A Study on the Mechanical Properties of the Bamboo Fiber in Composite Material using a Numerical Analysis

A thesis submitted in partial fulfillment of the requirements for the Degree of Masters of Mechanical Engineering in Design of Mechanical System

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School of Mechanical Engineering

Jimma Institute of Technology

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Abstract

Nowadays, natural composites are more preferable than synthetic fibers because of their degradability, lightweight, low density, excellent mechanical property, low cost, and environmentally friendly. In this thesis work, the mechanical properties of bamboo fiber based composite materials using different fiber orientations, $[0°]_5$, $[\pm15°]_5$, $[\pm30]_5$ and $[\pm45°]_5$, is estimated with the help of SolidWorks Simulation software. For this study, I considered axial compressive load applied faraway at three different positions, (350, 275, 0) mm, (350, 275, 275) mm, and (350, 110, 110) mm, for the analysis of the proposed chair leg design with the specification of 350mm height and 40mm outer diameter and the volume fraction of 60% fiber and 40% matrix. A total load for these case studies is 1,962N (200kg). The analysis was done on the mechanical properties for each lamina and laminate, based on different fiber orientations and loading cases.

The analysis results show that the highest stress is appeared at the outermost ply for every fiber orientation case. Also, the results reveal that $[0°]_5$ is the best orientation angle for the proposed case study and $[\pm15°]_5$ orientations angle was founded as the second choice of fiber orientations from the four orientation cases. Finally, I suggested that to improve the strength of the cylindrical bamboo fiber based composite material chair leg, the future works need to be focused on the outermost ply.

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First and for most I would like to thank the almighty Allah for his showers of blessings throughout my research work to complete the research successfully. I would like to express my deep and sincere gratitude to my research advisor Dr. Seungwon Youn and to my co-advisor Mr. Abiyou Solomon (Ph.D. Candidate), for giving me opportunity to be one of their research students, for their follow up throughout of my research work and they gave me an estimated knowledge from their life and work experience.

I am extremely grateful to my parents for their loving, caring and supporting for my studying. I am especially thankful to my mother for her love, understanding, pray and continuous support for the completion of my M.Sc. research work. Also, I would like to express thanks to my friends and research colleagues.

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1. Introduction

1.1 Background

Human beings are always searching strong, stiff, lightweight and cheap materials through out of their life. Researchers found composite to fulfil most their needs and composite materials are becoming more preferable than other materials for the past 5 decades. After the invention of composite material many material science researchers and design engineers were trying to change different materials by composite material because of its mechanical properties. The concept of composite materials has a great role for the advancement of many technology areas i.e. aircraft structures, automotive structures and furniture's etc. In addition to this, substituting synthetic composites by using natural composite materials is a better choice to reduce the environmental pollution. Natural composites fulfill the shortage of the resource for making some products.

Composites can be defined as a select combination of dissimilar material formed with a specific internal structure and with a specific external shape or form [1, 2]. When the composite material contains a fiber material as reinforcement, it is called fiber based composite. Composites are designed to achieve unique mechanical properties and superior performance characteristics not possible with any of the component material alone [1]. Gupta [3] reported as the primary phase of a composite material is called a matrix having a continuous character. In other words, matrix is a material which acts as a binder and holds the fibers in the desired position there by transferring the external load to reinforcement. These matrixes are considered to be less hard and more ductile [3] and fiber is stronger and harder as compared to matrix material [4].

Depending on matrix phase, composites can be classified into metal matrix composites (MMCs), ceramic matrix composites (CMCs) and polymer matrix composites (PMCs) [5]. The above three kinds of matrix have their own characteristics so we select the matrix depending on the application area. Most of the time polymer matrix is selected due to their light weight, ease of use and availability than the others. The main disadvantage of polymer matrix is: they have low thermal resistance and high coefficient of thermal expansion. The most common polymer matrix is known as polyester, vinyl ester, epoxy, phenolic, polyimide, polyamide, polypropylene, polyether ether ketone (PEEK), and others [6]. But in this study epoxy is the main matrix.

Epoxy is one of the thermosetting polymers and they cannot be reshaped once they get the required shape. When preparing epoxy based composite materials we use fibers as reinforcement.

Fibers are classified as synthetic fiber and natural fiber. Synthetic fibers based composite materials are polluting the environment so natural fibers are more preferable but synthetic fibers have a good mechanical behavior over natural fibers. Natural fibers are classified as follows, see Figure 1.1:

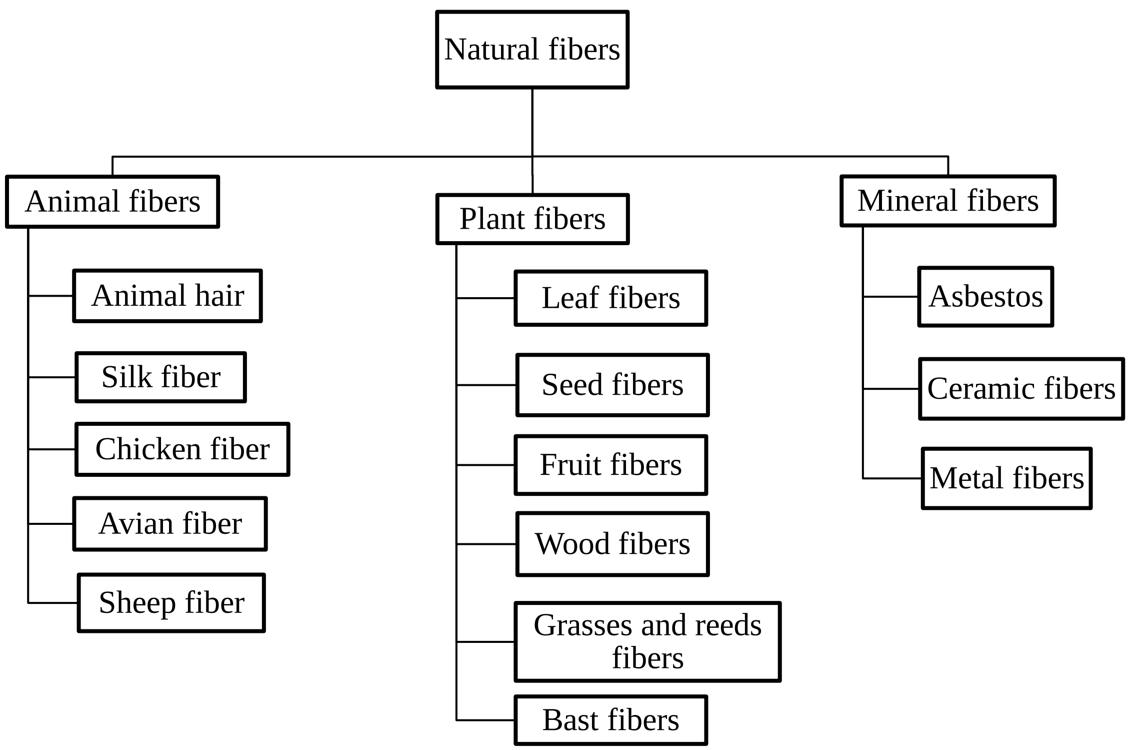


Figure 1.1. Classification of natural fibers based on source of origin [3]

There are many types of plant fibers in which at this time the world is using as reinforcement material. The plant fibers are sisal fiber, banana fiber, bamboo fiber, flax fiber, hemp fiber and others. For this thesis, bamboo plant fiber is selected because bamboo fibers possess one of the most desirable combinations of low density (1.4 g/cm^3) and good mechanical properties [7]. Bamboos are one of the largest members of the grass family and they are fast-growing grasses that have woody stems. There are more than 1,000 bamboo species around the world. They are differentiated by their chemical composition, number of vascular bundles, density and average size. The structure of bamboo itself is a composite material of a hollow culm, consisting of long and aligned cellulose fibers immersed in a ligneous matrix [2]. It takes three to five years to reach its optimum strength. The chemical composition of bamboo fiber is known to consist of cellulose, hemicellulose, lignin, ash and other extractives. The unwanted compositions can be removed by the application of some treatments.

The specific gravity, the tension and compression strength of the culm wall increase from the internal to the external surface of the culm [8] and the fibers vary within the culm wall, decreasing in density from the exterior to the interior [7]. The structure of bamboo plant and the density variation of the fiber from interior to exterior are presented in the Figure 1.2 and 1.3.

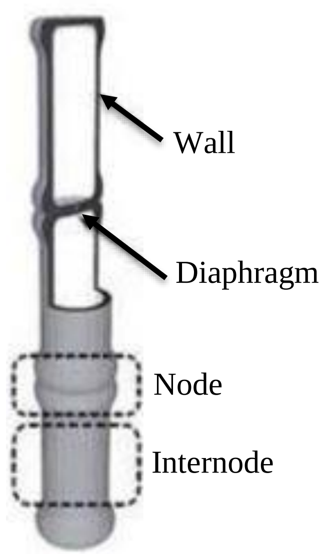
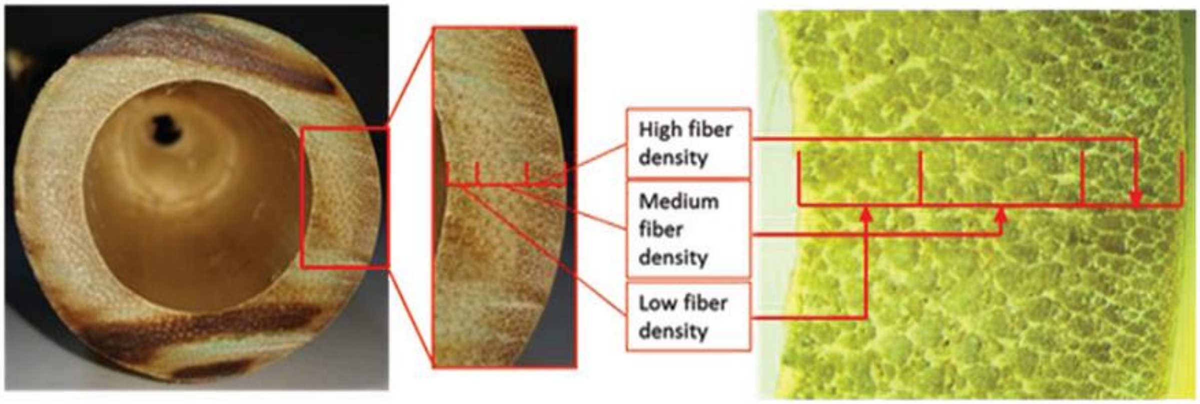


Figure 1.2. The structure of the bamboo culm [5]



(a) (b) (c)

Figure 1.3. The section view of a bamboo culm and density variation of the fiber from interior to exterior [8] : (a) Section view of bamboo culm (b) Bamboo culm wall (c) Magnified view of bamboo culm wall

In fact, bamboo plants are used for many purposes by changing its form depending on the required application. These can be either in a form of a long strip, whole bamboo, sections, and short bamboo fibers. Longer bamboo strips are used in making structural composite that is used in automobile roofing's, shorter bamboo fibers are used in making of medium density fiber board, ply bamboo are made up of bamboo veneer and medium sized bamboo flake can be used for making of bamboo flake board [9] cited in [3]. Even before harvesting this plant it plays a great role on the process of reducing carbon dioxide from the environment. Researchers found that it has higher consumption rate of carbon dioxide (CO_2) than the other trees in the same growing condition. At the present time researchers and scientists are trying to find better composite material from natural fibers and bamboo fiber is one of the best natural reinforcement fiber materials because of its chemical composition. Due to this, many researchers from different countries tried to find the best composite material using bamboo fibers or by using other natural fibers as reinforcement and epoxied or other binding materials as a matrix. Some of these researches are reviewed in Chapter 2.

