger area, which resulted in the increase of tensile strength of material. In addition, according to Chen et.al (2017), there is a strength increment towards the specimen because these multiple failures require more energy to cause the damage [7]. This is due to the specimen had no time to initiate the failure at internal defects or stress concentrated area at high strain rate.

CHAPTER 3. METHODOLOGY

In this chapter 3, there will be information regarding the procedures conducting this project. Together with this, the process of fabrication of mold, the design that been chosen and the experiment that has been done on the project. Apart from that, the experimental set up and the results that have been obtained from the experiment will also be discussed.

3.1 Flow of Research

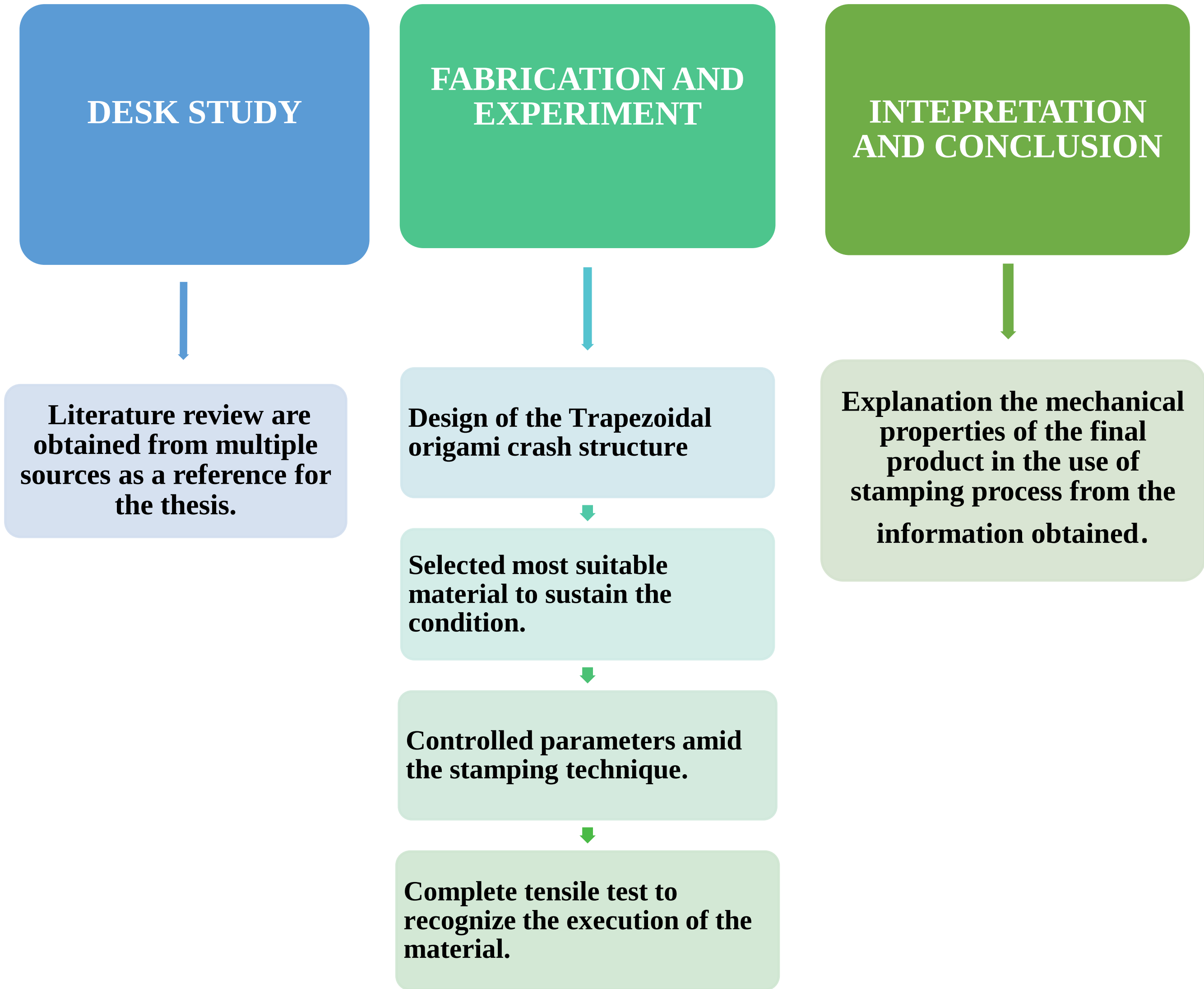


Figure 12: Flow Of Research Chart

3.2 Project Flow Chart

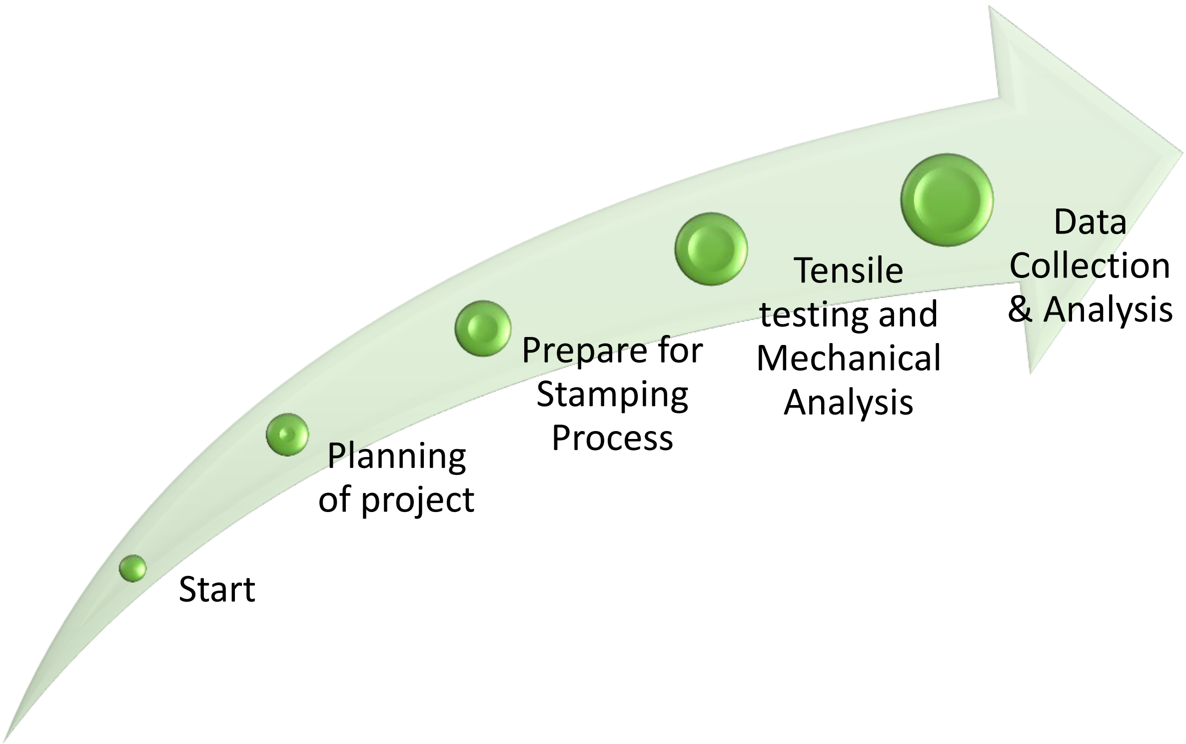


Figure 13: Project Flow Chart

3.3 **Design of The Trapezoidal Folded Lobe Shape and Fabrication of Mould**

3.3.1 Fabrication of Female Mould Using CNC Milling Machine

A 200mm× 200mm trapezoidal folded lobe shape and mould was design using CAD software which is AUTOCAD according to the desired geometry dimension. Then, an aluminium 6061 plate was cut using CNC milling according to the trapezoid origami structure profile which is trapezoidal folded lobe shape.

