Strength of Quasi isotropic glass fiber laminate

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Abstract:
This thesis investigates the mechanical properties of 2 types of quasi-isotropic laminate. The laminates are glass fiber (UD warp knitted textile at 1152 g per m^2) infused using (ATLAC ENOVA 6215 resin). The laminates were manufactured using vacuum lamination technique. The sheets were then cut using water cutting technique in order to create the samples. The sample have a dimension of 15 mm in width, 180 mm in length, and thickness depending on the type of laminate. 6 layers quasi-isotropic laminate has an average thickness of 5.5 mm, and 8 layers quasi-isotropic laminate has an average thickness of 7.4 mm. The samples were subjected to 3-point bending test in order to determine the mechanical properties (bending modulus and bending strength). Composite Compressive Strength Modeller software (CCSM) was used to model 2 types of quasi-isotropic laminate (6 and 8 layers) with different orientation of layers in order to investigate failure analysis and find the most optimal lay-up of quasi-isotropic in terms of young's modulus, shear modulus, and bending modulus in x, y, xy direction. The hypothesis of this thesis is that both laminates have the same young's modulus but laminate 2 has a longer crack length than laminate 1 because in redirect cracks at a big angle making the total crack length longer. The hypothesis was that the laminate 2 as compared to laminate 1 has a 41% larger strength due to higher failure strain. Experiment results for support distances at 60 mm show this to be true with a percentage error of 7.11%. Experiment results for speed of the force at 10 mm/s show this to be true with a percentage error of 8.6%. Experiment results for other speeds and lengths showed a higher percentage error. The thesis answers the question of what is the ideal quasi-isotropic setup that gives at minimum investment the largest strength. According the result obtained from the samples tested and CCSM software, 6 layers quasi-isotropic laminate gives at minimum investment the largest strength.

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FOREWORD

I would like to express my gratitude to my supervisor Mr.Rene Herrmann for his guidance and support throughout the whole process of my thesis.

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1 INTRODUCTION

This thesis is about the bending strength of glass-fiber composites with isotropic modulus in the x-y plane. This called quasi-isotropic orientation.

Composite material is characterized to be the combination of two or more materials remaining at original phases.

This will result in a component with better properties than the individual component's properties. [1] Composite material can be classified in two type, isotropic materials and anisotropic material. In case of isotropic material, the properties are the same in all direction while in anisotropic materials, the properties are not the same in all direction.

2 LITERATURE REVIEW

2.1 Composite Laminate

The term composite laminate can be defined as the assemblage of layers of fibrous composite materials where they can be joined to provide specific properties. *Lamina* is a lay-up in which all the layers are placed in the same orientation. *Laminate* is a lay-up in which the layers are placed in different orientation or angles. Quasi isotropic is when the volume contribution of all fiber bundles forms constant angles to any external force within the plane. The modulus is within the plane constant. Quasi-isotropic laminate carries equal load in all direction. Another example of quasi-isotropic laminate is (0°,120°,-120°) lay-up. [1] Both of the orientation have been manufactured and examined in terms of mechanical properties (bending modulus, shear modulus, stress at break, and maximum strain). 3-point bending test was applied for 32 samples, 16 samples had the orientation of (0°,45°,-45°, and 90°) and the other 16 samples had the orientation of (0°,120°,240°).

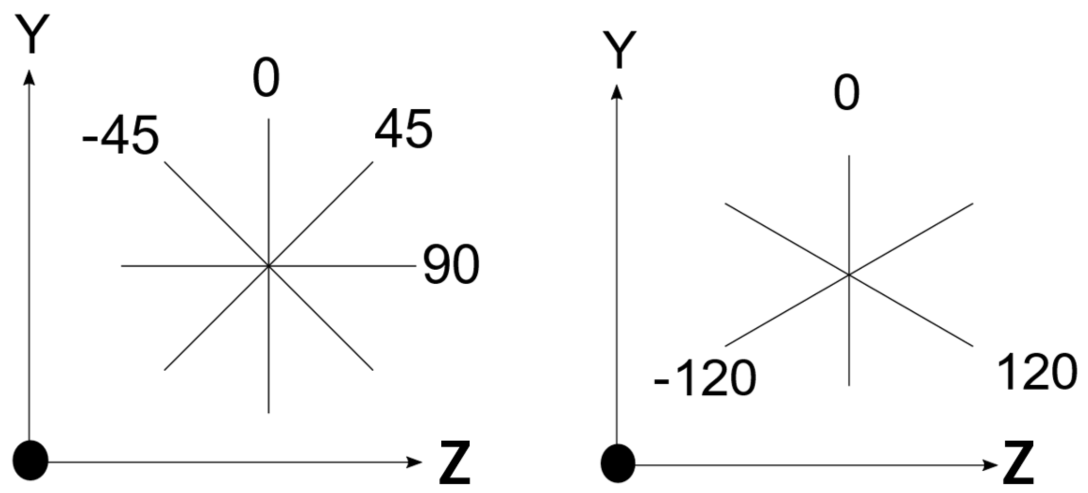

Figure 1 In top view shows the alternative fibers placement.

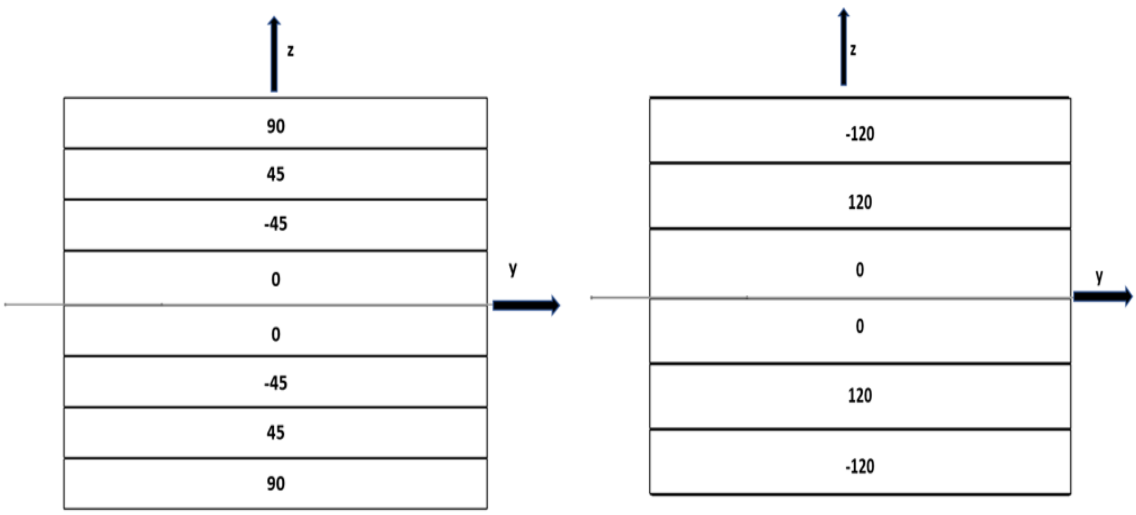

Figure 2 Cross section of laminates, showing fiber angles.

2.2 Fiber Reinforcement

There are many ways to reinforce composite materials. Particles, whiskers, or fibers can be used for reinforcement. This thesis will focus on fiber reinforcement as a material used for composite laminates. The experiment was conducted using glass fiber reinforcement.

Fiber can be defined as a “material that has a long axis that is many times greater than its diameter.” [1]

2.3 Strength of Fibers

Fibers have higher strengths than the bulk form of the same material. “The probability of a flaw per unit length present in a sample is an inverse function of the volume of the material”. [1] knowing that fibers tend to have low volume per unit length, they are much stronger than the bulk of the same material because they have fewer intrinsic faults.

2.4 Objectivity and Aim

The purpose of this thesis is to model mathematically two different type of quasi-isotropic laminate setup and define young’s, bending, shear modulus, and bending failure using CCSM modelling software.

The aim of the thesis is to determine what is the ideal quasi-isotropic layup that gives at minimum investment the largest strength in bending.

As a test material, glass fiber UD warp knitted textile at 1152 g per m^2 is used. The specimens were vacuum infused using ATLAC ENOVA 6215 resin. The size of each specimen is roughly 180 mm length by 15 mm width and the thickness depends on the number of layers. 8 layers laminate have roughly 7.5 mm and the 6 layers laminate have roughly 5.5 mm. The fiber volume fraction in both materials are comparable.
Laminate 1 contain 8 layers of evenly spaced yarns at 45 degrees angle difference.
laminate 2 contain 6 layers of evenly spaced yarns at 60 degrees angle difference.