1.2 Problem statement

Now a day's researchers and scientists are focused on natural composite materials because of their lightweight, small initial capital, good stiffness and less pollutant. Due to this they are trying to replace metals, woods, glass fibers etc. by using different natural fibers such as bamboo, jute, sisal, banana etc.. Among the other natural fibres bamboo-epoxy composite is better because it fulfils the desired properties which were mentioned earlier. Because of this, it becomes a major research area. In most of libraries, cafes and restaurants the chair legs and table legs are made by metal alloys or wood materials. The metal alloys are costly and easily damaged by corrosion and the wood products have higher weight than natural composite materials.

Due to this, this research work is focused on to replace these products using natural composite materials i.e. bamboo. The reason that bamboo plant is selected from many types of natural fibres is because of its better mechanical properties from other plant fibres and the availability bamboo plant in Ethiopia. Ethiopia has 1 million hectare of bamboo plantation this means Ethiopia covers 67% from Africa and 7% from world bamboo plantation [10]. So, doing successive researches on this plant, bamboo, may have a great impact on the country economy and it would be a good substitution for synthetic fibres and metal materials.

The proposed product, chair leg, is not only useful for chair and table applications but also we can apply on simple machine stand and structural parts within the allowable strength for the products.

1.3 Objective

1.3.1 General objective

- General objective of this thesis is analyzing the mechanical behavior of bamboo fiber-epoxy composite with different fiber arrangement through the case study applying bamboo fiber-epoxy composite for chair leg.

1.3.2 Specific objective

Specific objectives of this thesis are,

1) To calculate the mechanical properties of lamina using rule of mixture for bamboo fiber-epoxy composite.
2) To analysis the load-stress for the chair leg made by bamboo fiber based composite by using SolidWorks software.
3) To compare the results for the combination of different fiber orientation and different loading condition.
4) To select appropriate fiber arrangement for the proposed case study of chair leg.

1.4 Product specification

I would like to propose and to analyse a cylindrical chair leg using natural (bamboo) fibre composite. The specification of the product is stated as follow.

Product type:	Cylindrical hollow chair leg made by bamboo fibre composite
Outer diameter:	40mm
Inner diameter:	30mm
Length:	350mm (straight)
Lamina thickness:	1mm
Number of lamina:	5
Laminate thickness:	5mm
Volume fraction:	Fibre = 60% Matrix = 40%

To analysis the mechanical properties of the product, the bamboo fiber configured in different fiber orientations. Which are: -

Orientation (1): $0^0/\ 0^0/0^0/0^0/0^0$

Orientation (2): $15^0/-15^0/15^0/-15^0/15^0$

Orientation (3): $30^0/-30^0/30^0/-30^0/30^0$

Orientation (4): $45^0/-45^0/45^0/-45^0/45^0$

1.5 Thesis structure

This research work is organized with six chapters. In the first chapter background of the study and problem statement, objective of the study and product specification are mentioned. The second chapter focuses on the review of recent literatures, this chapter is organized with the sub-topics of the pre-investigation of carbon/glass composite, natural fiber composite, bamboo fiber composite and the summary of the literature reviews. The third and fourth chapters deal with the methodology of this research work. The third chapter contains general analytical methodology of the composite material and analytical work procedure, materials, assumptions, rule of mixture and constitutive equations. The chapter four focuses on the modeling and analysis procedure. It contain: numerical analysis procedure, modeling, input data and analysis of the model. Then, the fifth chapter presents simulation result of the product under the category of the fiber orientation and discusses on the result of the simulation. In conclusion, the results of this research work are summarized and the suggestion for the future work is stated.

2. Related works

2.1 Literature review

Composite materials are the composition of two or more different materials and it has two phases. The first phase is reinforcement and the second phase is the matrix phase. The reinforcement may be in the form of particulate or fiber. In this topic I will focus on the fiber based composites.

Under this topic there are many research works. The researchers have done these researches depending on different volume fraction ratios, fiber orientations, application areas and reinforcement types or both of the above cases. Then, this research works is reviewed based on important points that is useful for this thesis. These points are:

1. Pre-investigation on carbon/glass fiber composites
2. Pre-investigation on natural fiber composites
3. Pre-investigation on bamboo fiber composites

2.1.1 Pre-investigation on carbon/glass fiber composites

In this section, I have summarized some research works which depend on carbon/glass fiber reinforced composites and hybrid composites. Hybrid composites can be described as using two kinds of reinforcement in a one composite material.

Carbon glass fibers are the most common reinforcements in the composite materials which are used by the researchers. Many researches have been done on carbon fiber, glass fiber and hybrid carbon/glass fiber based composites for educational and production purposes. In most of research works the authors use comparison method for finalizing their works. For the comparison they use different types of reinforcement methods, volume fractions and different fiber orientations [10-18].

There are different types of carbon/glass fiber composites which are reviewed under this topic. These are,

1. Intera- and inter layer hybrid composites
2. Filament wound hybrid composites
3. Fabric hybrid composites
4. Laminated hybrid composites

The mechanical properties of the lamina and laminate may depend on the mechanical properties, orientation angle and the volume proportion ratios of the fiber and the matrix. Most of the researches, reported that the increase in the volume fraction of the fiber has a great advantage on the composite mechanical properties. The authors proved that in hybrid carbon/glass fiber composites the increase in the ratio of the carbon fiber in the composite material improves the material mechanical properties of the composite [13, 15-17].

In addition to this, they have found that 100% carbon fiber reinforced composite materials have better mechanical properties than hybrid carbon/glass fiber composite and glass fiber composites [10, 14-18] and the strength of hybrid carbon/glass fiber composite is lower than carbon fiber composite and glass fiber composite [12, 16, 18]. But Jagannatha et al. [15] found that the tensile strength, yield strength, peak load, ductility and hardness of hybrid carbon/glass fiber composite is greater than glass fiber based composite materials the authors used 40% of epoxy matrix and Wu et al. [17] agreed with Jagannatha et al. [15] on the result of tensile strength but the compressive strength of the hybridized composite is lower than the glass fiber based composite, the author used different intra- and inter-layer configuration and volume fractions of carbon fiber in the hybridized composites. Durairaj et al. [10] also made an experiment on 100% polyester resin sample, the authors reported that the sample exhibited lower mechanical properties than carbon and glass fiber composite samples.

So, using carbon fiber alone is more preferable and recommended by researchers to get a strong composite material and many of the researches show us carbon fiber composite is much better than hybrid and glass fiber reinforced composites. But, due to the problem of cost of carbon fiber it is difficult to use carbon fibers everywhere so the researchers have to found cheap and strong materials, this is why most of the researchers are doing researches and focused on the area of material engineering.

2.1.2 Pre-investigation on natural fiber composites

There are different types of natural fibers which are extracted from plant, animal and minerals. The sub-categories were presented in introduction part of this research work, see Figure 1. This sub topic is mainly focused on one of the sub-categories of natural fibers that are called plant fiber. Some of common plant fibers are sisal, banana, bamboo, jute, and kenaf fibers etc..

Natural composites have a good specific strength, low weight, low cost, fairly good mechanical properties, non-abrasive, bio-degradable, and eco-friendly characteristics, because of these properties they would be a good substitution of synthetic fibers [19-23]. Researchers have conducted many research works to improve the mechanical properties of natural fibers and to check their load-bearing capacity for the specific application areas.

Most of the researchers in their investigation found that the treatment of the fiber surface improves the mechanical and physical properties of the fiber. The treatment takes place by differentiating the concentration percentage of the chemical, the time taken for the treatment and different post-curing process of the fiber and the composite. This improvement of the fiber surface has a positive effect on mechanical properties of the lamina and the laminate. As a reason the authors stated that the treatment improves the adhesion strength between the fiber and the matrix. Most of the authors concluded that the higher the concentration percentage of the chemical will increase the mechanical properties of the natural fibers [19-22].

The other method which the researchers used to improve the mechanical behavior of the composite is hybridization. The most common hybrid composite materials are the combination of natural and synthetic fibers. Widely used natural fibers are jute, sisal, kenaf, banana, and abaca and also glass fiber is the most common synthetic fiber in the product of natural-synthetic fiber composite materials. Some of the authors reported that the hybrid composite, with the optimum amount of natural fiber, has better mechanical properties than individually reinforced composite material [28, 29]. Venkatasubramanian et al. [28] used three kinds of fiber as a reinforcement in the hybrid composite, two natural (abaca-banana fiber) and one synthetic fiber (glass fiber). Then the authors compared with the hybrid composite which contain one natural and one synthetic fibers. As a result, the authors found that abaca-banana-glass composite with a 60% fiber and 40% resin volume fraction has better mechanical properties. Siqueira et al. [30] and Sharba et al. [31] do not agreed with the above statements. Because Siqueira et al. [30] found that the flexural strength and modulus of the composite material is decreased when they add sisal fiber in the glass fiber composite and also the compressive and tensile strength of the individual glass fiber reinforced composite material is better than the hybrid composite material, kenaf-glass fiber reinforced composite material. But the composite with 3 glass- 1 kenaf- 3 glass have a better compressive modulus [31].

The application of natural fibers has been written by many researchers, a few applications of the natural fibers are manufacturing biogas containers, chair, table, electrical appliances, pipes, helmets and for vehicle interior materials etc. [24, 26, 27].

2.1.3 Pre-investigation on bamboo fiber composite

Bamboo fiber is one of the plant fibers which is extracted from bamboo plant. Bamboo plants are giant fast growing grasses that have woody steams [32]. Bamboo fibers are more preferable than other plant fibers because it has high strength, growth rate and fixing the carbon dioxide [33]. The disadvantage of bamboo fiber according to Zakikhani et al. [33], bamboo fibers has low moisture resistance and the extraction methods of fiber from the bamboo culm are not appropriate for industrial and commercial production.

To improve the composite of bamboo fiber the researchers treat the fiber by chemicals, the treatments are reviewed on section 2.1.2, and they also used different types of extraction methods. The major categories of the extraction methods are: mechanical extraction method, chemical extraction method and combined extraction methods [33, 34, 35]. This extraction method is applied depending on their application in different research works and industries. As Subash et al. [35] reviewed from different research works, the extraction methods have an effect on the mechanical and physical properties of the bamboo fiber.

The other method of bamboo fiber based composite improving process is hybridization of the reinforcement. It can be done by natural/natural or by natural /synthetic fiber. When bamboo fiber hybridized with jute and flax, individually, the hybrid composite material mechanical properties will be increased. For both of the two hybridization cases 10% of bamboo with 20% of jute and 10% of bamboo with 30% flax the hybrid composites show high tensile and flexural strength [36, 37]. Then, the second method of hybridization is using natural and synthetic fibers in the hybrid composite. Commonly used synthetic fiber is glass fiber. The researchers found that, the increase in the percentage of glass fiber in the hybrid composite materials will improve the mechanical properties of the composite materials [38, 39]. In addition, chemically treated bamboo/glass fiber composite materials show high mechanical properties than the untreated bamboo/glass fiber composite [39, 40]. Retnam et al. [38] also used 0°/90° and ±45° orientations to boost up the mechanical strength of the bamboo/glass fiber hybrid composite. The authors found that ±45° orientation shows better mechanical strength than 0°/90° orientation.