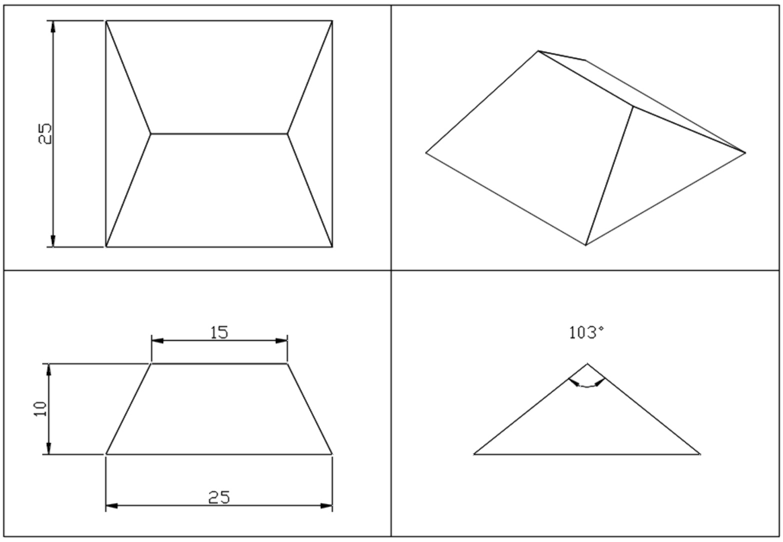


Figure 14: Single trapezoidal folded lobe

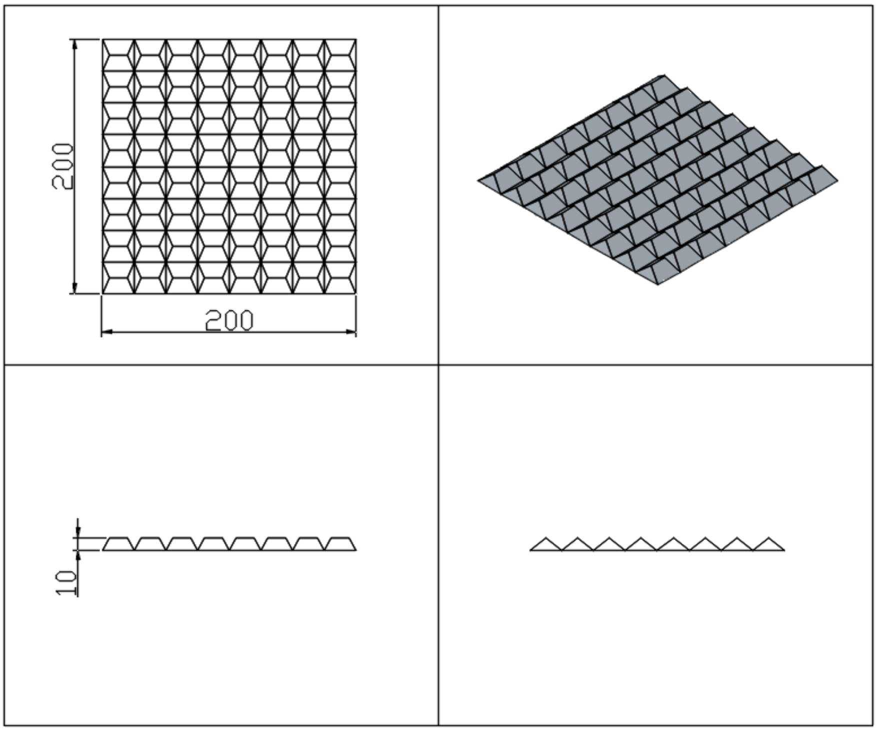


Figure 15: 200 × 200 mm trapezoidal folded lobe

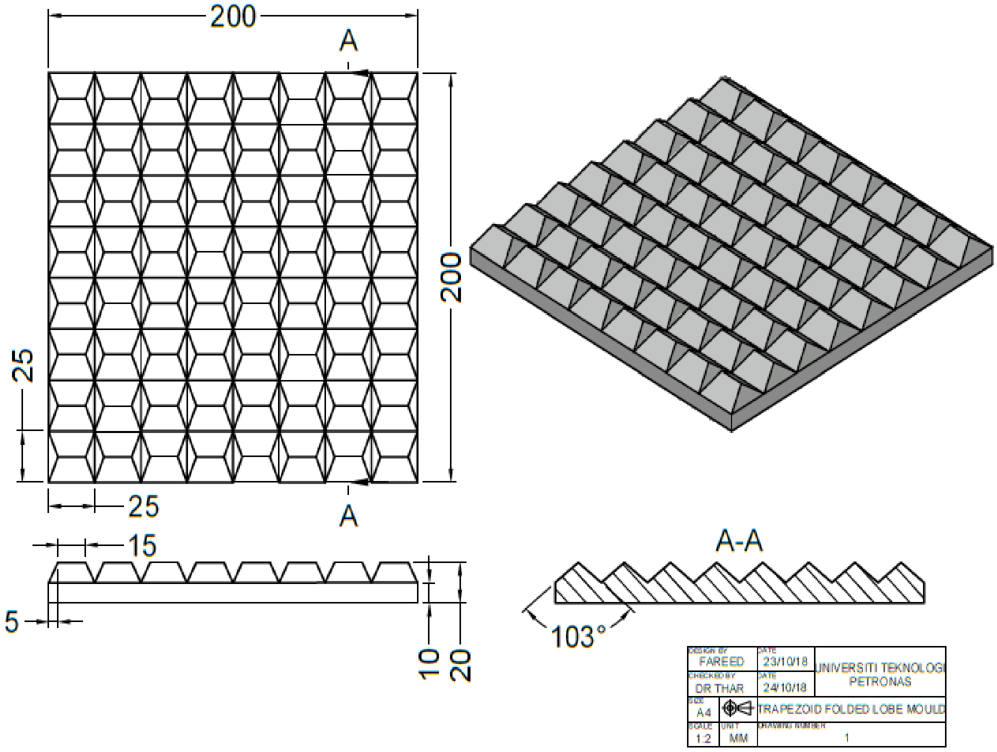


Figure 16: Design of trapezoidal folded lobe shape mould

The trapezoidal folded lobe aluminium mould as shown in Figure 17 which act as a female mould has been successfully fabricated according to the project timeline illustrated in the Gantt chart for FYP I. The cutting was done according to the geometry as shown in Figure 14 by using CNC milling. The cycle time needed to fabricate the patterned aluminium mould is around 7 hours. Figure 17 shows the trapezoidal folded lobe aluminium mould that have been milled using CNC milling machine.