Young’s modulus of both materials should be quasi isotropic and equal. The strength of lamina 1 and 2 maybe different as crack propagation is redirected along different yarn directions.

Hypothesis is that both laminates have the same young's modulus but laminate 2 has a longer crack length than laminate 1 because in redirect cracks at a big angle making the total crack length longer.

2.5 Crack Propagation

This thesis focusses on strength due to crack propagation theory for quasi isotropic laminate. As cracks propagate in the laminate, due to the fibers orientation, the crack redirect according to the angle of rotation of the fibers. Since the laminate is quasi-isotropic lamina, the cracks will be redirected at 60° angle and 45° angle depending on the 8 and 6 layers lamina.

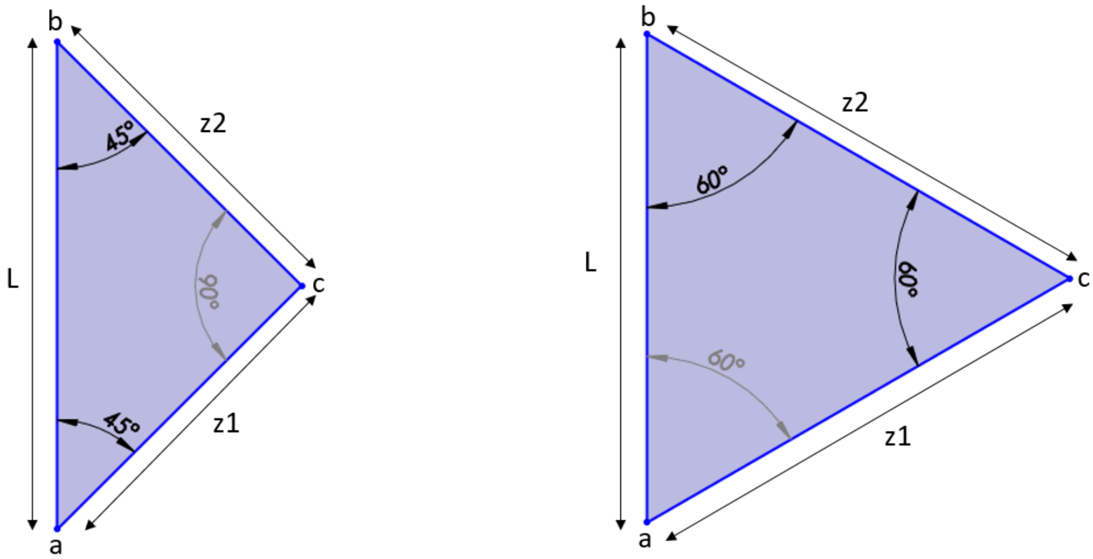

Figure 3 Cracks redirecting angles for both laminates

For the 8 layers quasi-isotropic laminate, the cracks will be redirected at 45 degree angle as we can see in figure 3 above. For the crack to reach from point a to point b, the crack must travel from point a to point c and from point c to point b. The length of the crack can be expressed as

$$z_1^2 + z_2^2 = L^2 \qquad \text{Equation 1}$$

Assuming that z_1 and z_2 are equal, we end up with the following equation

$$z_{45} = \sqrt{2}L \qquad \text{Equation 2}$$

As for 6 layers quasi-isotropic laminate, the cracks will be redirected at 45 degree angle as we can see in figure 3 above. In order for the crack to reach from point a to point b, the crack must travel from point a to point c and from point c to point b. The length of the crack can be expressed as

$$z_1 + z_2 = 2L \qquad \textit{Equation 3}$$

Assuming that L is equal, we end up with the following equation

$$z_{60} = 2L \qquad \textit{Equation 4}$$

In order for the crack to reach from point a to point b, work must be done.

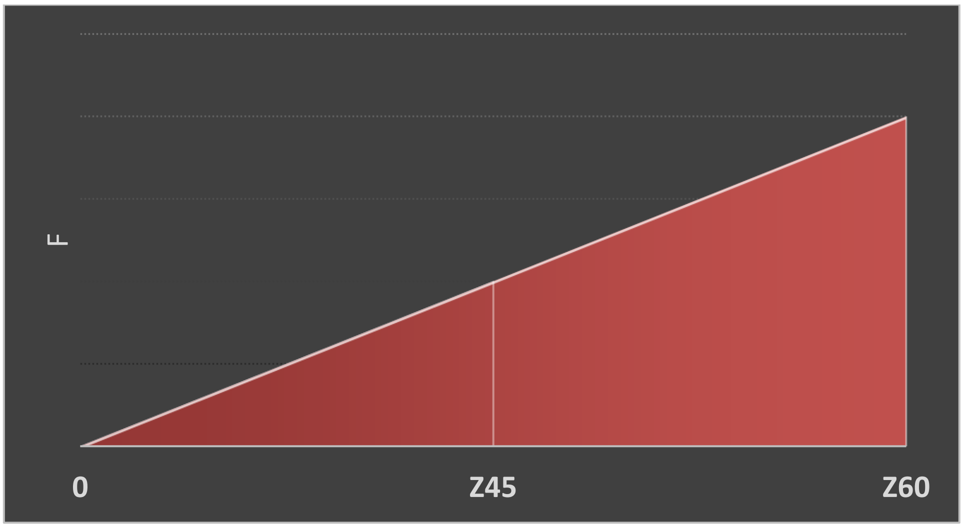

Figure 4 Crack progress graph

The work equation is defined as the integral of the force as a function of displacement (z). [2] The equation can be expressed as

$$w = \int_0^L F\, dy \qquad \textit{Equation 5 [2]}$$

Considering the normal stress equation

$$\sigma = \frac{F}{A} \qquad \textit{Equation 6 [3]}$$

Where,

σ = Stress (MPa)

F = Force (N)

A = Area (m^2)

Stress can also be expressed as

$$\sigma = E \times \varepsilon \qquad \textit{Equation 7 [4]}$$

Where,

σ = Stress (MPa)

E = Modulus of Elasticity (MPa)

ε = Strain

Assuming that the modulus of Elasticity (E) is equal in both laminate setup. knowing that the strain (ε) is proportional to the stress (σ). The length (L) is proportional to the stress (σ). We end up with the following

$$\frac{z_{60}}{z_{45}} = \frac{2L}{\sqrt{2}L} = \sqrt{2} \qquad \textit{Equation 8}$$

The assumption would be that 6 layers quasi-isotropic laminate with 60 degrees will extend 141% of the 8 layers laminate with 45 degrees until it reaches similar stress.

3 METHOD

3.1 Hooke's law

Hooks law can be defined as the force that is applied to an object need to extend or compress with distance x is proportionally linear to that distance. The Hooke's law of physics was named after a British scientist named Robert Hooke in the 17th century. Hooke's law states that the force is equal to a constant multiplied by a distance and it is expressed mathematically as

$$F_s = kx \qquad \textit{Equation 9 [5]}$$

Where,

$F_s = Force$ (N)

$k = Constant$ (N/mm)

$x = Distance$ (mm)

Similarly, in isotropic material, the stress and the strain of a certain material is actually linked by a linear expression. The equation can be expressed as

$$\sigma = -c\varepsilon \qquad \textit{Equation 10 [5]}$$

σ = Stress (MPa)

$c = Stiffness\ tensor$

ε = Strain

If the material is quasi-isotropic, the stiffness is equal in all directions. Therefore, the stress and strain relationship can be expressed as

$$\sigma = E\varepsilon$$ *Equation 11 [6]*

σ = Stress (MPa)

$E = Modulus\ of\ Elasticity$ (MPa)

ε = Strain

Another formula is used to define the strain of an isotropic material

$$\varepsilon = -s\sigma$$ *Equation 12 [2]*

Where,

ε = Strain

s = Compliance Matrix

σ = Stress (MPa)

3.1.1 Stiffness tensor (c)

The stiffness tensor c is expressed using 6 dimensional vectors and it can be expressed as

$$c = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{12} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{13} & C_{23} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{14} & C_{24} & C_{34} & C_{44} & C_{45} & C_{46} \\ C_{15} & C_{25} & C_{35} & C_{45} & C_{55} & C_{56} \\ C_{16} & C_{26} & C_{36} & C_{46} & C_{56} & C_{66} \end{bmatrix}$$ *Equation 13 [6]*

In composites engineering the stiffness tensor c is referred to with letter Q.