Fu et al. [41] applied finite element method to analyze different leg shapes of classic back chair which is made by recombinant bamboo. Square, trapezoidal and circular chair legs were analyzed under the balanced load, on the center of the sit plate, of 1100N and 500N load at the edge along the horizontal forward. They considered national standard GB 10357.3-89 for the working conditions. As a result of the analysis, they found that square chair leg is better shape for the recombinant bamboo chair leg because it has the smallest stress, and found round shape chair leg has the smallest deformation. In addition to this result, they found that stress and strain are inversely proportional to the cross-sectional area of the chair leg respectively.

2.2 Summary of the literature review

From the above section, I found that the mechanical properties of the composite material are highly depend on the mechanical and physical properties of the reinforcement, the fiber orientation and fiber volume fraction of the fiber. In addition to this, for the natural fiber based composites the fiber treatment and extraction method has an effect. Also hybridization of the reinforcement in the composite material has a great effect on the mechanical properties of the composite.

Most of the researchers use experimental method and numerical method together, experimental and analytical methods together or one of them. Then, they compare the final results to finalize their work. But, for performing experiment on the composite material it needs high budget and time. Due to these limitations, I preferred to use numerical methods by using SolidWorks Simulation for this research work on the bamboo fiber based composite material.

In addition to this, they perform experimental and numerical analysis using direct application of the loads on the product. This means they apply direct compressive load, direct tensile load and/ or bending load. So, for this thesis I preferred to apply a faraway load and check the mechanical properties of bamboo fiber based composite using numerical analysis.

3. Analytical formulation and experimental analysis

3.1 Analytical work procedure

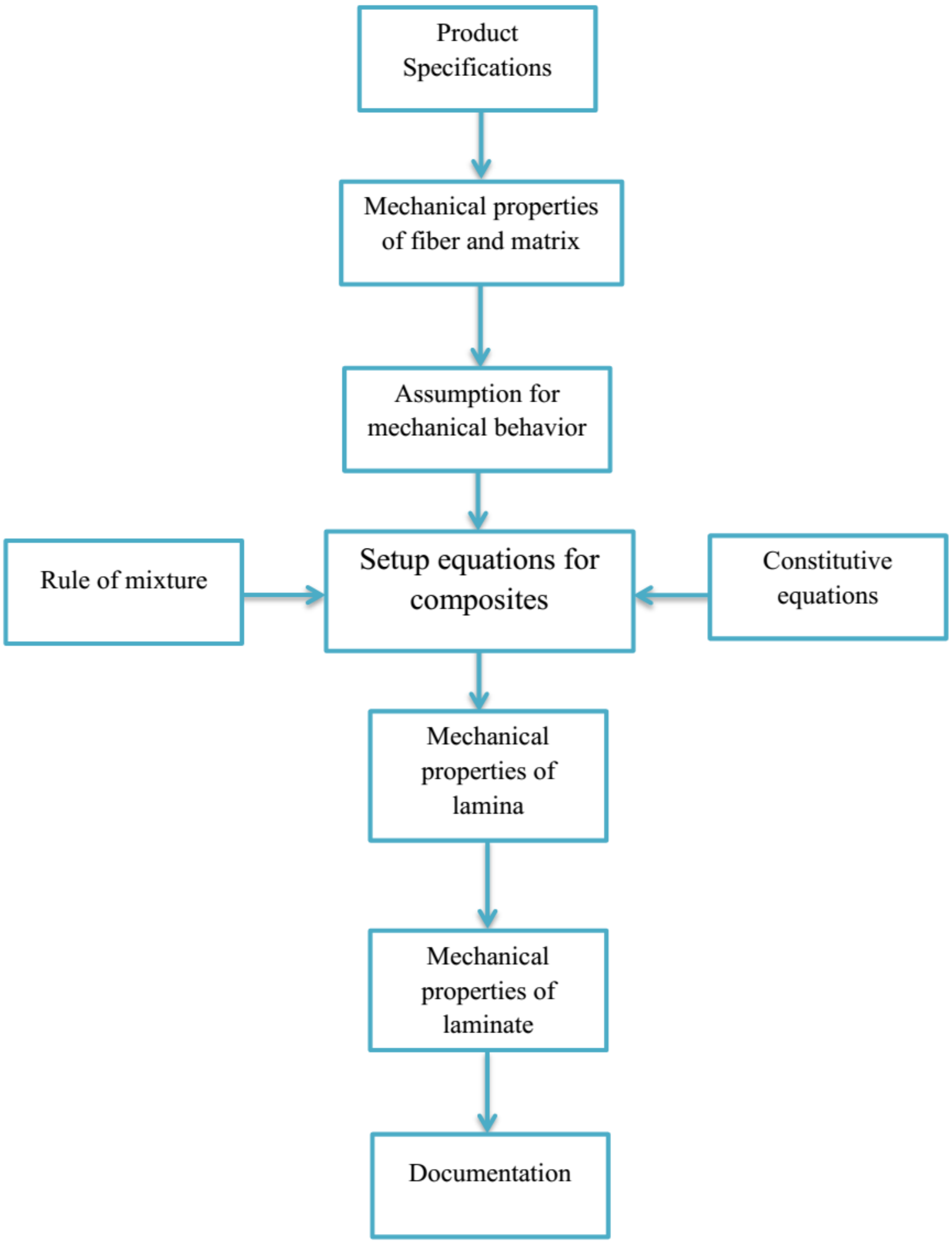


Figure 3.1. Analytical procedure

3.2 Materials

As aforementioned in the introduction there are different types of natural fibers i.e. sisal, banana, flax and bamboo fibers etc.. From all of these plant fibers bamboos have better mechanical property than other plant fibers [20].

In this thesis, work bamboo fiber is used as a fiber reinforcement and epoxy resin as a matrix or binding material. The composition will be 60% and 40% volume fraction for fiber and matrix respectively.

This research uses bamboo fiber/epoxy composite material with different fiber arrangement and loading conditions for the application of chair leg. There are four case sets of fiber orientations as in article 1.4.

Epoxy resins are the most widely used matrix because they are cheap, easy for fabricating complex parts, and easy of availability. Epoxy resins are classified under thermoset resin materials which have good mechanical, wetting and adhesion properties and are easy to dispose.

Table 3.1. Material properties [36, 42]

No.	Mechanical Properties	Materials	
		Bamboo fiber	Matrix (epoxy)
1	Young's modulus, E (GPa)	27.0	3.50
2	Poisson's ratio, υ	0.22	0.33
3	Shear modulus, G (GPa)	11.07	1.50

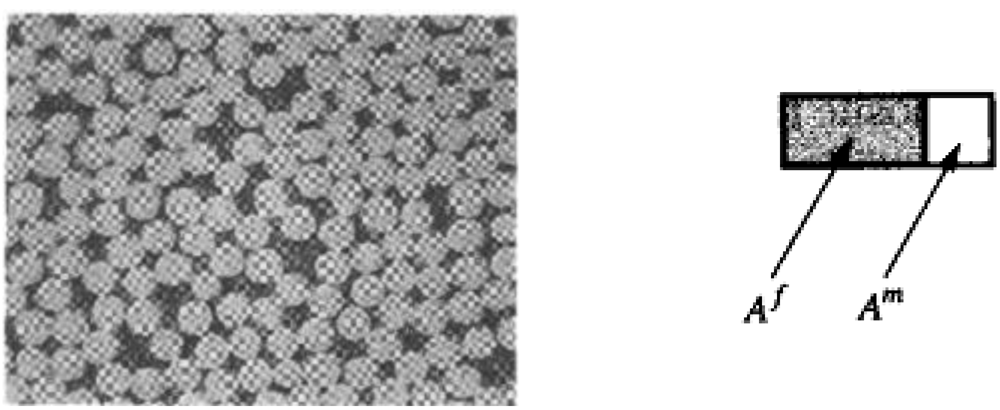
3.3 Assumptions

Before starting the analytical analysis, we have to take some assumptions to simplify our work. Assumptions for this axial compressive problem of a cylindrical shell are listed as follows.

1. The material for cylindrical shell shape chair leg is orthotropic material.
2. The classical lamination theory will be applied.
3. The lamination angle is measured with respect to X-axis.
    a. $0^0 -$ parallel to X - axis
    b. $90^0 -$ perpendicular to X - axis
4. Legs are straight
5. Loads area symmetric

3.4 Rule of mixture

To study the elasticity properties of the lamina one have used the rule of mixture formulas. This rule uses the elasticity properties and volume fraction of the fiber and the matrix as a main ingredient for the calculation. Firstly, one have to consider a section cut from a single layer, which consists of fiber and matrix.



(a) Actual section view (b) Schematic drawing

Figure 3.2. Section view for composite material

Constitutive equations for orthotropic ply is,

$$\left.\begin{aligned} \varepsilon_1 &= \frac{\sigma_1}{E_1} - \upsilon_{12}\frac{\sigma_2}{E_2} \\ \varepsilon_2 &= \frac{\sigma_2}{E_2} - \upsilon_{21}\frac{\sigma_1}{E_1} \\ \gamma_{12} &= \frac{1}{G_{12}}\tau_{12} \end{aligned}\right\} \tag{1}$$

where,

ε_1, ε_2: strain in longitudnal and transvers direction

$\upsilon_{12}, \upsilon_{21}$: poissons's ratio

G_{12}: shear modulus of the ply

γ_{12}: shear strain

τ_{12}: shear stress

One can assume that effective stress resultant ($\sigma_1 a$) is distributed between fiber and matrix stripes.

$$\sigma_1 a = \sigma_1^f a_f + \sigma_1^m a_m \tag{2}$$

where,

a, a_f, a_m: area of composite, fiber and matrix, respectively

σ_1, σ_1^f, σ_1^m: longitudinal normal Stress on composite, fiber and matrix respectively

The structural parameters can be described as,

$$\left.\begin{aligned} V_f &= \frac{a_f}{a} \\ V_m &= \frac{a_m}{a} \\ 1 &= V_f + V_m \end{aligned}\right\} \tag{3}$$

where,

V_f, V_m: volume fraction of fiber and matrix

Then equation (2) with equation (3) can be written as,

$$\sigma_1 = \sigma_1^f \frac{a_f}{a} + \sigma_1^m \frac{a_m}{a}$$

$$\sigma_1 = \sigma_1^f V_f + \sigma_1^m V_m \tag{4}$$

The constitutive equations can be written as

$$\varepsilon_1 = \frac{1}{E_f}(\sigma_1^f - \upsilon_f \sigma_2), \qquad \varepsilon_1 = \frac{1}{E_m}(\sigma_1^m - \upsilon_m \sigma_2) \tag{5}$$

$$\varepsilon_2^f = \frac{1}{E_f}(\sigma_2 - \upsilon_f \sigma_1^f), \qquad \varepsilon_2^m = \frac{1}{E_m}(\sigma_2 - \upsilon_m \sigma_1^m) \tag{6}$$

$$\gamma_{12}^f = \frac{1}{G_f}\tau_{12}, \qquad \gamma_{12}^m = \frac{1}{G_m}\tau_{12} \tag{7}$$

where,

γ: shear strain

G: shear modulus

τ: shear stress

υ_f: Poisson's ratio of the fiber

υ_m: Poisson's ratio of the matrix

Then, one can find longitudinal stresses using equation (4), i.e.