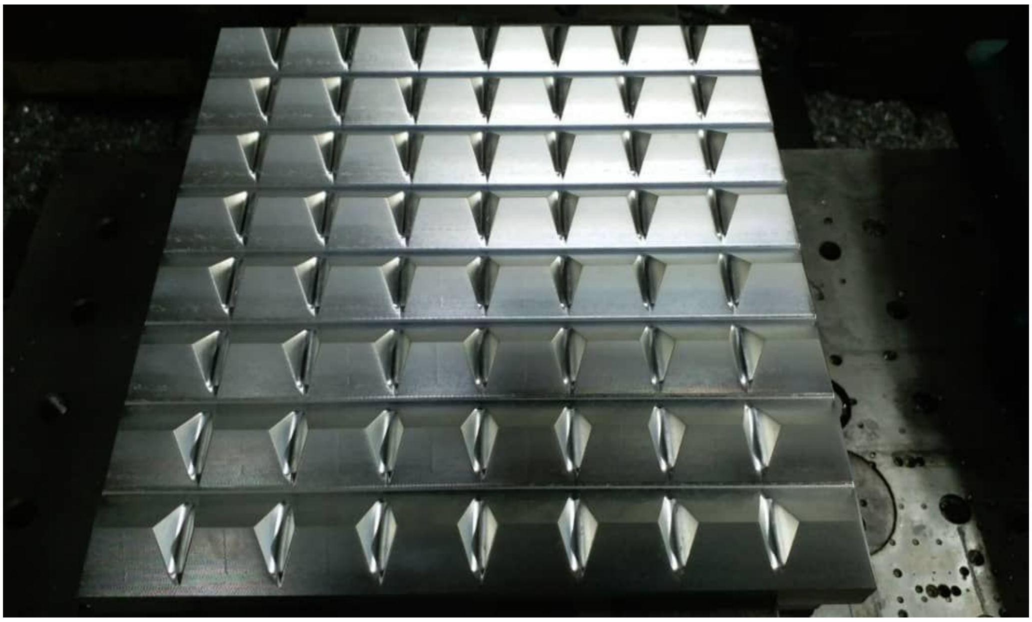


Figure 17: Trapezoidal folded lobe aluminium mould

The material of aluminium sheet used is aluminium 6061. Aluminium 6061 is selected due to its good mechanical properties. Aluminium alloy has high corrosion resistance because a thin oxide films will form immediately when aluminium surface exposed to atmosphere to prevent oxidation occur.

Commercially aluminium 6061 has a tensile strength of about 60 MPa. Thus, its usefulness as a structural material in this form can withstand high stamping pressure. Besides, aluminium has high strength-to-weight ratio. The strength-to-weight ratio of aluminium 6061 is much higher than that of many common grades of constructional steels. The comparison can be observed from Figure 12. This property permits design and construction of strong, lightweight structures that are particularly advantageous for anything that move.

The most important factors aluminium 6061 was chosen because it is easier to fabricate it into any desired shape. The ease which aluminium can be machined is one of the important assets contributing to the low cost of finished aluminium parts. The metal can be turned, milled, bored, or machined in other manners at the maximum speeds of which most machines are capable.

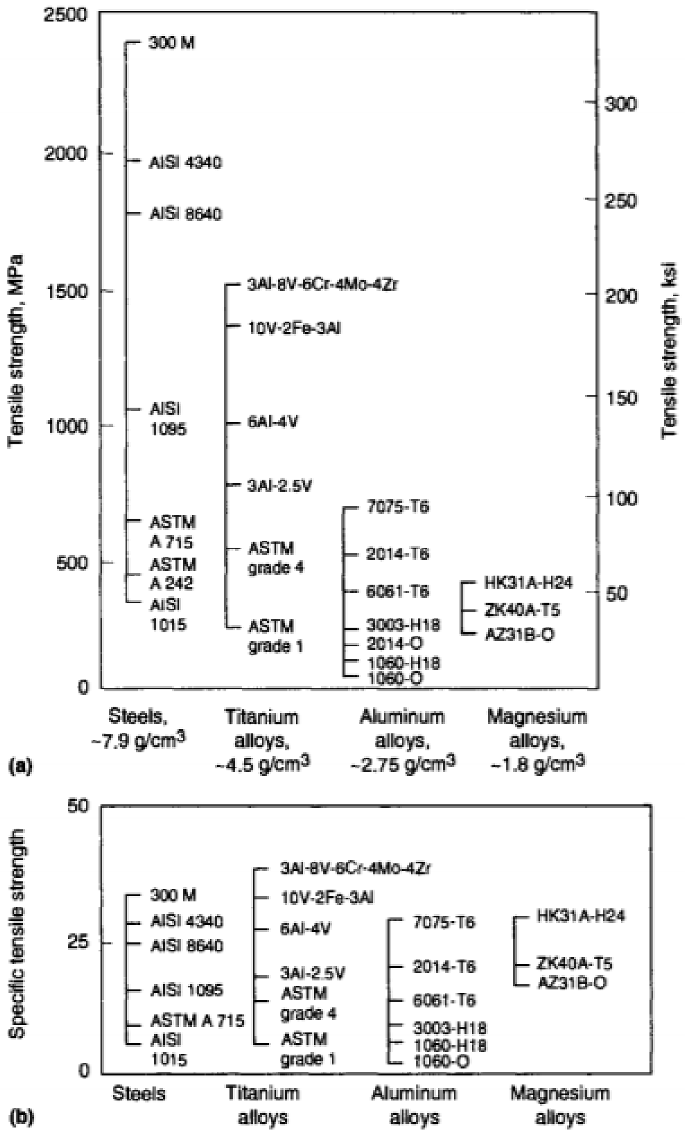


Figure 18: Comparison of aluminum alloys with competing structural alloys on the basis of tensile strength and specific tensile strength (tensile strength, in ksl, divided by density, in g/cm)

3.3.2 Fabrication of Male Mould by Stamping Process

Rubber moulding is the process of exposing the raw material to heat and pressure in order to cure the rubber which also known as vulcanisation. Vulcanisation allows the rubber to have many of the favourable properties that rubber products are known to have. This chemically stability gives rubber durability and makes it resistant to degradation when exposed to heat, light, extreme weather and chemicals.

A rubber piece was placed into the cavity of a mould that have the dimension of 200mm × 200mm and in between the mould and rubber will lies the trapezoidal folded lobe shape aluminium sheet. The male mould was fitted onto the female mould and it was placed into the compression moulding machine. The platens were preheated to 200°C before the process. Then, the rubber material was pressed against the aluminium sheet with enough temperature and pressure to ensure the rubber piece acquires the origami profiles of the fabricated aluminium sheets. After several information gathering is done, the parameters that will be controlled during the stamping process to ensure good and acceptable results are shown in Table 3.

Parameters	**Thermoset**
Die temperature	200℃
Stamping pressure	20 tonnes
Hold time	15 minutes
Material temperature	No preheating
Pressing speed	19 cm/s

Table 4: Stamping process parameters to fabricate male mold

The rubber was chose for the material of the male mould because of its benefits which includes simple process, cost-effectiveness, unlimited quantities and broad use. Figure 13 shows the rubber mould which took the shape of the trapezoidal folded lobe shape.