3.1.2 Compliance tensor (s)

The compliance matrix is the inverse of the stiffness matrix and it is also 6 dimensional vectors and it can be expressed

$$s = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{12} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{13} & S_{23} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{14} & S_{24} & S_{34} & S_{44} & S_{45} & S_{46} \\ S_{15} & S_{25} & S_{35} & S_{45} & S_{55} & S_{56} \\ S_{16} & S_{26} & S_{36} & S_{46} & S_{56} & S_{66} \end{bmatrix}$$

Equation 14 [6]

3.2 Vacuum Lamination

Vacuum lamination is one of the most used technique to create composite materials. The vacuum creates mechanical pressure on the material. The vacuum pressure has many purposes

- Removing all trapped air in between the layers
- Keeping the fiber layers compacted and stuck together in order to keep it steady during the curing time
- Reducing the humidity
- Optimizing fiber to resin ratios [2]

Before the laminates were made, an outline was made for the process of the lamina. The idea was to create 2 sheets of lamina. Laminate 1 would be 8 layers of quasi isotropic lamina with an orientation of (0°,45°,-45°, and 90°). Laminate 2 would be 6 layers of quasi isotropic lamina with an orientation or (0°,120°,-120°). The fiber that was used in the experiment was (glass fiber UD warp knitted textile at 1152 g per m^2). The resin was (ATLAC ENOVA 6215). the release agent that was used is (Chemlease 75).

the Process of the vacuum Lamination was as follow

3.2.1 Surface preparation

The mould surface was cleaned with a paper to make sure that the surface is dust free and the vacuum is going to be tied. Sealant was placed on the table, so that there was 10 cm space between laminate outline. the corners were sealed extra carefully in order to make the laminate airtight.

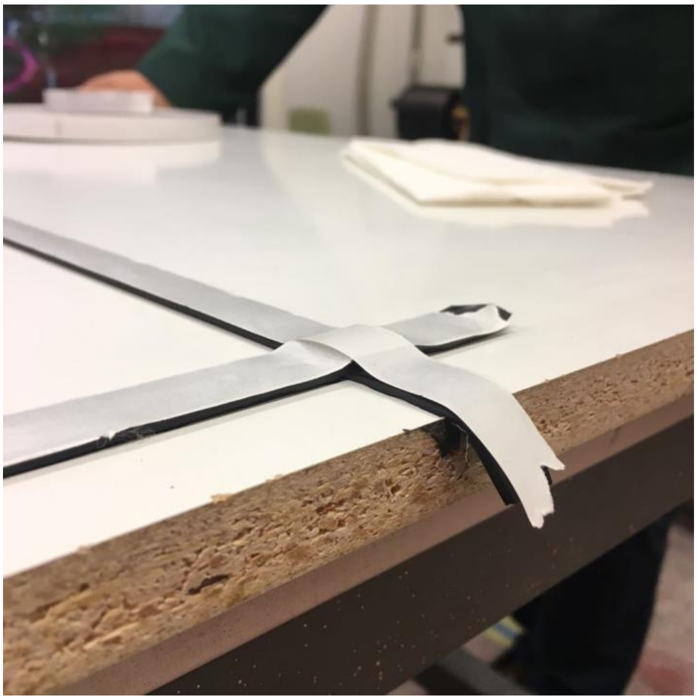

Figure 5Sealant tape placed on the table

The protective tape of the sealant tape was taken off. The release agent (Chemlease 75) was applied on the whole surface inside the sealant tape area. After that the wax was applied. The wax needed to dry before moving forward with the experiment.

3.2.2 Textile and resin preparation

The textile was cut and prepared. The first laminate (8 layers) was prepared first. The layers of the laminate were carefully placed with respect to the orientation. The laminate was covered with the peel ply textile, so that the laminate becomes safe of contamination. After this the peel ply textile was covered with a perforated red release film, so that it covered the inlet of the laminate surface. After this the release film was covered with a flow mat. Everything was then covered with a vacuum bag. A textile was placed below the peel ply, to improve vacuum pull. The vacuum outlet was placed at the both ends.

More vacuum sealant was added on the sides of the outlet above the vacuum bag. The vacuum pump was placed on one side of the outlets as it shows in the figure below. The vacuum pump was turned on, and the vacuum bag was tested for leakage.
The resin was then prepared the following way: The resin was then prepared the following way: 1540 g of resin + bucket (170 g) = 1370 g resin. 40 ml of peroxide was added per 1 kg, so approximately 50 ml of peroxide was used. The peroxide initiates the cross linking of the ester. The temperature sensor was placed on the laminate.

Figure 6 Resin inlet with temperature sensor

Note: Laminate 2 was created same way but with respect to it is orientation of 6 layers (0°,120°,-120°).

3.3 Water Cutting

Water Jet Cutting is an engineering technique used for cutting of materials. The technique uses high speed, high density, and high pressure as an energy for cutting the material. Water is pressurized to a maximum of 392 MPa and projected from a small nozzle of (0.1 mm in diameter). Water Jet Cutting is preferred tool for several reasons such as

- No heating is produced during the cutting

this is an important factor as heat could affect the material properties.

- A desirable shape can be achieved easily
- Dust free process [3]

One disadvantage is delamination at the starting position.

3.4 Samples

After the laminate sheets were already made, they were sent to a water cutting company (Laserle Oy) in order to produce 16 samples per sheet (32 samples total). These samples dimensions as follow

- for the 8 layers laminate: 180 mm length by 15 mm width by roughly 7.5 mm thickness
- for the 6 layers laminate: 180 mm length by 15 mm width by roughly 5.5 mm thickness

The dimensions were kept according these values due to Testometric machine specification for 3-Point bending test. One of the parameters for the 3-point bending test is (distance between the support) and the highest value for that is 150 mm.

3.5 3-point bending

3-point bending is a testing method that is conducted to determine and understand the mechanical properties of an object such as the modulus of elasticity in bending, flexural stress, flexural strain. [4]

A test specimen is placed on the supporting pins and a load is applied in the middle. The speed of the load can be adjusted in a range between (1 mm/s to 200 mm/s). The result is given in a form of position vs force.

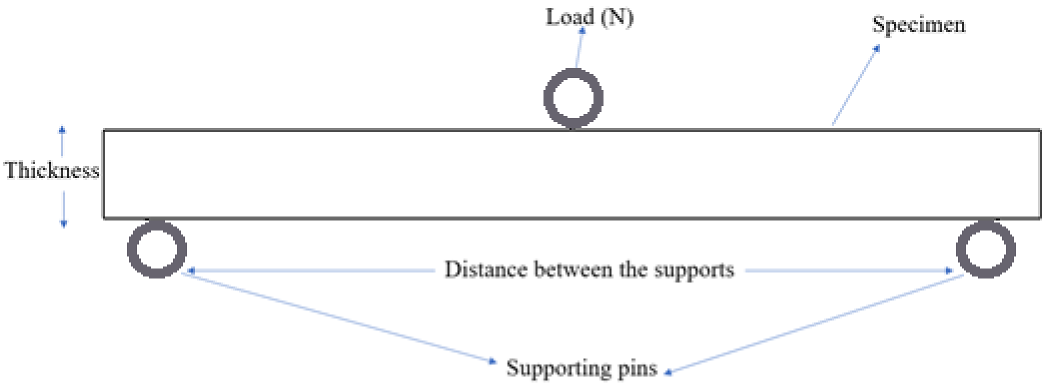

Figure 7 3-Point bending diagram

As for the experiment, all 32 samples were subjected to 3-point bending test. Two parameters were set for the experiment, distance between the support and speed of the load applied. The tests were set in a way that the force keep increasing till the sample break partially or completely. Data was generated by the Testometric machine. The data represent position vs force applied.

Table 1Tests for samples of 8, 6 layers Quasi isotropic laminate

	Speed of the force applied (mm/s)				
Distance between the support (mm)		1	10	120	200
	60	sample 1	sample 2	sample 3	sample 4
	100	sample 5	sample 6	sample 7	sample 8
	120	sample 9	sample 10	sample 11	sample 12
	150	sample 13	sample 14	sample 15	sample 16

The shorter the span between the supports the more the measured modulus is a combination of shear and bending modulus. Large support span is bending modulus only.