$$\left.\begin{array}{l} \sigma_1^f = E_f \varepsilon_1 + \upsilon_f \sigma_2 \\ \sigma_1^m = E_m \varepsilon_1 + \upsilon_m \sigma_2 \end{array}\right\} \tag{8}$$

By substituting equation (8) into (4) it can be expressed ε_1 in terms of σ_1 and σ_2. Equating this result with the first constitutive equation (1), as a result one can get,

$$E_1 = E_f V_f + E_m V_m \tag{9}$$

$$\frac{\upsilon_{12}}{E_2} = \frac{\upsilon_f V_f + \upsilon_m V_m}{E_f V_f + E_m V_m} \tag{10}$$

let's consider equation (4) for the strain,

$$\varepsilon_2 = \varepsilon_2^f V_f + \varepsilon_2^m V_m$$

Express ε_2 in terms of σ_1 and σ_2 using equation (6) & (8). Then matching this result with the second constitutive equation of (1) one can get,

$$\frac{1}{E_2} = \frac{V_f}{E_f} + \frac{V_m}{E_m} - \frac{V_f V_m (E_f \upsilon_m + E_m \upsilon_f)}{E_f E_m (E_f V_f + E_m V_m)} \tag{11}$$

$$\frac{\upsilon_{21}}{E_1} = \frac{\upsilon_f V_f + \upsilon_m V_m}{E_f V_f + E_m V_m} \tag{12}$$

by using equation (9) and (12) I can get υ_{21} as,

$$\upsilon_{21} = \upsilon_f V_f + \upsilon_m V_m \tag{13}$$

then the last equation for shear modulus, G, of the ply is,

$$\frac{1}{G_{12}} = \frac{\upsilon_f}{G_f} + \frac{\upsilon_m}{G_m} \tag{14}$$

All the above micro-mechanical equations of composite materials are useful for determining laminas (plié's) properties. After determining these important properties, by using experimental data, one can start to calculate the laminate properties using constitutive equations.

3.5 Constitutive equations

Constitutive equations of anisotropic layers are, in matrix form,

$$\begin{vmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{vmatrix} = \begin{vmatrix} A_{11} & A_{12} & A_{14} \\ A_{21} & A_{22} & A_{24} \\ A_{41} & A_{42} & A_{44} \end{vmatrix} \begin{vmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{vmatrix} + z \begin{vmatrix} A_{11} & A_{12} & A_{14} \\ A_{21} & A_{22} & A_{24} \\ A_{41} & A_{42} & A_{44} \end{vmatrix} \begin{vmatrix} k_x \\ k_y \\ k_{xy} \end{vmatrix} \tag{15}$$

or

$$\begin{vmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{vmatrix} = [A_{mn}] \begin{vmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{vmatrix} + z[A_{mn}] \begin{vmatrix} k_x \\ k_y \\ k_{xy} \end{vmatrix} \tag{16}$$

where,

$$[A_{mn}] = \begin{vmatrix} A_{11} & A_{12} & A_{14} \\ A_{21} & A_{22} & A_{24} \\ A_{41} & A_{42} & A_{44} \end{vmatrix}$$

where, the stiffness coefficients of the materials are $A_{mn} = A_{nm}$.

For the derivation of the constitutive equations for the plies, one introduce force functions as stress resultants (N) and couples (M). They are written as,

$$\left.\begin{array}{lll} N_x = \int_{-e}^{s} \sigma_x \, dz, & N_y = \int_{-e}^{s} \sigma_y \, dz, & N_{xy} = \int_{-e}^{s} \tau_{xy} \, dz \\ M_x = \int_{-e}^{s} \sigma_x z \, dz, & M_y = \int_{-e}^{s} \sigma_y \, zdz, & M_{xy} = \int_{-e}^{s} \tau_{xy} \, zdz \end{array}\right\} \tag{17}$$

where,

e: the distance from the bottom to the reference plane of the lamina

s: the distance from the top to the reference plane of the lamina

Substitute equation (15) into (17) then one arrives at constitutive equations that link stress resultants and couples with the corresponding generalized strains. It can be written as,

$$\left.\begin{array}{l} N_x = B_{11}\varepsilon_x^0 + B_{12}\varepsilon_y^0 + B_{14}\gamma_{xy}^0 + C_{11}k_x + C_{12}k_y + C_{14}k_{xy} \\ N_y = B_{21}\varepsilon_x^0 + B_{22}\varepsilon_y^0 + B_{24}\gamma_{xy}^0 + C_{21}k_x + C_{22}k_y + C_{24}k_{xy} \\ N_{xy} = B_{41}\varepsilon_x^0 + B_{42}\varepsilon_y^0 + B_{44}\gamma_{xy}^0 + C_{41}k_x + C_{42}k_y + C_{44}k_{xy} \\ M_x = C_{11}\varepsilon_x^0 + C_{12}\varepsilon_y^0 + C_{14}\gamma_{xy}^0 + D_{11}k_x + D_{12}k_y + D_{14}k_{xy} \\ M_y = C_{21}\varepsilon_x^0 + C_{22}\varepsilon_y^0 + C_{24}\gamma_{xy}^0 + D_{21}k_x + D_{22}k_y + D_{24}k_{xy} \\ M_{xy} = C_{41}\varepsilon_x^0 + C_{42}\varepsilon_y^0 + C_{44}\gamma_{xy}^0 + D_{41}k_x + D_{42}k_y + D_{44}k_{xy} \end{array}\right\} \tag{18}$$

The above constitutive equations include membrane stiffness coefficient which specify the layer stiffness under in-plane deformation.

$$B_{mn} = B_{nm} = \int_{-e}^{s} A_{mn} dz \quad (19)$$

or

$$B_{mn} = I_{mn}^{(0)}$$

bending stiffness coefficients,

$$D_{mn} = D_{nm} = \int_{-e}^{s} A_{mn} z^2 dz \quad (20)$$

or

$$D_{mn} = I_{mn}^{(2)} - 2eI_{mn}^{(1)} + e^2 I_{mn}^{(0)}$$

and membrane-bending coupling coefficients,

$$C_{mn} = C_{nm} = \int_{-e}^{s} A_{mn} z dz \quad (21)$$

or

$$C_{mn} = I_{mn}^{(1)} - eI_{mn}^{(0)}$$

where,

$$I_{mn}^{(r)} = \int_{0}^{h} A_{mn} t^r dt, \quad (22)$$

or

$$I_{mn}^{(r)} = \frac{1}{r+1} \sum_{i=1}^{k} A_{mn}^{(i)} (t_i^{r+1} - t_{i-1}^{r+1})$$

k: the number of the lamina

z: any point on the lamina

r = 0, 1, 2

and the stiffness coefficients A_{mn} are,

$$
\left.\begin{aligned}
A_{11} &= \overline{E}_1 c^4 + \overline{E}_2 s^4 + 2E_{12} c^2 s^2 \\
A_{12} &= A_{21} = \overline{E}_1 \upsilon_{12} + (\overline{E}_1 + \overline{E}_2 - 2E_{12}) c^2 s^2 \\
A_{14} &= A_{41} = [\overline{E}_1 c^2 + \overline{E}_2 s^2 + 2E_{12}(c^2 - s^2)]cs \\
A_{22} &= \overline{E}_1 s^4 + \overline{E}_2 c^4 + 2E_{12} c^2 s^2 \\
A_{24} &= A_{42} = [\overline{E}_1 s^2 + \overline{E}_2 c^2 + 2E_{12}(c^2 - s^2)]cs \\
A_{44} &= (\overline{E}_1 + \overline{E}_2 - 2\overline{E}_1 \upsilon_{12}) c^2 s^2 + G_{12}(c^2 - s^2)^2 \\
A_{55} &= G_{13} c^2 + G_{23} s^2 \\
A_{56} &= A_{65} = (G_{13} - G_{23})cs \\
A_{66} &= G_{13} s^2 + G_{23} c^2
\end{aligned}\right\} \qquad (23)
$$

where,

$$
\overline{E}_{1,2} = \frac{E_{1,2}}{1-\upsilon_{12}\upsilon_{21}}, \qquad E_{12} = \overline{E}_1 \upsilon_{12} + 2G_{12}, \quad c = \cos\emptyset, \quad s = \sin\emptyset
$$

After making the above process one have to determine stress acting in each layer of laminate. To do this one should have to find strains of each layer using the following equations.

$$
\left.\begin{aligned}
\varepsilon_x^{(i)} &= \varepsilon_x^0 + z_i k_x \\
\varepsilon_y^{(i)} &= \varepsilon_y^0 + z_i k_y \\
\gamma_{xy}^{(i)} &= \gamma_{xy}^0 + z_i k_{xy}
\end{aligned}\right\} \qquad (24)
$$

Where, z_i is the layer normal coordinate changing over the thickness of the *i*th layer. Then by using hooks law one can find the stresses as,

$$
\left.\begin{aligned}
\sigma_x^{(i)} &= \overline{E}_x^{(i)}\left(\varepsilon_x^{(i)} + \upsilon_{xy}^{(i)} \varepsilon_y^{(i)}\right) \\
\sigma_y^{(i)} &= \overline{E}_y^{(i)}\left(\varepsilon_y^{(i)} + \upsilon_{yx}^{(i)} \varepsilon_x^{(i)}\right) \\
\tau_{xy}^{(i)} &= G_{xy}^{(i)} \gamma_{xy}^{(i)}
\end{aligned}\right\} \qquad (25)
$$

where, $\overline{E}_{1,2} = \frac{E_{1,2}}{1-\upsilon_{12}\upsilon_{21}}$ and $\overline{E}_x^{(i)}, \overline{E}_y^{(i)}, G_{xy}^{(i)}, \upsilon_{yx}^{(i)}, \upsilon_{xy}^{(i)}$ are elastic constants of the layer in general coordinate.

Formally, $\sigma_z^{(i)} = 0$ but this is only true for the plane laminate and it is not valid for the cylinder. The corresponding equation is written as follows.

$$\tau_{yz}^{(i)} = 0 \text{ and } \tau_{xz}^{(i)} = 0 \tag{26}$$

then,

$$\frac{\partial \sigma_z}{\partial z} = -\left(\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y}\right) \tag{27}$$

for cylindrical coordinate,

$$\frac{\partial}{\partial z}\left[\left(1+\frac{z}{R}\right)\sigma_z\right] = -\left[\left(1+\frac{z}{R}\right)\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} - \frac{\sigma_y}{R}\right]$$

After integrating the above formula and substituting shear values from equation (25) one get,

$$\sigma_z = \frac{R}{R+z}\left[\frac{1}{R}\int_0^z\left(A_{21}\varepsilon_x^0 + A_{22}\varepsilon_y^0\right)dz + C\right] \tag{28}$$

where,

R: is radius of the cylinder

strains in principal coordinates

$$\left.\begin{aligned} \varepsilon_1^{(i)} &= \varepsilon_x^{(i)}\cos^2\emptyset_i + \varepsilon_y^{(i)}\sin^2\emptyset_i + \gamma_{xy}^{(i)}\sin\emptyset_i\cos\emptyset_i \\ \varepsilon_2^{(i)} &= \varepsilon_x^{(i)}\sin^2\emptyset_i + \varepsilon_y^{(i)}\cos^2\emptyset_i - \gamma_{xy}^{(i)}\sin\emptyset_i\cos\emptyset_i \\ \gamma_{12}^{(i)} &= 2(\varepsilon_y^{(i)} - \varepsilon_x^{(i)})\sin\emptyset_i\cos\emptyset_i + \gamma_{xy}^{(i)}\cos 2\emptyset_i \end{aligned}\right\} \tag{29}$$

and the corresponding stresses are

$$\left.\begin{aligned} \sigma_1^{(i)} &= \overline{E}_1^{(i)}\left(\varepsilon_1^{(i)} + \upsilon_{12}^{(i)}\varepsilon_2^{(i)}\right) \\ \sigma_2^{(i)} &= \overline{E}_2^{(i)}\left(\varepsilon_2^{(i)} + \upsilon_{21}^{(i)}\varepsilon_1^{(i)}\right) \\ \tau_{12}^{(i)} &= G_{12}^{(i)}\gamma_{12}^{(i)} \end{aligned}\right\} \tag{30}$$

Equations from (1) to equation (14) is used to calculate the elasticity properties of the lamina. Also, equations from (15) to (30) is used to calculate the lamina and laminate stress and strain for composite material [43].