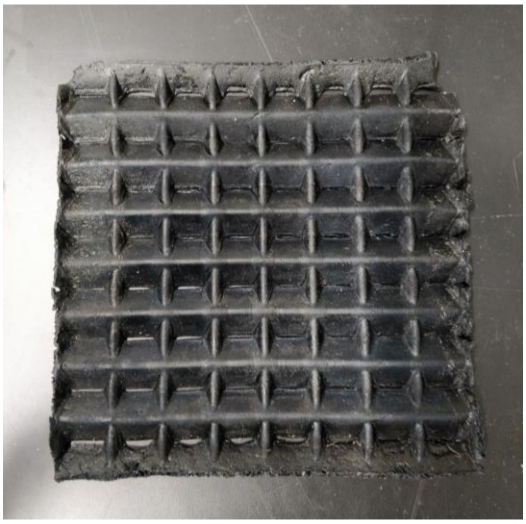


Figure 19: Rubber mould

3.3.3 Fabrication of Trapezoidal Folded Lobe Sample by Stamping Process

The process to fabricate trapezoidal folded lobe composite material is basically the same as the previous process to fabricate the male mould. The composite material was placed onto the patterned sheet at female mould. Then, the male mould was placed onto the composite material. Next, the male mould was fitted onto the female mould for compression and the composite material was compressed under controlled parameters as shown in Table 4. Figure 14 shows the composite material that have been pressed according to the mould design. The composite material consists of 2 types of axis which is Y-axis and X-axis. During the crushing test, the sample will be tested in Y-axis and X-axis direction.

Parameters	**Thermoset**
Die temperature	200℃
Stamping pressure	2 tonnes
Hold time	8 mins for each composite material
Material temperature	No preheating
Pressing speed	19 cm/s

Table 5: Stamping process parameters to fabricate patterned composite material

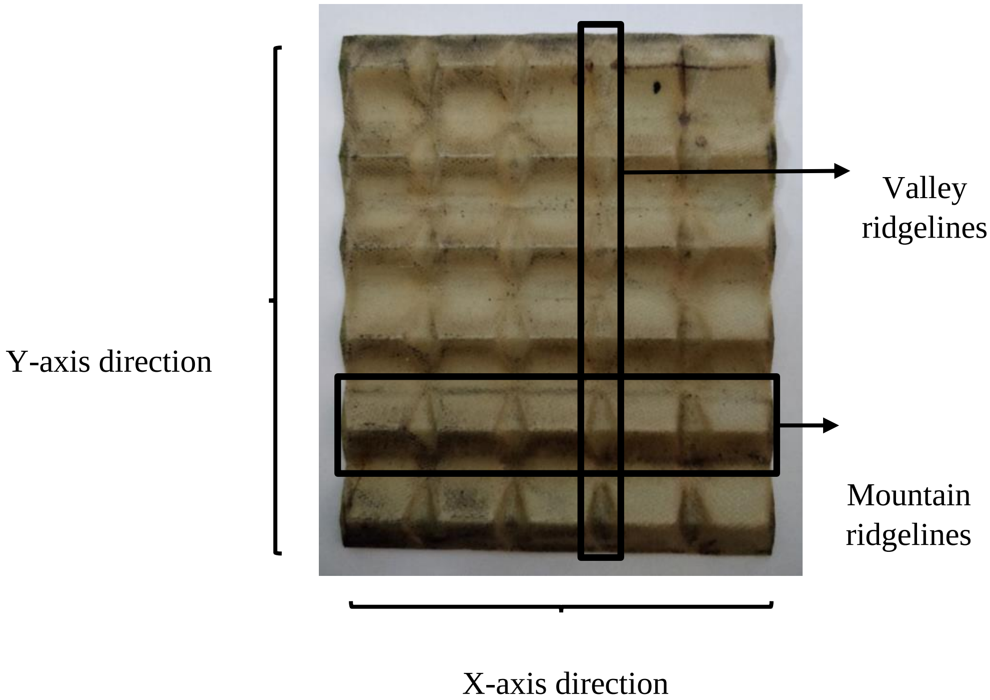


Figure 20: Trapezoidal folded lobe composite material

3.4 Gannt Chart

FYP 1 Gantt Chart

Task	Week													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Project title confirmation and discussion	▲													
Review and methodology			✡											
Literature review														
Extended proposal submission						▲								
Pre-experiment preparation and further studies						✡								
Proposal Defense							▲							
Improvisation of the project														
Documentation of the project report														
Interim report submission														▲

Table 6: Gannt Chart FYP1

3.5 FYP 1 Key Milestones

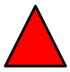
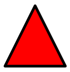
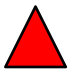
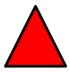
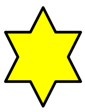
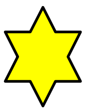
Week	FYP Markers	FYP1 Activities
1		Title confirmation
6		Extended proposal submission
7		Proposal defence presentation
14		Interim report submission
Week	**Project Markers**	**FYP1 Activities**
3		review and methodology
6		Pre-experiment preparation and further studies

Table 7: Key Milestones FYP1

3.6 FYP 2 Gantt Chart

Tas k	**Week**														
	1	2	3	4	5	6	7	8	9	10	1 1	12	1 3	14	15
Design development of selected trapezoidal design	■	■	■	■											
Sample simulation for stiffness and flexibility testing					■	■ ★									
Finalized mold design and fabrication of the mold							■	■							
Progress Report Submission								■ ▲	■						
Corrugated sheet of fiber-glass composite preparation									■	■ ★					
Pre-Sedex										■ ▲					
Vibration testing and data analysis											■	■ ★			
Submission of dissertation/technical paper													■	■	
Viva													■	■ ▲	
Submission of Hardbound copy															■ ▲

Table 8: Gannt Chart FYP2

3.7 FYP 2 Key Milestones

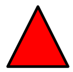
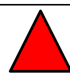
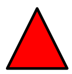
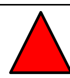
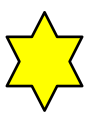
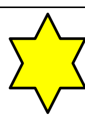
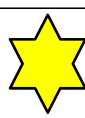
Week	FYP Markers	FYP 2 Activities
8		Progress Report Submission
10		Pre-Sedex
14		Viva
15		Submission of dissertation (Hardbound copy)
Week	**Project Markers**	**FYP 2 Activities**
5-6		Sample simulation for stiffness and flexibility testing
9-10		Corrugated sheet of fiber-glass composite preparation
11-12		Vibration testing and data analysis

Table 9: Key Milestones FYP2

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, we will be discussing the results obtained from simulation done on the material which is the fiber composite material. Firstly, we take note on the tensile and mechanical testing followed by the bending stress and deformation test. The simulation is done on Ansys Software, the results then analysed and tabulated. This is to ensure to obtain the accurate results and these simulations is done to test on the mechanical properties of this fibre composite material.