3.6 Creep Deformation

Creep deformation is defined as the ability of a material to deform permanently under mechanical stress below the yielding point through long period of time. [10] Long exposure of a material to high mechanical stress cause material to deform, high temperature has also an effect on Creep phenomena. Creep phenomena is an important topic in Material development and analysis. As the 3-point bending has been carried out with different speeds as one of the parameters for the samples testing, it is important to consider the effect of Creep deformation since number of the samples were subjected to 3-point bending at 1 mm/s and 10 mm/s. Creep deformation is not possible for the fast test speed, in another word, there is no stress relief for the samples with high speed.

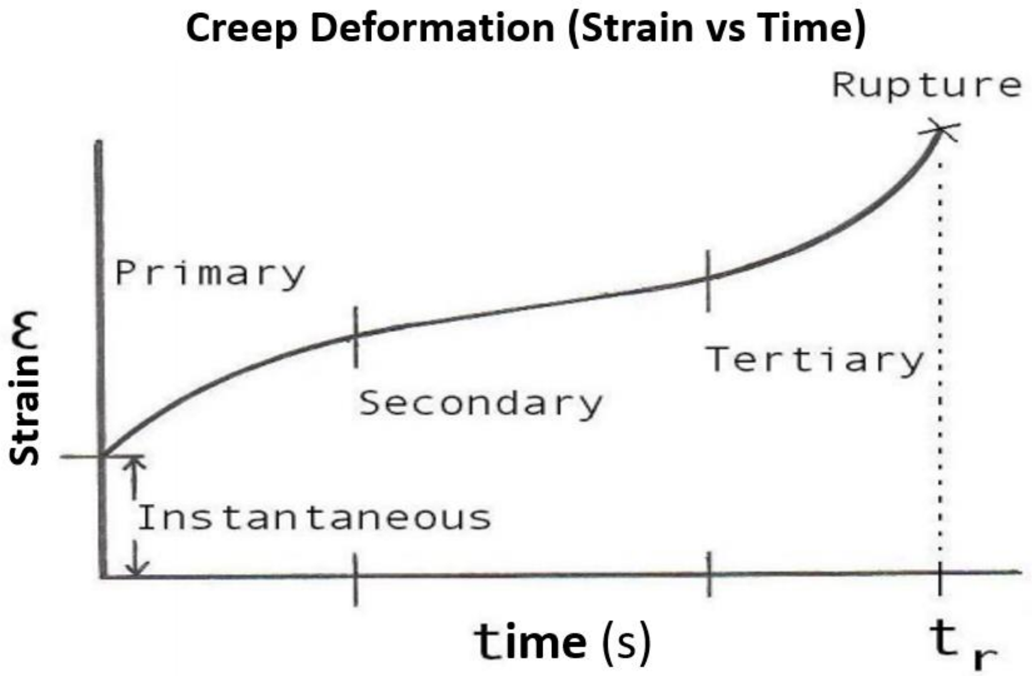

Figure 8 Classical Creep Curve [11]

Creep deformation has 3 stages, in the first stage, Creep starts at a rapid rate. The second stage is where deformation happens at a uniform rate. Third stage has a clear acceleration in Creep rate, and it finalize where the material reaches the yielding point and breaks. [11]

3.7 Static bending modulus and bending strength

Bending modulus (flexural modulus) is the tendency of a certain material to resist bending. Bending modulus can be calculated as the ratio of stress to strain. Bending testing is the most used method for testing Mechanical properties of a material. Flexural testing can be achieved using 3-point bending and 4-point bending. The bottom of a test specimen is in tension and the top surface is in compression. the maximum shear stress happens at the center of the specimen where a load is applied. [1] 3-point bending was used to determine the bending modulus. the equation of bending modulus can be expressed as

$$E_{bend} = \frac{L^3 \times F}{4 \times w \times h^3 \times d}$$ *Equation 15 [1]*

Where,

E_{bend} = Bending Modulus (MPa)

F = Force applied (N)

$w = Width\ of\ specimen$ (mm)

$L = Distance\ between\ the\ supports$ (mm)

$h = thickness\ of\ specimen$ (mm)

$d = deflection$

In a linear manner the slope would be the force over deflection. However, when it come nonlinear manner, in order to get a more accurate value, the slope must be extracted from the graph from linear point as it is shown in the figure below.

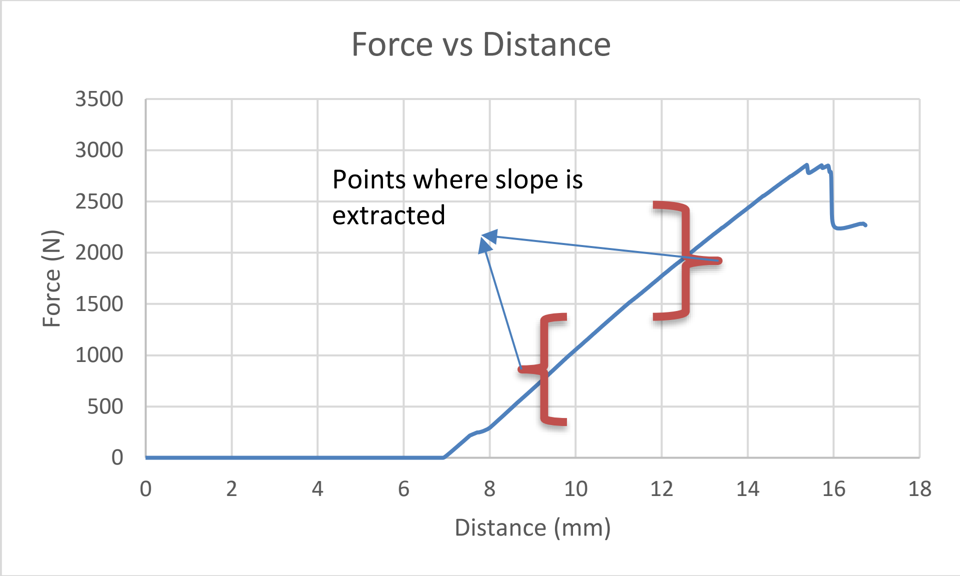

Figure 9 3-point bending graph

Since the specimens have a rectangular shape, we can use the second moment of inertia

$$I = \frac{1}{12} \times w \times h^3$$ *Equation 16 [1]*

Where,

I = Second moment of inertia (m^4)

w = Width of specimen (mm)

h = Thickness of specimen (mm)

Combining equation 14 and 15 we end up with the following equation

$$E_{bend} = \frac{L^3 \times k}{48 \times I}$$ *Equation 17*

Where,

$E_{bend} = bending\ modulus$ (MPa)

L = $length\ (distance\ between\ the\ support)$ (mm)

$k = slope$

$I = second\ moment\ of\ inirtia$ (m^4)

In order to calculate the maximum stress at which the specimen break (stress at break) we use the following equation

$$\sigma = \frac{F_{max} \times L \times h}{8 \times I}$$ *Equation 18 [8]*

Where,

$\sigma = stress$ (MPa)

$L = distance\ between\ the\ support$ (mm)

$h = thickness\ of\ the\ specimen$ (mm)

$I = second\ moment\ of\ inertia$ (m^4)

The maximum strain at the point which the specimen breaks (strain at break) can be calculated using the following

$$\varepsilon = \frac{6 \times d_y \times h}{L^2}$$ *Equation 19 [8]*

Where,

$\varepsilon = strain$

$d_y = deflection$

$h = thickness\ of\ specimen$ (mm)

$L = distance\ between\ the\ support$ (mm)

3.8 Warping of bended plates

Warping can be defined as deformation in shape due to bending of a material. if we consider 3-point bending, the top surface of the material starts to compress in the x direction. This leads to tension in the y direction in the top surface. As for the bottom surface, the x direction becomes in tension, as a result of the, the y direction becomes in compression. The applied load starts to be concentrated in the center of the tested specimen. This is very important to consider when analyzing the mechanical properties of a material.