3.6 Experimental work procedure

3.6.1 Preparation of bamboo fiber bundle

Preparation of bamboo fiber from the raw bamboo is the first process in the experimental analysis procedure. The preparation process of bamboo fiber bundle is presented in Figure 3.3.

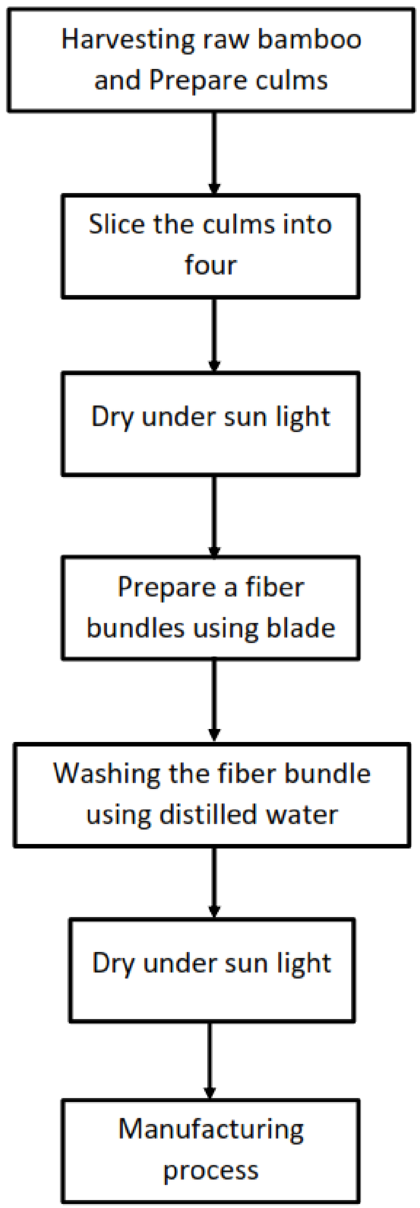


Figure 3.3. Preparation process of bamboo fiber bundles

Table 3.2. Specifications of

Parameters	Values	Remark
Length, mm	304 ± 26	
Diameter, mm	0.4 ± 0.1	
Treatment	$-$	No
Weight, kg	0.166	Weight of the fiber for one chair leg

3.6.2 Experimental analysis process

The experimental analysis on bamboo composite chair leg is done after the preparation of bamboo fiber bundle. The composite cylindrical chair leg is manufactured as follows.

1. Prepare six steel circular hollo shaft differ by 2mm in diameter.
2. Assemble the inner hollo shafts and the bottom cover, see Figure 3.4.

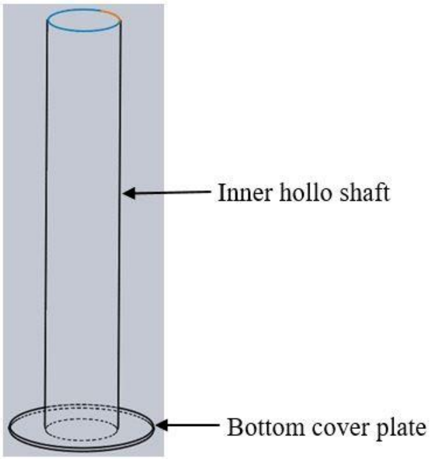


Figure 3.4. Inner hollo shaft and bottom cover assembly

3. Insert the first lamina cylinder.

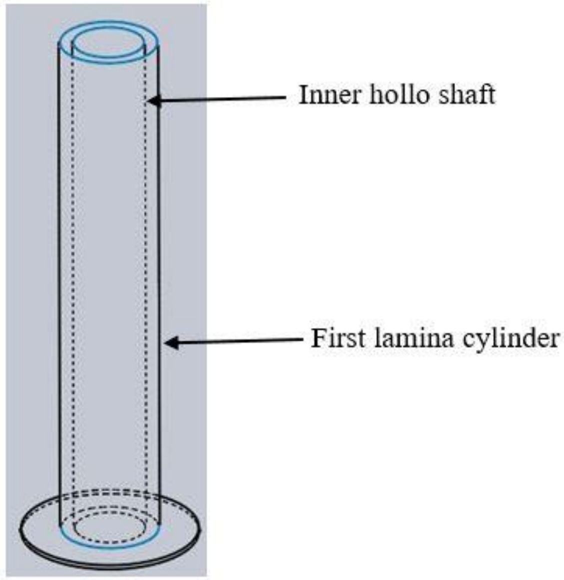


Figure 3.5. Assembly of first lamina cylinder

4. Apply jell releaser on the outer side of the inner cylinder and on the inner side of first lamina cylinder.
5. Apply epoxy resin in the section between the inner and the 1^{st} lamina cylinder.
6. Place the fiber in it.
7. Pour the epoxy resin again.
8. Distribute the epoxy equally by using ruler.
9. Place the fiber in it again.
10. Distribute the epoxy resin by rotating the first lamina cylinder.
11. Remove the first lamina cylinder after waiting 2:00 hours until the epoxy dry and stick with the fiber bundle.
12. Insert the second lamina cylinder.
13. Repeat the above steps (4 -12) for the remaining lamina.
14. Wait for 24 hours and remove the steel cylindrical shafts.

After preparing the bamboo composite cylindrical hollo shafts using the above preparation process and one can assemble in the seating plate. Then one can make an experiment on the final product by placing stress and displacement sensors on each leg.

3.7 Limitations to do analytical and experimental analysis

This research work is focused on numerical analysis using SolidWorks Simulation, because there was a limitations to make an experimental analysis. The limitations are:

- Lack of budget
- Lack of time
- Lack of experimental devices.

Also using analytical analysis for remote load application is difficult because the derivation is complicated and very vast. These limitations prohibited me from making experimental and analytical analysis for the proposed chair leg.

To minimize these limitations and to find the effect of fiber orientation on bamboo fiber based composite, I preferred to make numerical analysis by using Solidwork's simulation software 2018 to predict the effect of axially applied faraway compressive load on different bamboo fiber orientations.

4. Modeling and Analysis

4.1 Numerical analysis procedure

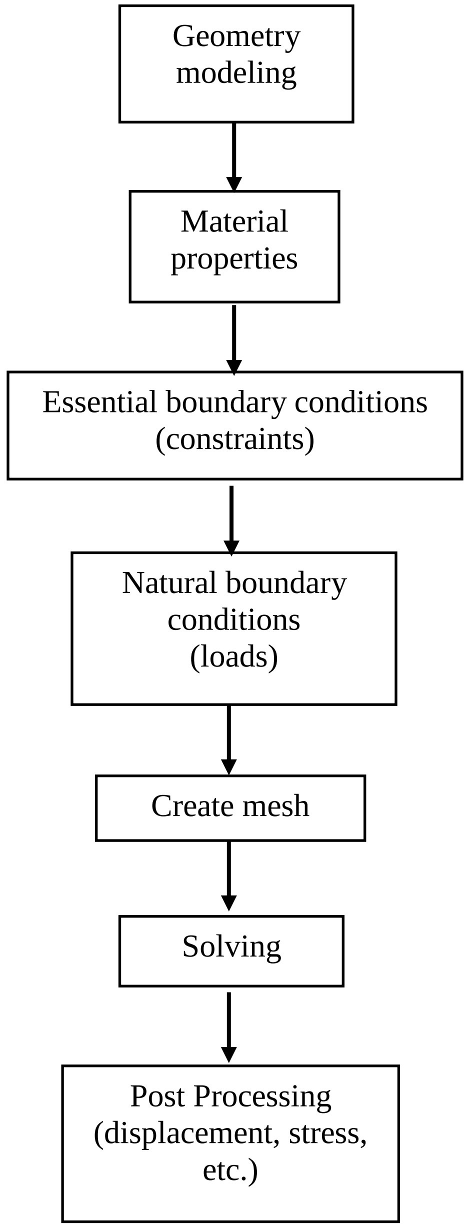


Figure 4.1. General procedure for the FEA

4.2 Modeling

Important parameters, which used for making mechanical analysis and modeling of bamboo fiber based composite chair leg are,

1. Material properties for fiber and matrix and volume fraction respectively
2. Angle of the fiber orientation
3. Number of the ply (lamina)
4. Inner and outer diameter of the leg
5. Length of the leg
6. Load and its position

Using the above variables and the mechanical properties of fiber and matrix, I estimated the mechanical properties of the bamboo fiber based chair leg. For the application location of the load, I used Gaussian sampling point method to find the weakest point on the upper part of seating plate. It is shown as in the Figure 7,

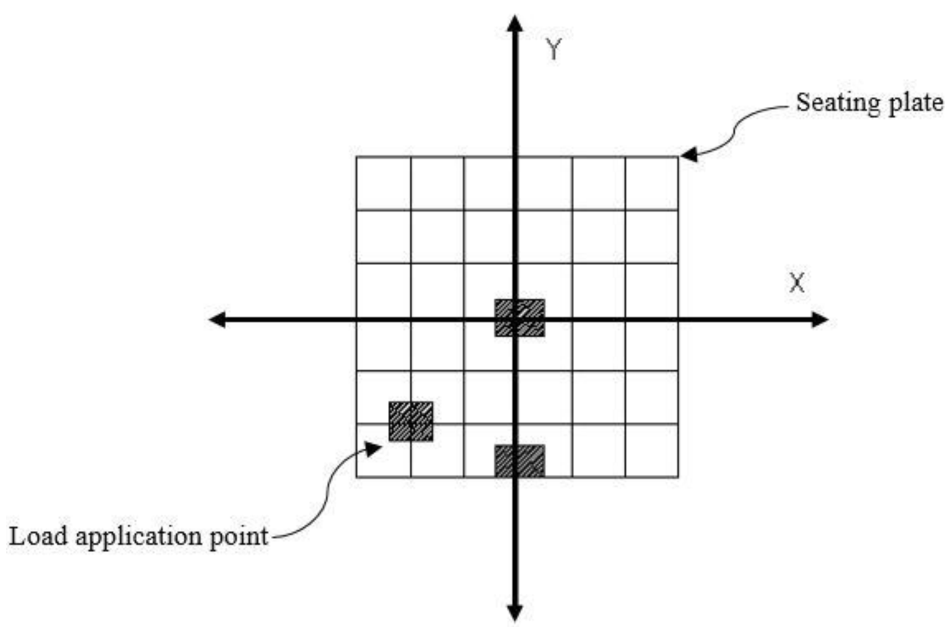


Figure 4. 2. Gaussian sampling point method

The loads considered for simple chair, for library, café etc., are 150kg for small load, 200kg for medium load and 300kg for large load. In this research work, I preferred medium load condition, 200kg, for a safe design because an average global adult weight at 2012 is 62kg [44]. The load will be applied at some area as a distributed pressure on the selected position.