4.2 Mechanical Deformation

For the mechanical properties, I have done simulation on the total deformation of the surface using quadrilateral mesh by face meshing. The results were attached in the below figures for observation. Moreover, I have done the bending deformation together to check on the materials properties to ensure that the strength of the material is suitable for the dynamic analysis

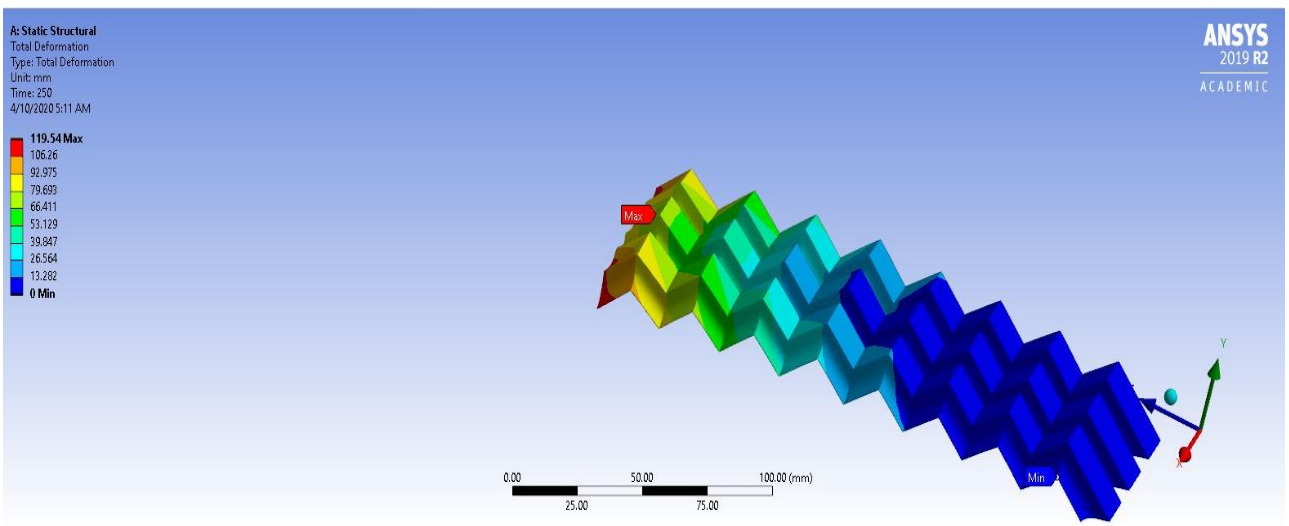


Figure 21: Total Deformation

The figure above shows the deformation of the composite fibre material as total deformation. The results generally can be in ANSYS WorkBench as total deformation or directional deformation. Both of them are used to obtain displacements from stresses. The main difference is the directional deformation calculates for the deformations in X, Y, and Z planes for a given system. For this case the maximum total deformation is 119.54mm.

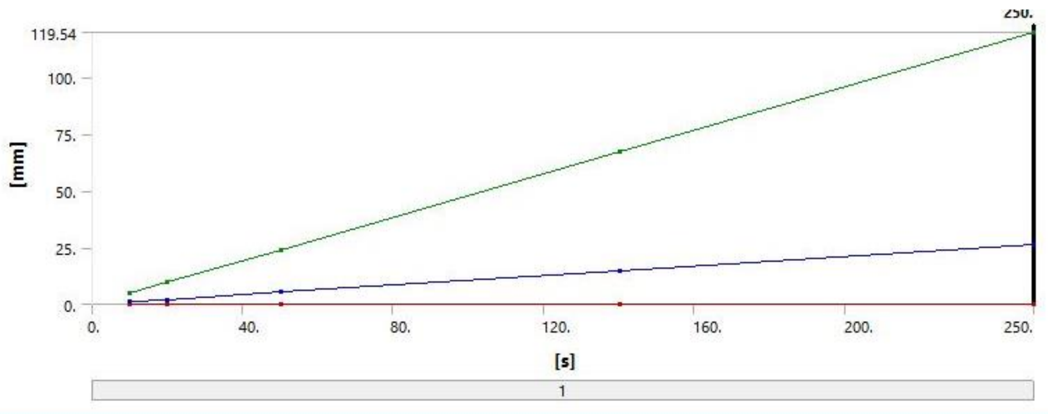


Figure 22: Graph of Total deformation

Tabular Data

	Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1	10.	0.	4.7816	1.0441
2	20.	0.	9.5632	2.0883
3	50.	0.	23.908	5.2207
4	140.	0.	66.942	14.618
5	250.	0.	119.54	26.104

Table 10: Total Deformation Results

The graph above shows the maximum deformation in 250s time step and on each different 5 time steps the maximum and average of the data is calculated and tabulated.

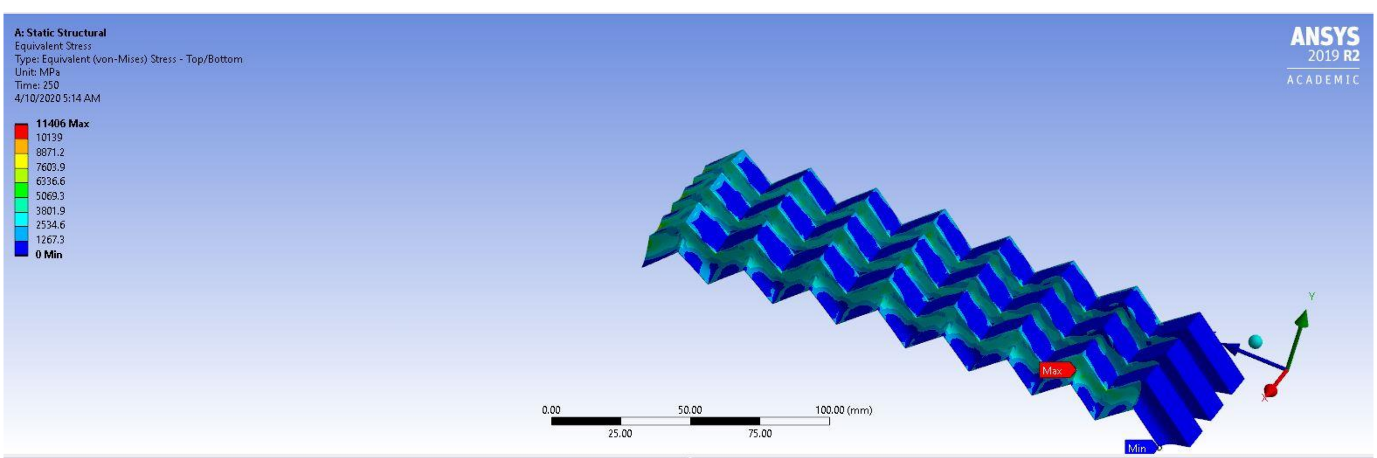


Figure 23: Equivalent Stress

Equivalent stress is used when there is a multiaxial stress state with multiple stress components acting simultaneously in the structure. In such case we can utilize chosen standard to change the entire stress tensor into a single equivalent component that can be treated as a malleable pressure and accordingly contrasted and material's quality without any problem. Different criteria might be use however among them there is unified with especially bigger prevalence than the others - von Mises yield standard or in any case most extreme twisting vitality basis. It's generally utilized in building as Finite Element Analysis programs use it as a default stress measure.

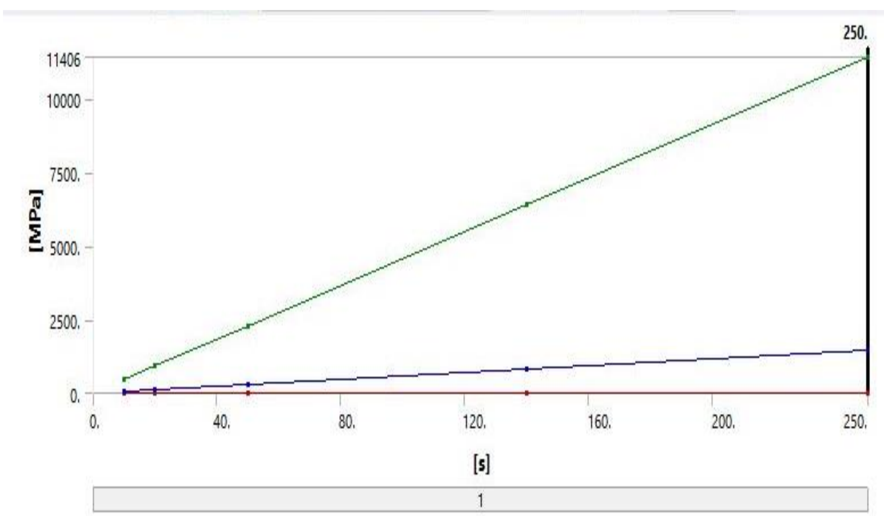


Figure 24: Graph of Equivaklent Stress

Tabular Data

	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	10.	0.	456.23	58.241
2	20.	0.	912.47	116.48
3	50.	0.	2281.2	291.21
4	140.	0.	6387.3	815.38
5	250.	0.	11406	1456.