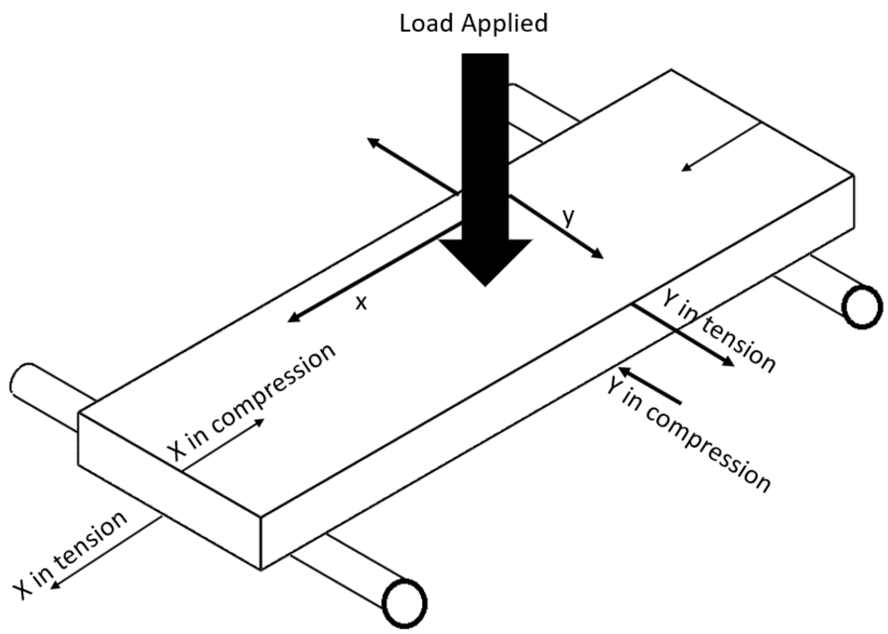

Figure 10 Warping directions

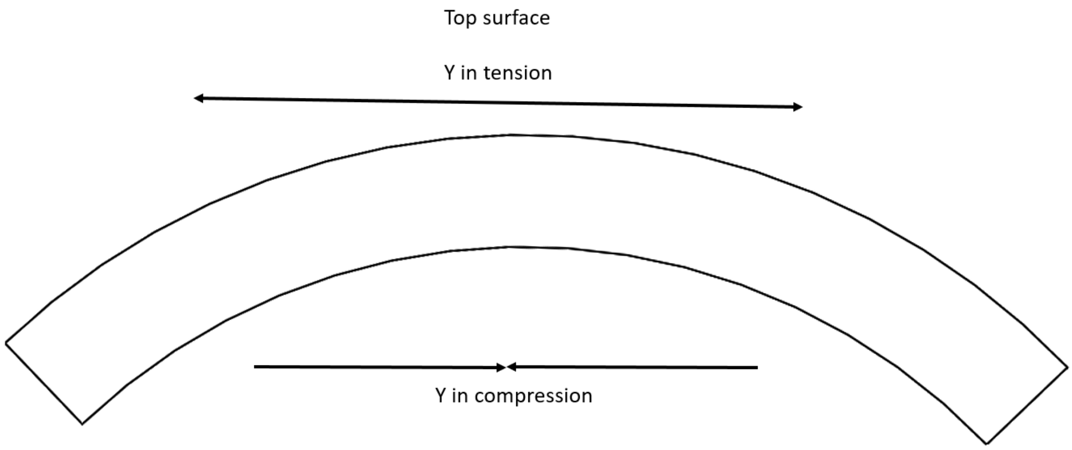

Figure 11 Cross sectional view of specimen showing warping function

3.9 Mohr's circle for bended plates

Mohr's circle is a graphical representation for plane stress. Mohr's circle was invented by Christian Otto Mohr. Mohr's circle is used in certain calculation relating to shear and normal stress. Using Mohr's circle method, we can calculate the maximum normal stress in x and y and the shear stress xy. in basic brittle material such as concrete, we can use the following equation

Principal Planes (Principal Stress Act)

$$\sigma_1 = \frac{\sigma_x+\sigma_y}{2} + \sqrt{(\frac{\sigma_x-\sigma_y}{2})^2 + {\tau_{xy}}^2}$$ *Equation 20 [13]*

Plane of Maximum Shear stress

$$2 \times \theta = tan^{-1} - \frac{\sigma_x-\sigma_y}{2\times\tau_{xy}}$$ *Equation 21 [13]*

Average stress

$$\sigma_{avg} = \frac{\sigma_x+\sigma_y}{2}$$ *Equation 22 [13]*

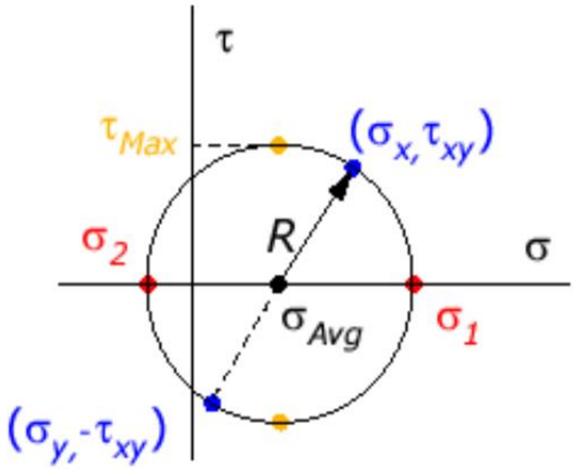

Figure 12 Mohr's Circle [13]

When dealing with composites materials, Mohr’s theory can be used to determine normal stress and shear stress relation with minor adjustment on the theory. The Mohr’s circle becomes an ellipse due to the combination of 2 or more materials.

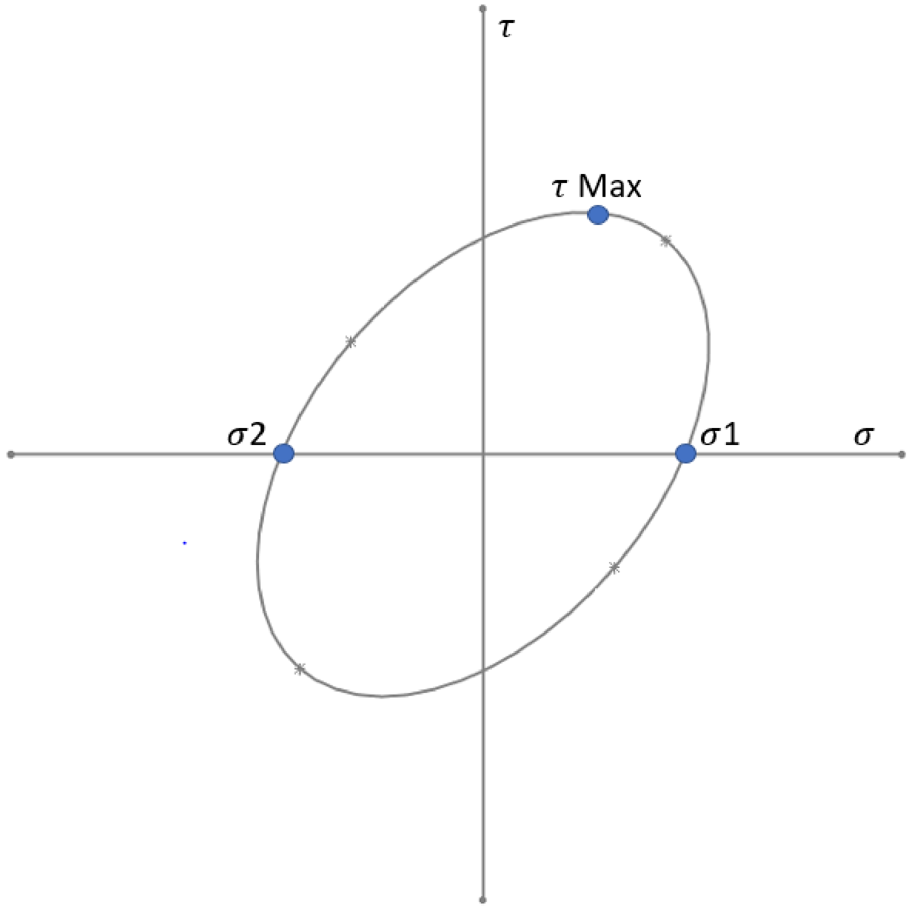

Figure 13 Mohr's Ellipse

3.10 CCSM Modeller

“Composite Compressive Strength Modeller (CCSM) is a design tool for deformation analysis and failure prediction of composite materials”. [13] The tool was used to model quasi-isotropic laminate (6 and 8 layers) with different orientation of layers in order to investigate failure analysis and find the most optimal lay-up of quasi-isotropic in terms of young’s and bending modulus in x, y, xy direction.