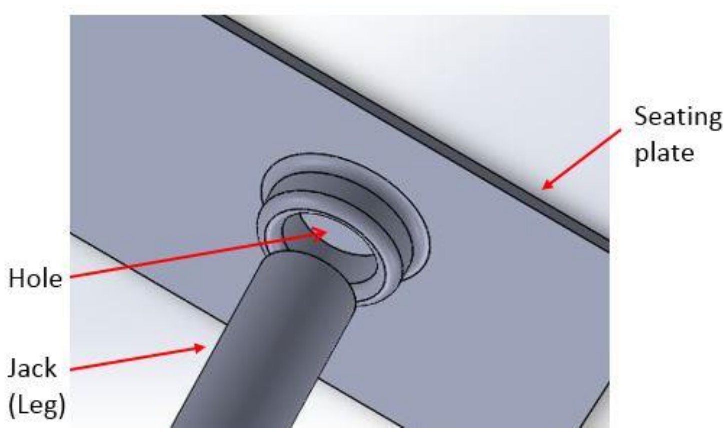
Fiber orientation is one of the important parameters, because the applied axial load is distributed to each fiber. I configured 4 different combinations for 6 plies.

1. Orientation (1): 0^0/ $0^0/0^0/0^0/0^0$
2. Orientation (2): $15^0/-15^0/15^0/-15^0/15^0$
3. Orientation (3): $30^0/-30^0/30^0/-30^0/30^0$
4. Orientation (4): $45^0/-45^0/45^0/-45^0/45^0$

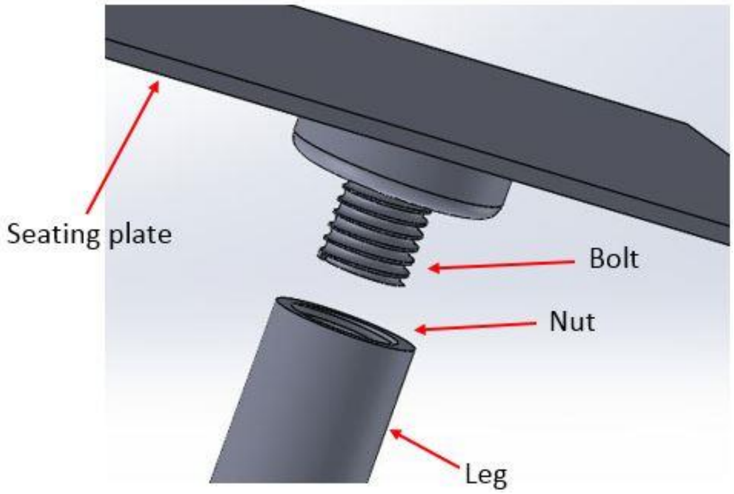
As I described earlier, this research work is focused on the analysis of natural composite chair leg in which bamboo fibre rolls as a reinforcement and epoxy is for a matrix. I can use different plate materials i.e. light natural composite boards, plastic plates etc. as a seating plate. In this research, I designed the chair with the combination of plastic seating plate and bamboo fibre legs for to see the characteristics of bamboo fiber legs.

Before starting detail design, I configured 3 types of connecting structures for the leg and the seat plate. The concepts are: -

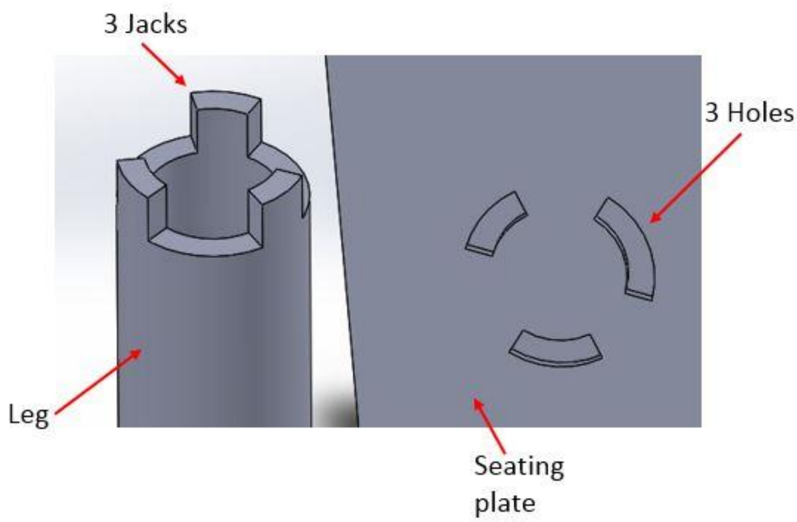
1. Hole and jack (Figure 8 (a))
2. Bolt and nut (Figure 8 (b))
3. 3 holes and jack (Figure 8 (c))



(a) Hole and jack



(b) Bolt and nut



(c) 3 holes and jack

Figure 4.4. Connecting concepts

To select the best concept, one need to list down the selection criteria, concepts and rank values first. It is done as, Connecting design concepts

 Bolt and nut

 Hole and jack

 3 Holes and jacks

Selection criteria’s

A. Ease of assembly
B. Ease of manufacturing
C. Wear resistance
D. Corrosion resistance
E. Ease of maintenance

Weight

1. Poor
2. Good
3. Very good
4. Excellent

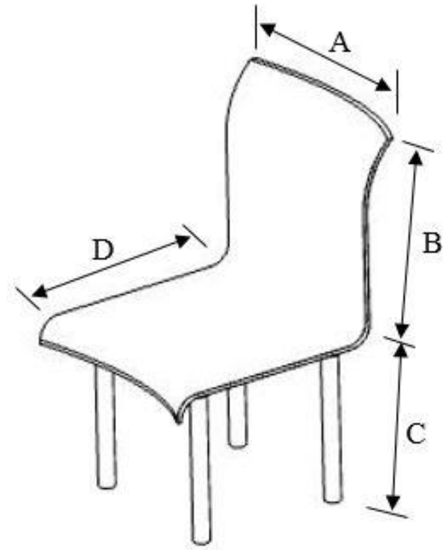
Table 4.1. Concept selection

Design concepts	**Selection criteria’s**					**Sum**	**Rank**
	A	B	C	D	E		
	3	2	1	1	1	8	3
	3	3	2	4	3	**15**	**1**
	3	1	2	4	2	12	2

Following the reviewed result, I selected hole and jack design concept as a result from Table 2. After selecting the highest rank concept, I have modeled the chair by using SolidWorks 2018 with the specified parameters and concept. The dimensions of the design are set by considering the human ergonomic effect for the average man and women body size. Those data are taken from “American defense department human factor standardization manual book.” The chair modeling is shown in Figure 9, and main parameters are described in Table 3.

After doing the above concept selection and putting the required dimensions, I started to analyze the mechanical properties of the composite lamina. The analysis is done by using the fiber and matrix material data which is obtained from journals and material data websites.

(a) Chair model



(b) Chair dimensions

Figure 4.5. Chair 3D model and dimensions

Table 4.2. Design dimensions

Symbols	Length (cm)
A	$54.5 \approx 55$
B	50
C	$35.3 \approx 35$
D	$48.3 \approx 48$

In post-process, I have used von Mises failure criteria in SolidWorks software as the von Mises failure criteria gives more accurate and average values [45].

$$\sigma_y = \sqrt{\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}} \quad (31)$$

4.3 Input data

In this session input data are presented; Table 4.3. show that the volume fraction, the amount and application point of the load and the fiber orientation of the ply and Table 4.4. describe the mechanical properties, volume fraction and weight fraction of the fiber and the matrix and the mechanical properties of the lamina.

Table 4.3. Summary of input data

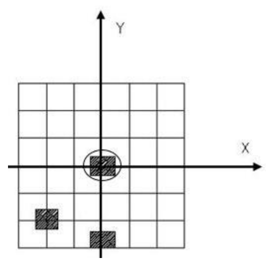
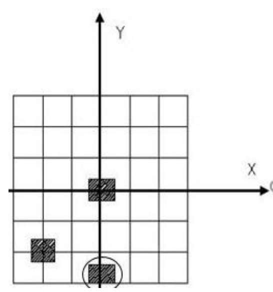
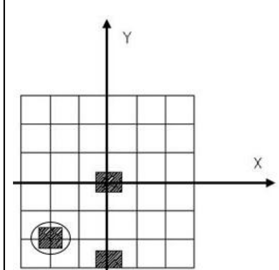
<table>
<tr><th rowspan="2">Volume fraction</th><th rowspan="2">Load</th><th colspan="2">Loading point</th><th rowspan="2">Fiber orientation</th></tr>
<tr><th>Case</th><th>Point on the plane (Gaussian point)</th></tr>
<tr><td rowspan="3">60% of bamboo fiber and 40% of epoxy</td><td rowspan="3">200kg (medium scale load for simple chair design)</td><td>Case 1 (center)</td><td>
</td><td>Orientation (1)
Orientation (2)
Orientation (3)
Orientation (4)</td></tr>
<tr><td>Case 2 (front-mid)</td><td>
</td><td>Orientation (1)
Orientation (2)
Orientation (3)
Orientation (4)</td></tr>
<tr><td>Case 3 (quarter 1/3rd)</td><td>
</td><td>Orientation (1)
Orientation (2)
Orientation (3)
Orientation (4)</td></tr>
</table>

Table 4.4. Summary of the composite materials and lamina mechanical properties

Mechanical properties of materials

No.	Material	Young's modulus, **E**, GPa	Shear modulus, **G**, GPa	Poisson's ratio, **υ**	Density, **ρ**, kg/m^3
1	Bamboo fiber	27	11.066	0.22	1500
2	Epoxy matrix	3.5	1.5	0.33	1540

Volume and weight fractions

	Materials	Volume fraction, **v**	Weight fraction, **w**	Note
3	Bamboo fiber	60%	59.37%	$v_f + v_m = 1$ $w_f = v_f \frac{\rho_f}{\rho_c}$ $w_m = v_m \frac{\rho_m}{\rho_c}$
4	Epoxy matrix	40%	40.63%	

Mechanical properties of bamboo fiber/epoxy composite lamina

	Composite lamina	Young's modulus, GPa		Shear modulus, GPa		Poisson's ratio		Density, kg/m^3
		E_x	**$E_y = E_z$**	**$G_{xy}=G_{xz}$**	**G_{yz}**	**$\upsilon_{xy}= \upsilon_{xz}$**	**υ_{yz}**	
5	Bamboo fiber/ epoxy composite	12.9	5.774	3.694	2.302	0.286	0.254	1524

Five strength parameters

	Composite lamina	Tensile strength in **X**, GPa	Tensile strength in **Y**, GPa	Compressive strength in **X**, GPa	Compressive strength in **Y**, GPa	Shear strength in **XY**, GPa
6	Bamboo fiber/ epoxy composite	0.2	0.032	0.1514	0.1278	0.0401