Table 11: Equivalent Stress Results

The table shows the data for the maximum and average data obtained from the simulation for ewuivalent stress which provides the maximum stress of 11406 Mpa and the aveage is 1456 Mpa which is quite great for the material that is used. The graph also shows as the toime step increases the equivalent stress also increases.

4.3 Bending Deformation

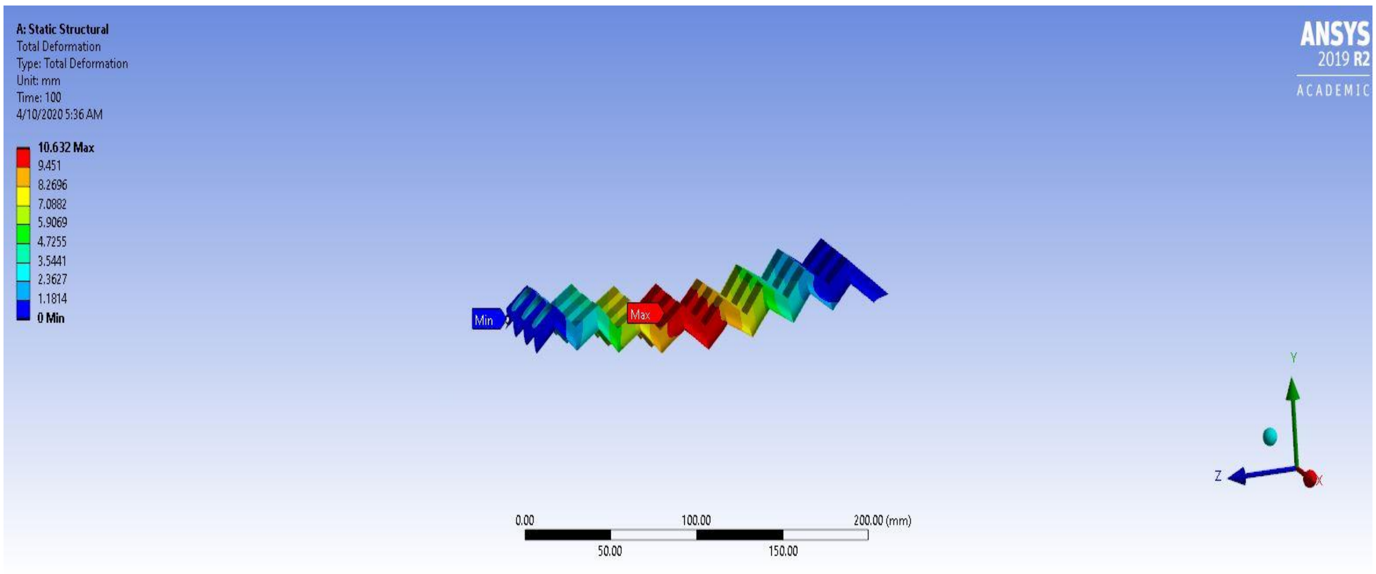


Figure 25: Bending Deformation

For bending stress deformation I have included the force in the surface bosy split into 2 sides then the load has been weighted in the middle of the fiber composite material to get the data of the bending stresses. This has to be calculated to ensure the physical properties and to test the tensile strength of the composite material. In this case the maximum stresss was 10.632mm using with the time step of 100s. the data then brought forward in graph and table.

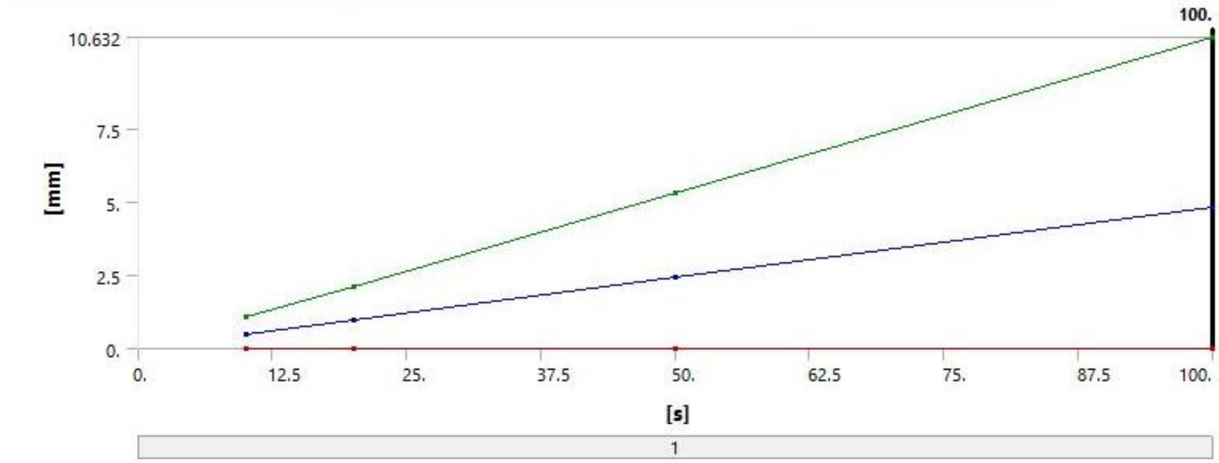


Figure 26: Graph of Bending Deformation

Tabular Data

	Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1	10.	0.	1.0632	0.48304
2	20.	0.	2.1265	0.96609
3	50.	0.	5.3162	2.4152
4	100.	0.	10.632	4.8304

Table 12: Bending Deformation Results

The bending stress is then graphed with the data for time step of 100s to calculate the maximum and the average deformation for each time step above to obtain more accurate results. The grap moves with linearly because the force that applied in this simulation is 20000 N and the deformation occurs linearly against the material.