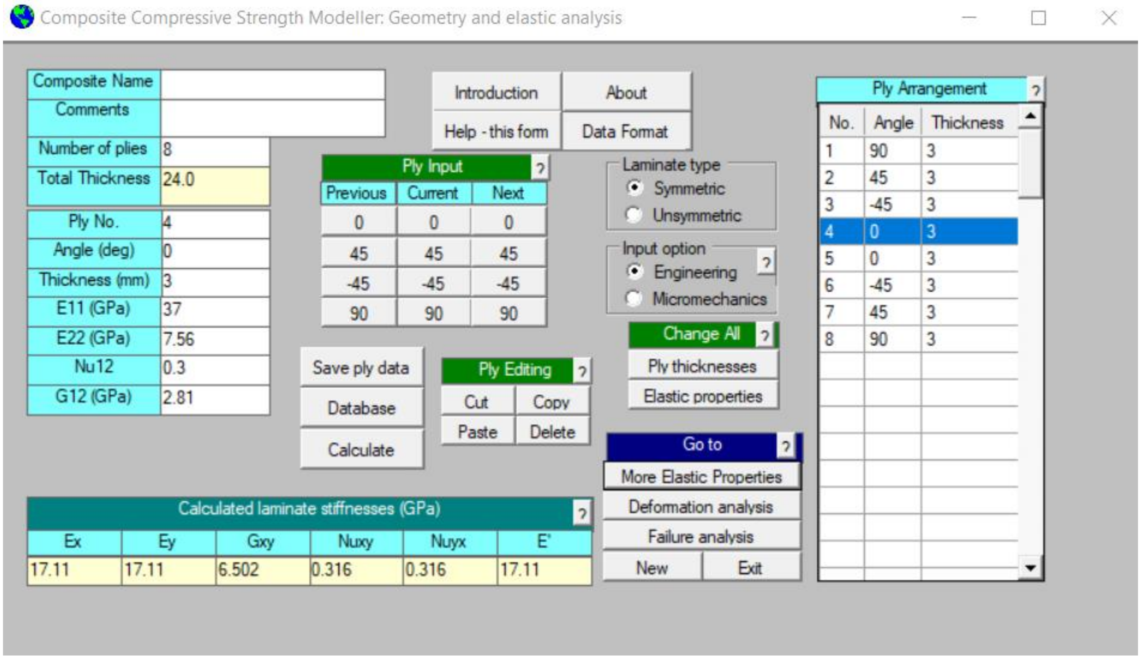

Figure 14 CCSM front page example

3.10.1 CCSM elastic analysis

The software generates the Lamina stiffness matrix and the lamina compliance matrix. The total thickness of both laminates were set to be 24 mm in order to make a good comparison. Using the Compliance matrix we can calculate the young's modulus in x and y direction, shear modulus, and the bending modulus in x, y and xy. The following equations were used

$$E_x(young's\ modulus) = \frac{1}{(s_{11} \times t_{tot})} \qquad \text{Equation 23 [15]}$$

$$E_y(young's\ modulus) = \frac{1}{(s_{22} \times t_{tot})} \qquad \text{Equation 24 [15]}$$

$$G_{xy}(young's\ modulus) = \frac{1}{(s_{33} \times t_{tot})} \qquad \text{Equation 25 [15]}$$

$$E_{bend-x}(bending\ modulus) = \frac{12}{(s_{44} \times t_{tot}^3)} \qquad \text{Equation 26 [15]}$$

$$E_{bend-y}(bending\ modulus) = \frac{12}{(s_{55} \times t_{tot}^3)}$$ *Equation 27 [15]*

$$E_{twist-xy}(bending\ modulus) = \frac{12}{(s_{66} \times t_{tot}^3)}$$ *Equation 28 [15]*

3.10.2 CCSM Failure analysis

CCSM conventional failure analysis criteria was used to determine which ply of the laminate would fail first due to in-plane stress. “The prediction of first ply failure due to in-plane stresses is a straightforward application of the appropriate multiaxial lamina strength criterion in combination with the lamina stress analysis from the classical lamination theory”. [16]

3.11 Universal testing machine

The Universal testing machine was used to determine the mechanical properties of the testing samples of both laminates. The test that was conducted using the universal testing machine is 3-point bending test. From the 3-point bending test we can determine bending modulus, bending strength and strain of each sample. The testing machine that was used is Testometric M350-5 CT.

4 RESULTS

CCSM software was used to model 2 types of quasi-isotropic laminate. Each laminate was modeled and the angle were rotated 5° each time in order to determine which quasi-isotropic layup is optimal. Table 2 shows that the young's modulus was same for every 8 layers quasi-isotropic layup.

Table 2 Young's modulus result for 8 layers laminate

Angle (∅)	**E_x (Young modulus) GPa**	**E_y (Young modulus) GPa**	**G_{xy} (Shear modulus) GPa**
(0°,45°,90°, -45°)	17.110	17.110	6.502
(5°,50°,95°, -50°)	17.110	17.110	6.502
(10°,55°,100°, -55°)	17.110	17.110	6.502
(15°,60°,105°, -60°)	17.110	17.110	6.502
(20°,65°,110°, -65°)	17.110	17.110	6.502
(25°,70°,115°, -70°)	17.110	17.110	6.502
(30°,75°,120°, -75°)	17.110	17.110	6.502
(35°,80°,125°, -80°)	17.110	17.110	6.502
(40°,85°,130°, -85°)	17.110	17.110	6.502
(45°,90°,135°, -90°)	17.110	17.110	6.502

Table 3 shows the bending modulus is different for each layup. (0°,45°,90°, -45°) had the highest bending modulus in the x direction. (40°,85°,130°, -85°) layup has the highest bending modulus in the y. (45°,90°,135°, -90°) layup has the highest bending modulus in the xy.

Table 3 Bending modulus result for 8 layers laminate

Angle (∅)	E_x (Bend modulus) GPa	E_y (Bend modulus) GPa	E_{xy} (Bend modulus) GPa
(0°,45°,90°, -45°)	26.062	11.922	4.926
(5°,50°,95°, -50°)	24.056	12.311	4.443
(10°,55°,100°, -55°)	20.871	13.027	4.247
(15°,60°,105°, -60°)	18.363	14.042	4.774
(20°,65°,110°, -65°)	16.276	14.520	4.738
(25°,70°,115°, -70°)	15.021	15.326	5.519
(30°,75°,120°, -75°)	12.879	15.513	5.432
(35°,80°,125°, -80°)	11.800	15.908	6.067
(40°,85°,130°, -85°)	11.042	17.253	6.420
(45°,90°,135°, -90°)	9.528	16.734	6.773

Table 4 shows that the young's modulus was same for every 6 layers quasi-isotropic layup. The result is also the same that was obtained for 8 layers quasi-isotropic layup.

Table 4 Young's modulus result for 6 layers laminate

Angle (∅)	E_x (Young modulus) GPa	E_y (Young modulus) GPa	G_{xy} (Shear modulus) GPa
(0°,120°,-120°)	17.110	17.110	6.502
(5°,125°,-115°)	17.110	17.110	6.502
(10°,130°,-110°)	17.110	17.110	6.502
(15°,135°,-105°)	17.110	17.110	6.502
(20°,140°,-100°)	17.110	17.110	6.502
(25°,145°,-95°)	17.110	17.110	6.502
(30°,150°,-90°)	17.110	17.110	6.502
(35°,155°,-85°)	17.110	17.110	6.502
(40°,160°,-80°)	17.110	17.110	6.502
(45°,165°,-75°)	17.110	17.110	6.502
(50°,170°,-70°)	17.110	17.110	6.502
(55°,175°,-65°)	17.110	17.110	6.502
(60°,180°,-60°)	17.110	17.110	6.502
(65°,-175°,-55°)	17.110	17.110	6.502
(70°,-170°,-50°)	17.110	17.110	6.502
(75°,-165°,-45°)	17.110	17.110	6.502
(80°,-160°,-40°)	17.110	17.110	6.502
(85°,-155°,-35°)	17.110	17.110	6.502
(90°,-150°,-30°)	17.110	17.110	6.502
(95°,-145°,-25°)	17.110	17.110	6.502
(100°,-140°,-20°)	17.110	17.110	6.502
(105°,-135°,-15°)	17.110	17.110	6.502
(110°,-130°,-10°)	17.110	17.110	6.502
(115°,-125°,-5°)	17.110	17.110	6.502
(120°,-120°,0°)	17.110	17.110	6.502

Table 5 shows the bending modulus is different for each layup. (0°,120°,-120°) had the highest bending modulus in the x direction. (90°,-150°,-30°) layup has the highest bending modulus in the y direction. (35°,155°,-85°) has the highest bending modulus in the xy direction.