The mechanical properties of the lamina in Table 4.4. is calculated by using Mathcad software. The calculation process is performed as the following,

f: volume fraction of fiber

v: volume fraction of matrix

Properties of the matrix

$$E_m := 3.5 \cdot GPa \qquad \nu_m := 0.33 \qquad G_m := \frac{E_m}{2 \cdot (1 + \nu_m)} \qquad v := 0.6 \qquad \rho_m := 1540 \frac{kg}{m^3}$$

$$w_m := 40.63\% = 0.406$$

Properties of the fiber

$$E_f := 27 \cdot GPa \qquad \nu_f := 0.22 \qquad G_f := \frac{E_f}{2 \cdot (1 + \nu_f)} \qquad f := 0.4 \qquad \rho_f := 1500 \frac{kg}{m^3}$$

$$w_f := 59.37\% = 0.594$$

Properties of the composite with a fiber volume fraction (f)

$$E_1(f) := E_f \cdot f + E_m \cdot (1 - f) \qquad \nu_{12}(f) := f \cdot \nu_f + (1 - f) \cdot \nu_m$$

$$\rho_c := f \cdot \rho_f + (1 - f) \cdot \rho_m$$

$$Z_2(f) := \frac{f}{E_f} + \frac{(1 - f)}{E_m} - \frac{f \cdot (1 - f) \cdot (E_f \cdot \nu_m - E_m \cdot \nu_f)^2}{E_f \cdot E_m \cdot [E_f \cdot f + E_m \cdot (1 - f)]}$$

$$E_2(f) := \frac{1}{Z_2(f)} \qquad \nu_{23}(f) := \frac{\nu_f \cdot \nu_m}{f \cdot \nu_f + (1 - f) \cdot \nu_m}$$

$$G_{12}(f) := \frac{G_f \cdot G_m}{G_m \cdot \nu_f + G_f \cdot \nu_m}$$

$$G_{23}(f) := \frac{E_2(f)}{2 \cdot (1 + \nu_{23}(f))}$$

Then one can calculate the required variables,

$$E_1(f) = 1.29 \times 10^{10}\,\text{Pa}$$

$$E_2(f) = 5.774 \times 10^{9}\,\text{Pa}$$

$$\nu_{12}(f) = 0.286$$

$$G_{12}(f) = 3.694 \times 10^{9}\,\text{Pa}$$

$$\rho_c = 1.524 \times 10^{3}\,\frac{\text{kg}}{\text{m}^3}$$

$$G_{23}(f) = 2.302 \times 10^{9}\,\text{Pa}$$

$$\nu_{23}(f) = 0.254$$

4.4 Analysis

The analysis is performed by using SolidWorks Simulation 2018 by applying some assumptions and the material properties. The software has the ability to analyze composite laminates with up to 50 laminas using shell elements. The main four procedures that I followed to solve this composite problem on SolidWorks software is,

1st step: 3D modeling

Figure 4.6. Chair model

2nd step: input material properties

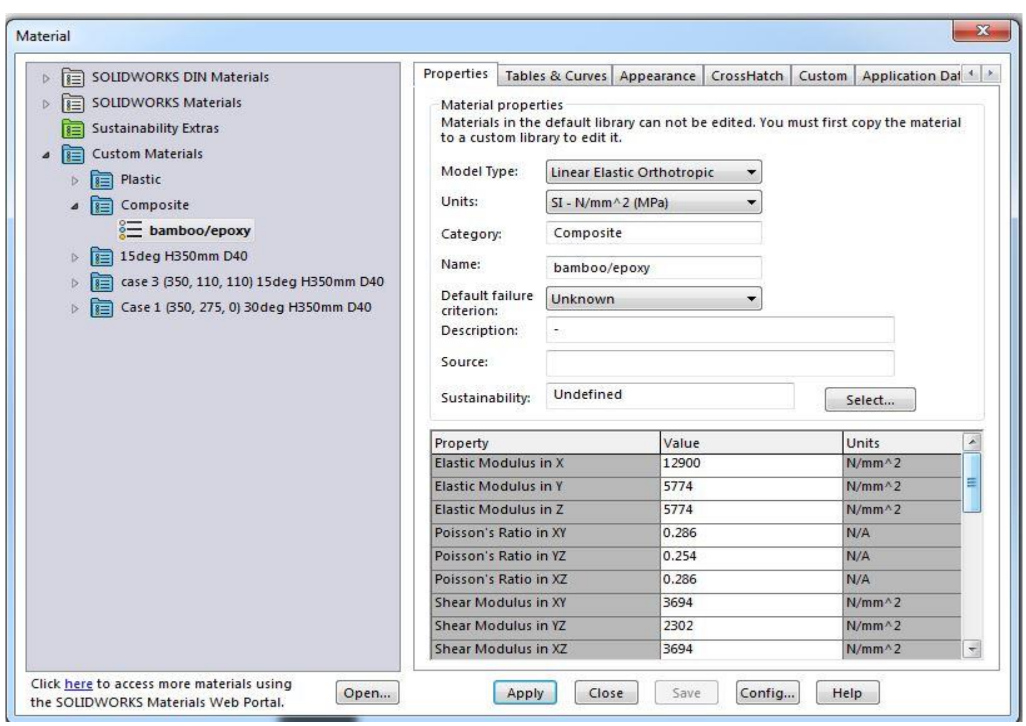


Figure 4.7. SolidWorks material property manager window

3rd step: applying constraints and external load

4th step: solving

5th step: post-process the results

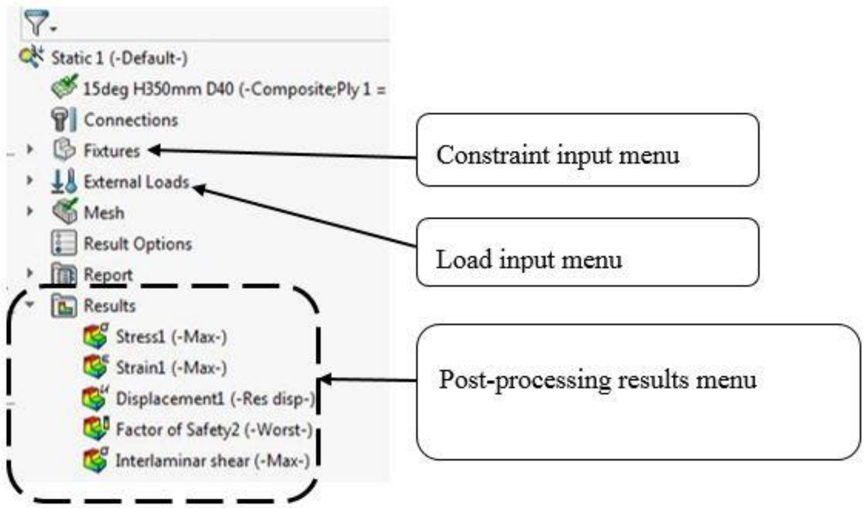


Figure 4.8. Constraint, load input and post- processing results menu

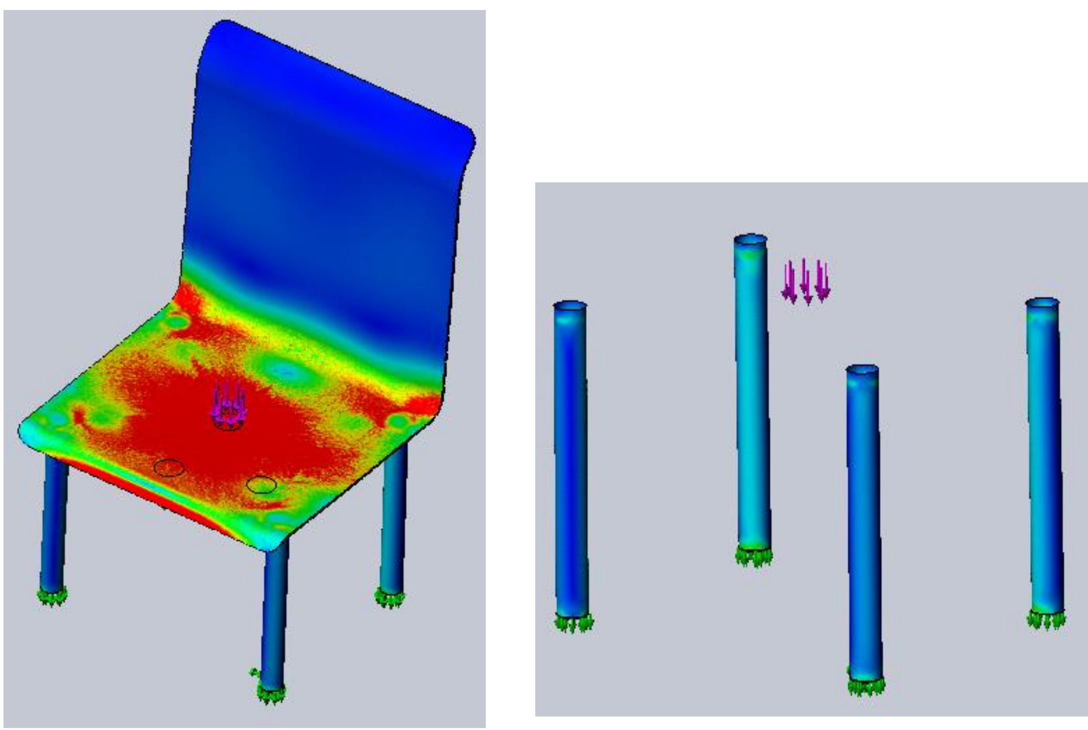
For this research work, von Mises stress, laminar shear stress and displacement is selected for post-processing results.

5. Result and discussion

5.1 Introduction

In this chapter, the numerical analysis results of the proposed bamboo fiber based composite hollow cylindrical chair leg is presented. To summarize the analysis results, first I categorized the cases into four different fiber orientations then under this major category the von-Mises stress, maximum strain and inter-laminar shear stress is estimated for each plies as a result of the three loading conditions. Then the maximum von-Mises stress, maximum strain, displacement, factor of safety and maximum inter-laminar shear stress across all plies is presented. Then in the discussion part the whole result is summarized and the best fiber orrientation is selected for the proposed chair leg.

5.2 Numerical anlysis result



(a) Full model of the chair (b) Four legs of the chair

Figure 5.1. Simulation result by the SolidWorks Simulation

5.2.1 Mechanical properties for each plies

This data is gathered by using probe from SolidWorks simulation result from highly stressed area on the leg.