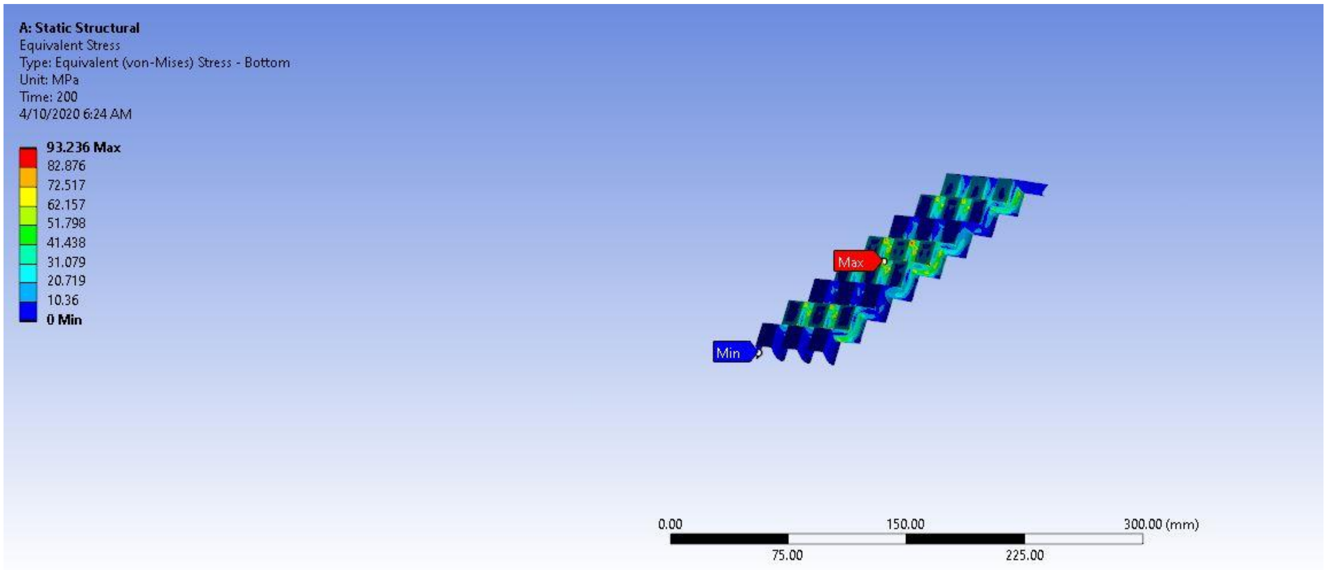


Figure 27: Bending Equivalent Stress

This figure shows the bending equivalent stress on the body surface with providing the result of maximum stress is 93.236 Mpa. This equivalent stress is calculated based on the mechanical and physical properties of the composite fiber material fiberglass. The results then tabulated and analysed by a graph that shows the equivalent stress across the time step. This result enables us to know the stress across the multiaxial components.

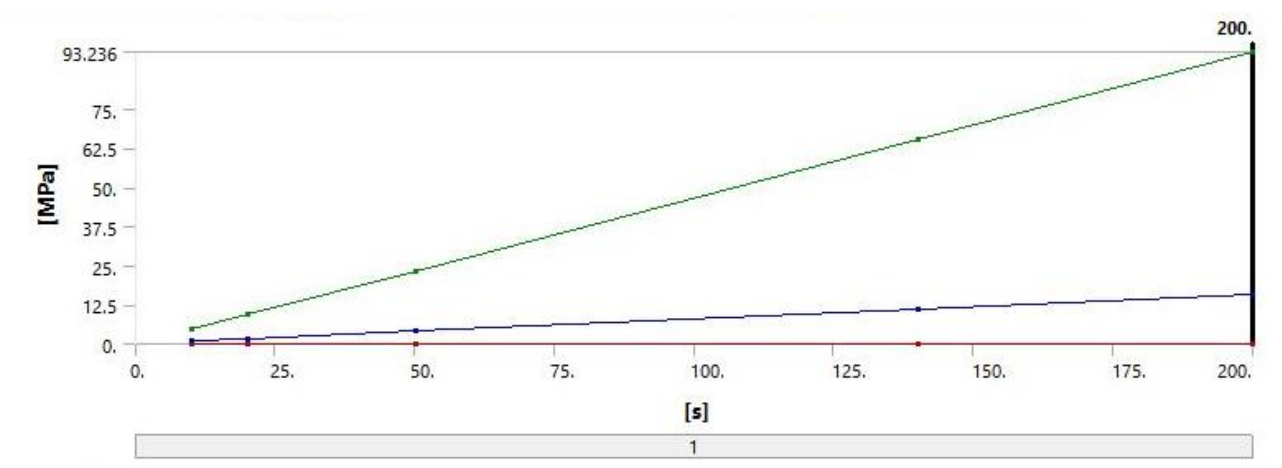


Figure 28: Graph of Bending Equivalent Stress

	Tabular Data			
	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	10.	0.	4.6618	0.79965
2	20.	0.	9.3236	1.5993
3	50.	0.	23.309	3.9983
4	140.	0.	65.265	11.195
5	200.	0.	93.236	15.993

Table13: Bending Equivalent Stress Results

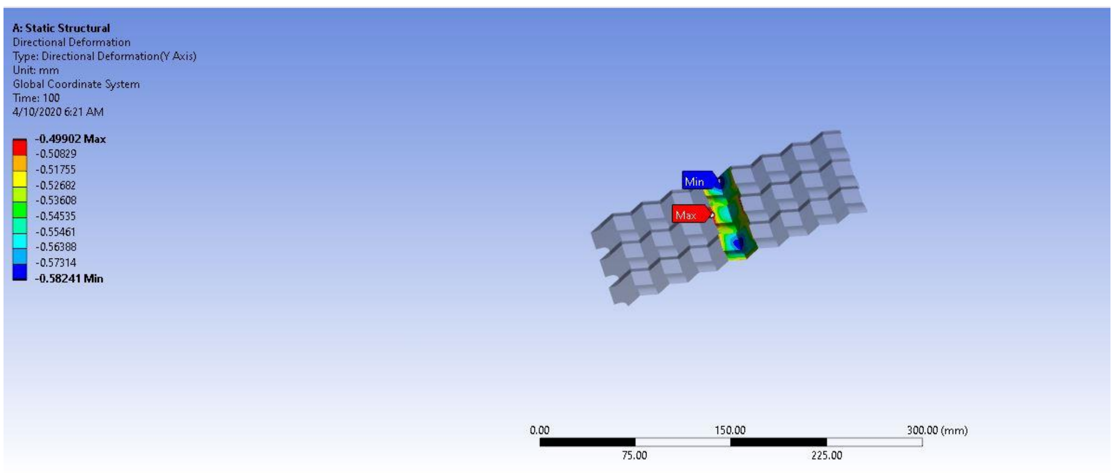


Figure 29: Directional Deformation

Directional deformation can be put as the displacement of the system in a particular axis or user defined direction. In this case I have simulated by dissecting into 2 parts then the centre of the composite fiber material was added a force of 5000N to obtain the directional deformation through y axis.

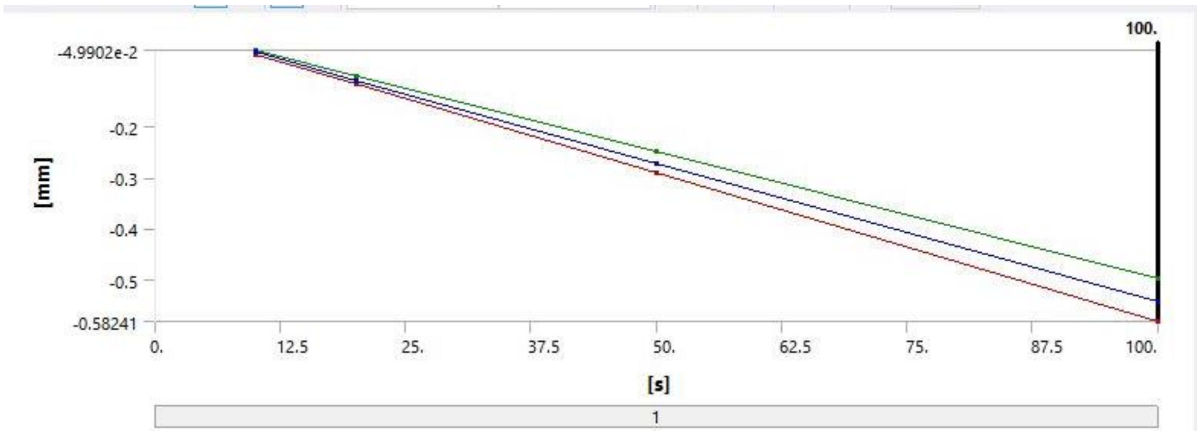


Figure 30: Graph of Directional Deformation

Tabular Data

	Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1	10.	-5.8241e-002	-4.9902e-002	-5.431e-002
2	20.	-0.11648	-9.9805e-002	-0.10862
3	50.	-0.2912	-0.24951	-0.27155
4	100.	-0.58241	-0.49902	-0.5431