Table 5 Bending modulus result for 6 layers laminate

Angle (∅)	E_x (Bend modulus) GPa	E_y (Bend modulus) GPa	E_{xy} (Bend modulus) GPa
(0°,120°,-120°)	28.061	11.769	4.108
(5°,125°,-115°)	27.628	10.866	4.901
(10°,130°,-110°)	24.939	9.513	4.696
(15°,135°,-105°)	23.636	9.125	5.637
(20°,140°,-100°)	21.270	8.762	6.293
(25°,145°,-95°)	18.393	8.403	6.983
(30°,150°,-90°)	17.219	7.889	7.023
(35°,155°,-85°)	16.364	8.426	7.704
(40°,160°,-80°)	15.611	8.642	7.591
(45°,165°,-75°)	15.527	8.997	6.709
(50°,170°,-70°)	15.156	9.062	5.437
(55°,175°,-65°)	14.701	12.036	5.781
(60°,180°,-60°)	15.400	13.768	5.058
(65°,-175°,-55°)	14.855	15.315	4.440
(70°,-170°,-50°)	14.458	16.543	3.676
(75°,-165°,-45°)	13.805	21.834	4.412
(80°,-160°,-40°)	12.846	24.340	3.798
(85°,-155°,-35°)	12.976	26.636	3.954
(90°,-150°,-30°)	11.769	28.061	4.108
(95°,-145°,-25°)	10.866	27.628	4.901
(100°,-140°,-20°)	9.513	24.939	4.696
(105°,-135°,-15°)	9.125	23.636	5.637
(110°,-130°,-10°)	8.762	21.270	6.293
(115°,-125°,-5°)	8.403	18.393	6.983
(120°,-120°,0°)	7.889	17.219	7.023

4.1 Bending data

The bending date was obtained from the universal testing machine. Each sample was subjected to 3-point bending. From the data that was obtained, bending modulus, bending strength and strain was calculated.

4.1.1 Bending modulus and Bending strength (speed)

The bending modulus and the bending strength of both lamina setup were calculated and compared with each other. Table 6 show the bending modulus and bending strength of both lamina setup comparison at a speed of 1 mm/s for 4 different lengths (distance between the support). From the data obtained we can see that lamina setup of 60° has a higher bending modulus and bending strength over lamina setup of 45°. Looking at the table 6, we can see that the bending strength (stress at break) of 6 layers quasi-isotropic laminate is higher by around 1.3 to 1.4 than that is found in 8 layers quasi-isotropic laminate. This result proves the assumption that state that 6 layers quasi-isotropic laminate with 60 degrees will extend 141% of the 8 layers laminate with 45 degrees until it reaches similar stress. However, it is important to consider the effect of Creep deformation. There is evidently Creep deformation in polymers if it is subjected to a load over a long period of time.

Table 6 Laminate Comparison with respect to speed at 1 mm/s

Lamina comparison with respect to speed at 1 $\frac{mm}{s}$						
Length (mm)	lamina setup 45°			lamina setup 60°		
	Bending modulus (MPa)	Stress at break (MPa)	Strain	Bending modulus (MPa)	Stress at break (MPa)	Strain
60	14400.03	442.23	0.035	23237.31	637.66	0.033
100	24346.13	608.16	0.031	27818.16	726.60	0.031

120	25500.65	602.86	0.027	28575.37	669.56	0.026
150	27934.71	610.97	0.024	29755.38	684.90	0.027

Table 7 show the bending modulus and bending strength of both lamina setup comparison at a speed of 10 mm/s for 4 different lengths (distance between the support). The findings in table 7 is similar to the finding in table 6. From the data we can see clearly that 6 layers quasi-isotropic laminate has a higher bending modulus and bending strength that that in 8 layers quasi-isotropic laminate.

Table 7 Lamina comparison with respect to speed at 10 mm/s

Lamina comparison with respect to speed at 10 $\frac{mm}{s}$						
Length (mm)	lamina setup 45°			lamina setup 60°		
	Bending modulus (MPa)	Stress at break (MPa)	Strain	Bending modulus (MPa)	Stress at break (MPa)	Strain
60	16678.79	487.93	0.035	22823.04	660.35	0.034
100	24849.51	634.31	0.030	28520.51	755.79	0.029
120	23611.11	600.25	0.030	27531.74	779.49	0.032
150	26610.47	591.52	0.025	29721.42	775.45	0.027

Table 8 show the bending modulus and bending strength of both lamina setup comparison at a speed of 120 mm/s for 4 different lengths (distance between the support). The findings in table 8 is similar to the finding in table 6 and 7. From the data we can see clearly that 6 layers quasi-isotropic laminate has a higher bending modulus and bending strength that that in 8 layers quasi-isotropic laminate.

Table 8 Lamina comparison with respect to speed at 120 mm/s

Lamina comparison with respect to speed at 120 $\frac{mm}{s}$						
Length (mm)	lamina setup 45°			lamina setup 60°		
	Bending modulus (MPa)	Stress at break (MPa)	Strain	Bending modulus (MPa)	Stress at break (MPa)	Strain
60	16898.76	478.27	0.033	22660.62	543.22	0.027
100	22857.53	610.58	0.029	29258.94	726.25	0.031
120	23462.05	606.27	0.027	31550.20	763.80	0.027
150	26415.41	614.34	0.026	25511.34	768.22	0.035

Table 9 show the bending modulus and bending strength of both lamina setup comparison at a speed of 200 mm/s for 4 different lengths (distance between the support). The findings in table 7 is similar to the finding in table 6,7 and 8. From the data we can see clearly that 6 layers quasi-isotropic laminate has a higher bending modulus and bending strength that that in 8 layers quasi-isotropic laminate except for 1 case where 8 layers quasi-isotropic-laminate at length of 120 mm had a higher bending strength to that in 6 layers quasi-isotropic laminate.

Table 9 Lamina comparison with respect to speed at 200 mm/s

Lamina comparison with respect to speed at 200 $\frac{mm}{s}$						
Length (mm)	lamina setup 45°			lamina setup 60°		
	Bending modulus (MPa)	Stress at break (MPa)	Strain	Bending modulus (MPa)	Stress at break (MPa)	Strain
60	17518.12	462.42	0.032	23934.62	604.74	0.029
100	21890.40	596.03	0.031	27883.75	772.01	0.031
120	23930.90	714.73	0.033	25545.53	698.53	0.033
150	25455.81	637.56	0.027	28881.00	860.73	0.035

4.1.2 Bending Modulus and Bending strength (support length)

Table 10 shows the lamina comparison with respect to length at 60 mm (distance between the support). Again we can see that the bending modulus and the bending strength is higher in 6 layers quasi-isotropic laminate than of this in 8 layers quasi-isotropic laminate.

Table 10 Lamina comparison with respect to length at 60 mm

Lamina comparison with respect to length at 60 mm						
Speed ($\frac{mm}{s}$)	lamina setup 45°			lamina setup 60°		
	Bending modulus (MPa)	Stress at break (MPa)	Strain	Bending modulus (MPa)	Stress at break (MPa)	Strain
1	14400.03	442.23	0.035	23237.31	637.66	0.033
10	16678.79	487.93	0.035	22823.04	660.35	0.034
120	16898.76	478.26	0.033	22660.62	543.22	0.027
200	17518.12	462.42	0.0319	23934.62	604.74	0.029

Table 11 shows lamina comparison with respect to length at 100 mm. The result was similar to that in table 10. The bending modulus and the bending strength in 6 layers quasi-isotropic laminate than of this in 8 layers quasi-isotropic lamina.

Table 11 Lamina comparison with respect to length at 100 mm

Lamina comparison with respect to length at 100 mm						
Speed ($\frac{mm}{s}$)	lamina setup 45°			lamina setup 60°		
	Bending modulus (MPa)	Stress at break (MPa)	Strain	Bending modulus (MPa)	Stress at break (MPa)	Strain
1	24346.13	608.16	0.031	27818.16	726.60	0.031
10	24849.51	634.31	0.030	28520.51	755.79	0.029
120	22857.53	610.58	0.030	29258.94	726.25	0.031
200	21890.40	596.03	0.031	27883.75	772.01	0.032

Table 12 shows lamina comparison with respect to length at 100 mm. The result was similar to that in table 10 and 11. The bending modulus and the bending strength in 6 layers quasi-isotropic laminate than of this in 8 layers quasi-isotropic lamina.

Table 12 Lamina comparison with respect to length at 120 mm

Lamina comparison with respect to length at 120 mm						
Speed ($\frac{mm}{s}$)	lamina setup 45°			lamina setup 60°		
	Stress at break (MPa)	Stress (MPa)	Strain	Bending modulus (MPa)	Stress at break (MPa)	Strain
1	25500.65	602.86	0.027	28575.37	669.56	0.026
10	23611.11	600.25	0.030	27531.74	779.49	0.032
120	23462.049	606.27	0.027	31550.20	763.80	0.027
200	23930.90	714.73	0.033	25545.53	698.53	0.033

Table 13 shows lamina comparison with respect to length at 100 mm. The result was similar to that in table 10, 11, and 12. The bending modulus and the bending strength in 6 layers quasi-isotropic laminate than of this in 8 layers quasi-isotropic lamina.

Table 13 Lamina comparison with respect to length at 150 mm

Lamina comparison with respect to length at 150 mm						
Speed ($\frac{mm}{s}$)	lamina setup 45°			lamina setup 60°		
	Bending modulus (MPa)	Stress at break (MPa)	Strain	Bending modulus (MPa)	Stress at break (MPa)	Strain
1	27934.71	610.97	0.024	29755.38	684.90	0.027
10	26610.47	591.52	0.025	29721.42	775.45	0.027
120	26415.41	614.34	0.026	25511.34	768.22	0.035
200	25455.81	637.56	0.027	28880.10	860.73	0.035

4.2 Failure mode

Table 14 and 15 shows the failure mode analysis obtained using CCSM software. The analysis shows which layer in the laminate is more likely to fail first under vertical load.

Table 14 Failure analysis for 8 layers quasi-isotropic laminate using CCSM software

Angle (Ø)	Predicted layer to fail first
(0°,45°,90°, -45°)	6th layer to fail first
(5°,50°,95°, -50°)	7th layer to fail first
(10°,55°,100°, -55°)	7th layer to fail first
(15°,60°,105°, -60°)	7th layer to fail first
(20°,65°,110°, -65°)	7th layer to fail first
(25°,70°,115°, -70°)	7th layer to fail first
(30°,75°,120°, -75°)	7th layer to fail first
(35°,80°,125°, -80°)	7th layer to fail first
(40°,85°,130°, -85°)	7th layer to fail first
(45°,90°,135°, -90°)	7th layer to fail first

Table 15 Failure analysis for 6 layers quasi-isotropic laminate using CCSM software

Angle (∅)	Predicted layer to fail first
(0°,120°,-120°)	5^{th} layer to fail first
(5°,125°,-115°)	6^{th} layer to fail first
(10°,130°,-110°)	6^{th} layer to fail first
(15°,135°,-105°)	1^{st} and 6^{th} layer to fail first
(20°,140°,-100°)	1^{st} and 6^{th} layer to fail first
(25°,145°,-95°)	1^{st} and 6^{th} layer to fail first
(30°,150°,-90°)	1^{st} and 6^{th} layer to fail first
(35°,155°,-85°)	1^{st} and 6^{th} layer to fail first
(40°,160°,-80°)	1^{st} and 6^{th} layer to fail first
(45°,165°,-75°)	1^{st} and 6^{th} layer to fail first
(50°,170°,-70°)	6^{th} layer to fail first
(55°,175°,-65°)	6^{th} layer to fail first
(60°,180°,-60°)	6^{th} layer to fail first
(65°,-175°,-55°)	6^{th} layer to fail first
(70°,-170°,-50°)	6^{th} layer to fail first
(75°,-165°,-45°)	6^{th} layer to fail first
(80°,-160°,-40°)	6^{th} layer to fail first
(85°,-155°,-35°)	6^{th} layer to fail first
(90°,-150°,-30°)	6^{th} layer to fail first
(95°,-145°,-25°)	6^{th} layer to fail first
(100°,-140°,-20°)	6^{th} layer to fail first
(105°,-135°,-15°)	6^{th} layer to fail first
(110°,-130°,-10°)	6^{th} layer to fail first
(115°,-125°,-5°)	6^{th} layer to fail first
(120°,-120°,0°)	6^{th} layer to fail first

5 DISCUSSION

The plan before proceeding with the experiment was to manufacture 2 types of quasi-isotropic laminate (6, and 8 layers) and subject the samples to 3-point bending in order to determine what is the idea quasi-isotropic layup that gives at minimum investment the largest strength. The answer is 6 layers quasi-isotropic laminate gives the largest strength at minimum investment. 2 parameters were set, speed of the force applied through 3-point bending and the distance between the support. Moreover, theoretical analysis was to be conducted using CCSM software. A few issues came along after the experiment was conducted. The first issue was the thickness of the specimen varied. More investigation and calculation on Creep deformation would have given more accurate results. Another issue would be relative error calculation was not conducted due to the limited time that I was given to finish the thesis work. According to the result that was obtained, the hypothesis of the thesis is proven to be true.

6 CONCLUSION

The samples were manufactured using vacuum lamination. Samples were cut using water cutting. The samples were subjected to 3-point bending in order to study and determine the mechanical properties of the material. The bending strength in 6 layers quasi-isotropic laminate was found to be higher that that in 8 layers quasi-isotropic laminate.

Table 16 shows the ratios of stress at break (bending strength) of the 2 types of laminates. The ratio indicates clearly that 6 layers quasi-isotropic laminate has a higher bending strength than that in 8 layers quasi-isotropic laminate.

As seen in table 16, one of the results was marked red as it does not match with the other numbers, this could be due to fault during the experiment.

Table 16 Ratio of stress at break (σ_60⁄σ_45)

Length (mm)	Speed (mm/s)				
	1	10	120	200	Average
60	**1.44**	**1.35**	**1.14**	**1.31**	**1.31**
100	**1.19**	**1.19**	**1.19**	**1.30**	**1.22**
120	**1.11**	**1.30**	**1.26**	**0.98**	**1.16**
150	**1.12**	**1.31**	**1.25**	**1.35**	**1.26**
Average	**1.22**	**1.29**	**1.21**	**1.23**	

As shown in table 16, the average that was found for different speeds are similar with a little variation. This is an indication that Creep deformation did not have an impact on the result obtained.

In order to calculate the percentage error as compared to the theoretical calculation the following equation can be used

$$percent\ error = \frac{|experimental - theoretical|}{theoretical} \times 100\%$$ *Equation 29 [17]*

Table 17 Percentage error for different speeds

Speed (mm/s)	Percentage Error (%)
1	13.68236994
10	8.609234963
120	14.26312598
200	12.58160476

Table 18 Percentage error for different lengths

Length (mm)	Percentage Error (%)
60	7.111922333
100	13.63540797
120	17.61671943
150	10.77186484

The theoretical calculation shows that the ratio of stress of 6 layers quasi-isotropic laminate over 8 layers quasi-isotropic laminate should be 1.41. The closest experimental test to that result was at length 60 mm with an error of 7.11%. As for speeds, the closest experimental test to the theoretical calculation was at speed of 10 mm/s with an percentage error of 8.6%.

As for result obtained using CCSM Software, the young's modulus and shear modulus was found to be the same in both lamina setup regardless of the orientation of the angle. These results prove the hypothesis that suggest that both laminas have same young's modulus.

As for the bending modulus obtained using CCSM software, the following result were found

- The term quasi-isotropic only refer to young’s modulus and shear modulus as result obtained from CCSM clearly shows.
- For 8 layers quasi isotropic laminate (0°,45°,90°, -45°) had the highest bending modulus in the x direction with a value of 26.06 GPa. (40°,85°,130°, -85°) layup has the highest bending modulus in the y with a value of 17.25 GPa. (45°,90°,135°, -90°) layup has the highest bending modulus in the xy with a value of 6.773 GPa.

- For 6 layers quasi-isotropic laminate (0°,120°,-120°) had the highest bending modulus in the x direction with a value of 28.06 GPa. (90°,-150°,-30°) layup has the highest bending modulus in the y direction with a value of 28.06 GPa. (35°,155°,-85°) has the highest bending modulus in the xy direction with a value of 7.7 GPa.
- 6 layers quasi-isotropic laminate has a higher bending modulus in the x, y, and xy direction.

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