Table 14: Directional Deformation Results

The graph was then plotted to analyse on the deformation and the results were tabulated for reference. The maximum stress that deforms the material is -0.49902 Mpa and the average is calculated with few time steps.

4.4 Bending Stress

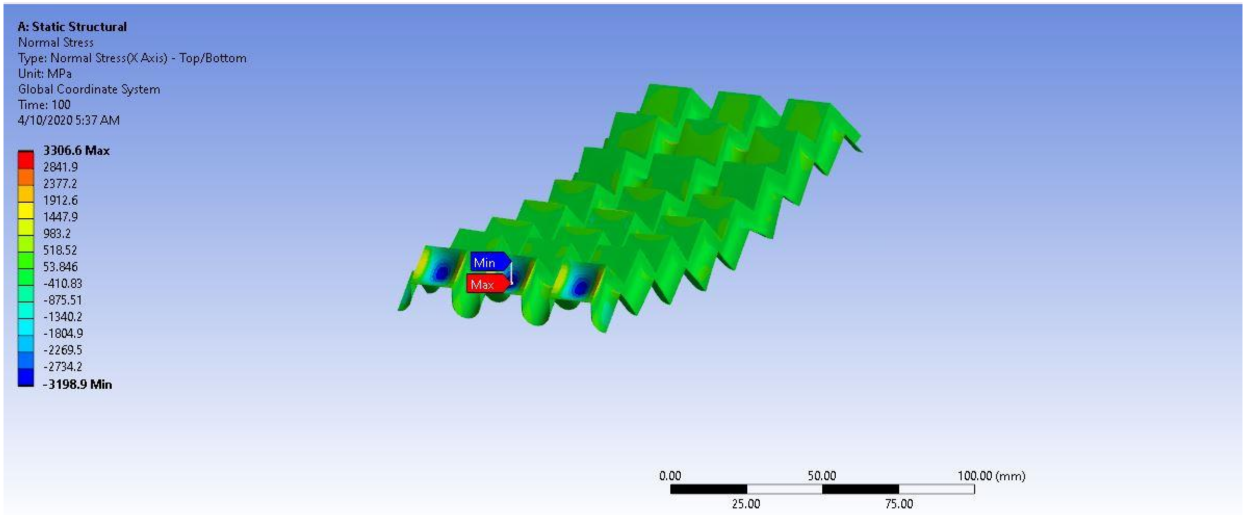


Figure 31: Bending Stress

Bending stress is the normal stress that is actuated at a point in a body exposed to loads that cause it to twist. At the point when a heap is applied perpendicular to the length of a beam (with two supports on each end), bending moments are induced in the beam. The stress at the horizontal plane of the neutral is zero. The maximum bending stress is calculated as 3396.6 Mpa which is high reliability of this material to be used for the industrial and medical lines.

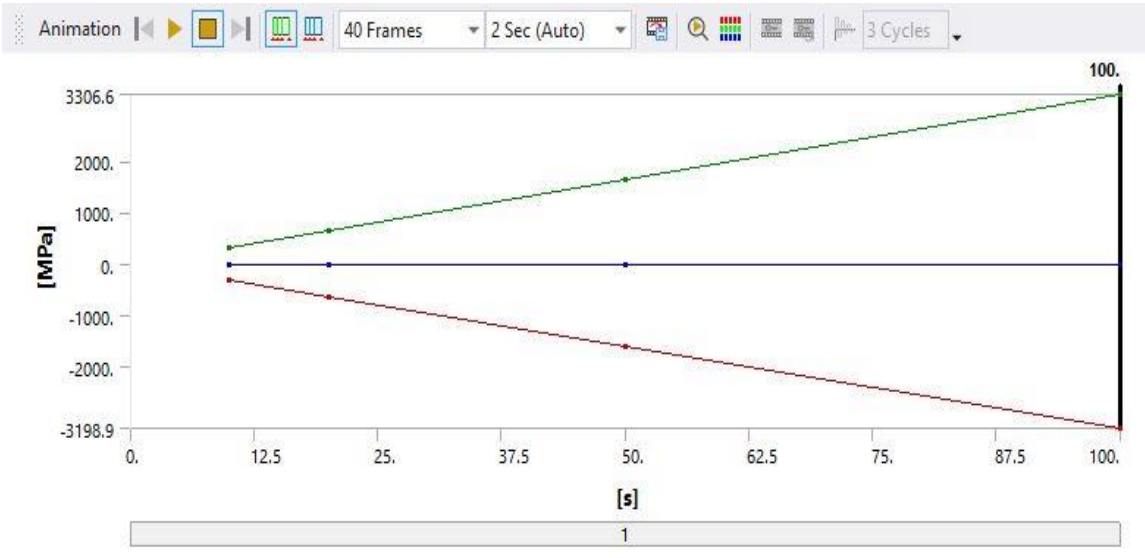


Figure 32: Bending Stress Graph

Tabular Data

	Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1	10.	-319.89	330.66	9.5417e-003
2	20.	-639.78	661.32	1.9083e-002
3	50.	-1599.4	1653.3	4.7709e-002
4	100.	-3198.9	3306.6	9.5417e-002

Table 15: Bending Stress Results

The table shows the minimum, maximum and average stress that has been calculated on the composite fiber material which enhances the analysation of this project with having great mechanical and tensile strength to be used in the industry.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

In this thesis, the trapezoidal origami inspired design has shown significant breakthrough for its mechanical properties collaborated with the fiber composite material. Though it is as yet rare for origami mathematics to be directly applied in engineering, the recent expansion of the field has led to algorithms that can be used to define the limits of folding and unfolding and provide the basis for foundational concepts such as rigid-foldability. Applications have been explored in areas such as aerospace, biomedical devices, packaging, storage, manufacturing, robotics, medical mechanisms, self-folding devices, core structures, and architecture. Ongoing research in origami engineering is improving folding efficiency in many engineering operations and recent innovations are expanding the future capabilities.

Based on my findings and research, it is proven that it will be significant to achieve my objectives using the methods and simulation to complete my study. On my FYP 2 I have done more research and start my lab procedures to have the prototype and more simulation will be done on it to get to know the mechanical properties and will also investigate the recommendations to increase its strength and flexibility.

As a conclusion, the results that will obtain from the testing and the simulation from Ansys Workbench was studied and further enhanced from FYP1. This is to ensure I have achieved all my objectives and the reliability of the findings. Although all my findings are proven theoretically, these mechanical properties needed to confirm further with the conducting the experiments.

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