Table 5.1. Mechanical properties for $[0°]_5$ orientation

No.	Load case's	Mechanical properties	Plies					Across all plies	max. displacement (mm)
			Ply 1	Ply 2	Ply 3	Ply 4	Ply 5		
1	Case 1	max. von Mises stress, (***MPa***)	5.501	4.323	4.092	3.981	3.101	5.891	2.188
		Inter-laminar shear stress, (***MPa***)	0.581	0.803	0.904	0.609	0	0.914	
2	Case 2	max. von Mises stress, (***MPa***)	7.236	6.793	5.210	4.372	4.101	8.146	2.390
		Inter-laminar shear stress, (***MPa***)	0.711	1.242	1.300	0.779	0	1.278	
3	Case 3	max. von Mises stress, (***MPa***)	10.140	8.419	6.105	5.834	4.621	10.500	3.102
		Inter-laminar shear stress, (***MPa***)	1.203	1.812	1.894	1.233	0	1.853	

Table 5.2. Mechanical properties for $[\pm 15°]_5$ orientation

No.	Load case's	Mechanical properties	Plies					Across all plies	max. displacement (mm)
			Ply 1	Ply 2	Ply 3	Ply 4	Ply 5		
1	Case 1	max. von Mises stress, (***MPa***)	8.770	6.768	5.095	4.364	3.852	10.940	1.972
		Inter-laminar shear stress, (***MPa***)	0.841	1.125	1.331	0.690	0	1.336	
2	Case 2	max. von Mises stress, (***MPa***)	11.830	6.216	5.517	4.688	4.121	11.330	2.301
		Inter-laminar shear stress, (***MPa***)	0.912	1.381	1.437	0.900	0	1.438	
3	Case 3 0	max. von Mises stress, (***MPa***)	13.246	8.613	6.928	5.151	4.023	13.112	2.812
		Inter-laminar shear stress, (***MPa***)	1.300	1.923	2.152	1.114	0	2.152	

Table 5.3. Mechanical properties for $[\pm 30°]_5$ orientation

No.	Load case's	Mechanical properties	Plies					Across all plies	max. displacement (*mm*)
			Ply 1	Ply 2	Ply 3	Ply 4	Ply 5		
1	Case 1	max. von Mises stress, (***MPa***)	9.671	7.041	6.120	5.471	4.144	11.517	1.901
		Inter-laminar shear stress, (***MPa***)	0.893	1.334	1.500	0.715	0	1.512	
2	Case 2	max. von Mises stress, (***MPa***)	12.113	9.410	7.162	5.318	4.255	12.630	2.150
		Inter-laminar shear stress, (***MPa***)	1.103	1.511	2.015	1.005	0	2.015	
3	Case 3	max. von Mises stress, (***MPa***)	13.853	9.913	6.881	5.722	5.032	13.791	2.652
		Inter-laminar shear stress, (***MPa***)	1.442	1.825	2.495	1.257	0	2.496	

Table 5.4. Mechanical properties for $[\pm 45°]_5$ orientation

No.	Load case's	Mechanical properties	Plies					Across all plies	max. displacement (*mm*)
			Ply 1	Ply 2	Ply 3	Ply 4	Ply 5		
1	Case 1	max. von Mises stress, (***MPa***)	11.203	8.917	7.131	6.522	5.116	12.340	1.879
		Inter-laminar shear stress, (***MPa***)	1.010	1.401	1.612	0.911	0	1.622	
2	Case 2	max. von Mises stress, (***MPa***)	12.991	9.812	8.071	6.991	6.021	13.225	2.060
		Inter-laminar shear stress, (***MPa***)	1.361	1.815	2.306	1.126	0	2.306	
3	Case 3	max. von Mises stress, (***MPa***)	14.526	11.664	9.167	7.552	6.802	14.909	2.513
		Inter-laminar shear stress, (***MPa***)	1.760	2.331	2.768	1.311	0	2.768	

5.2.1.1 Maximum stresses chart for each plies

A. Case 1: von Mises stress

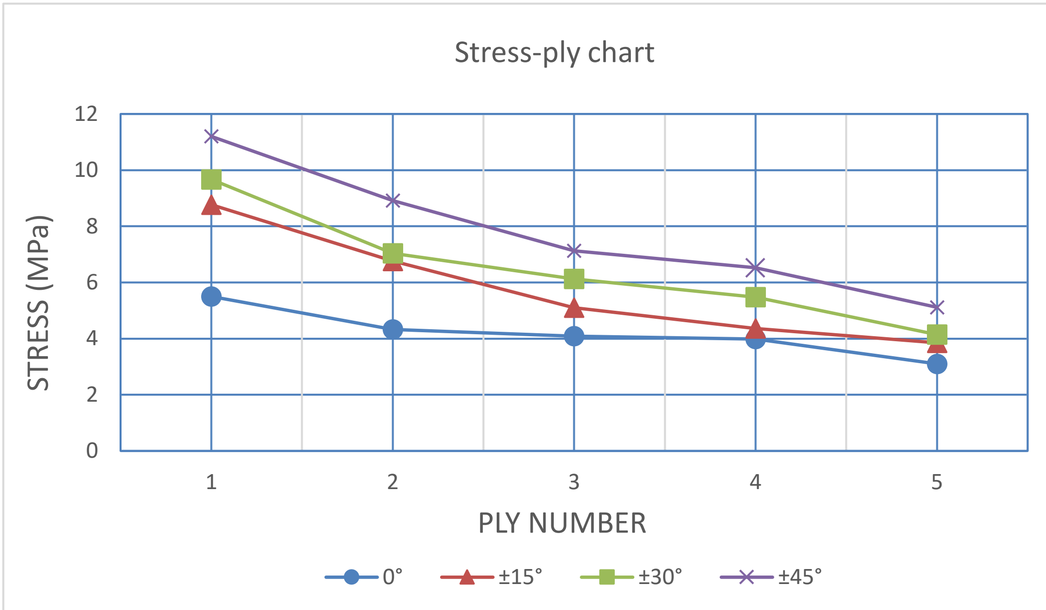


Figure 5.2. Maximum von Mises stress for loading case 1

B. Case 2: von Mises stress

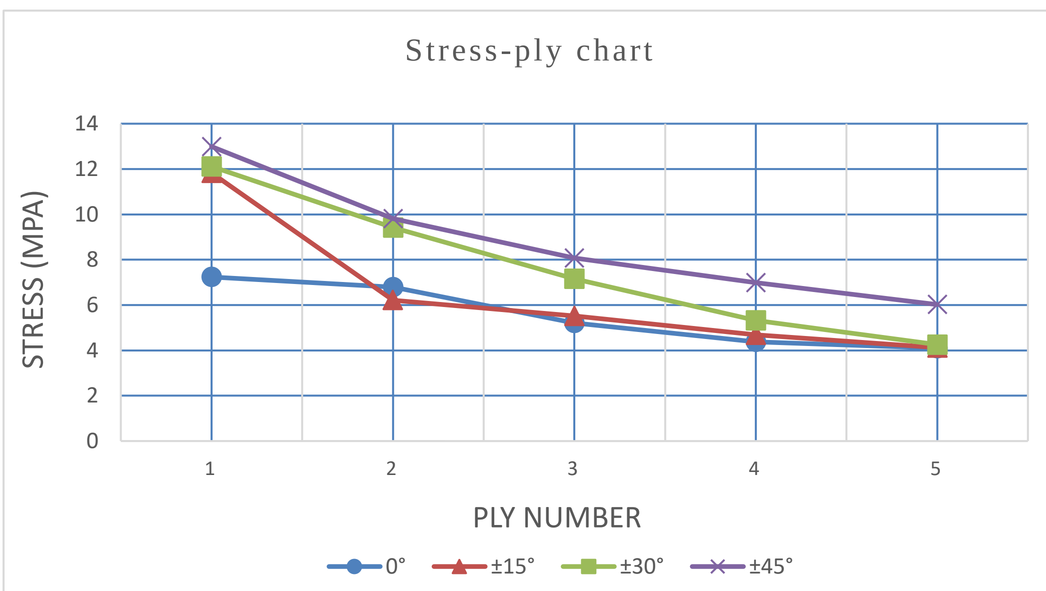


Figure 5.3. Maximum von Mises stress for loading case 2

C. Case 3: von Mises stress

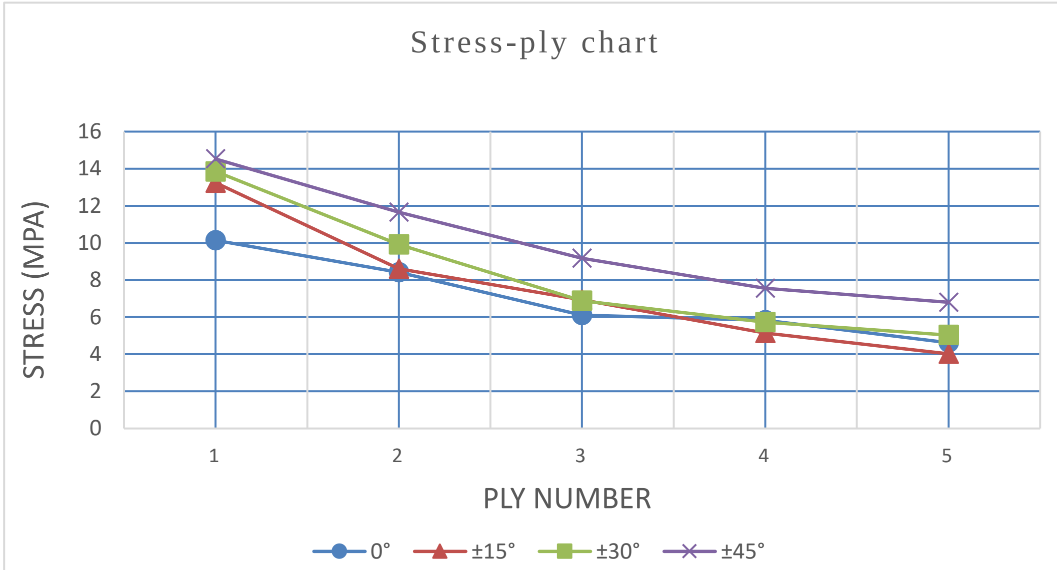


Figure 5.4. Maximum von Mises stress for loading case 3

D. Case 1: Inter-laminar shear stress

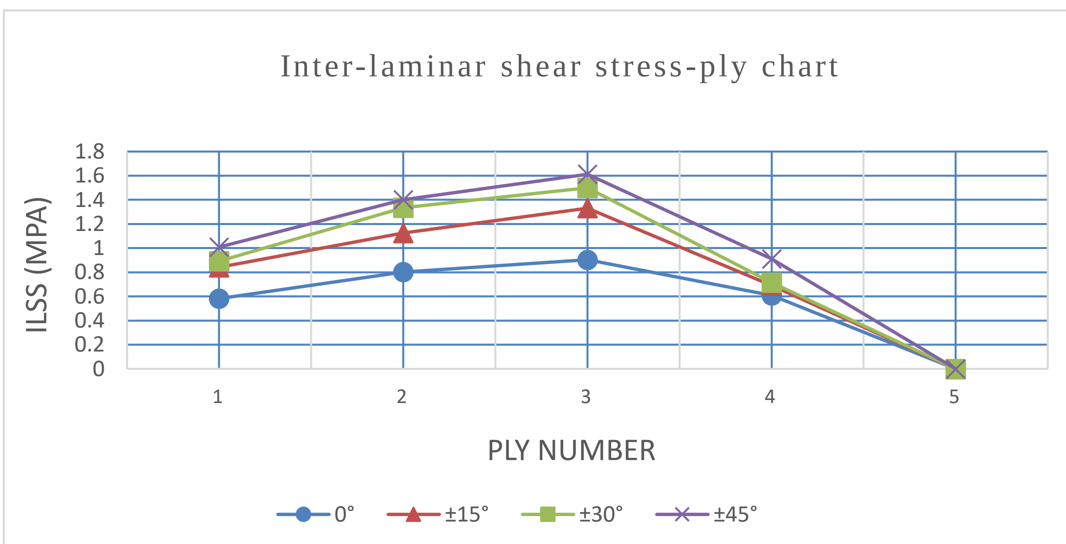


Figure 5. 5.Inter-laminar shear stress for loading case 1

E. Case 2: Inter-laminar shear stress

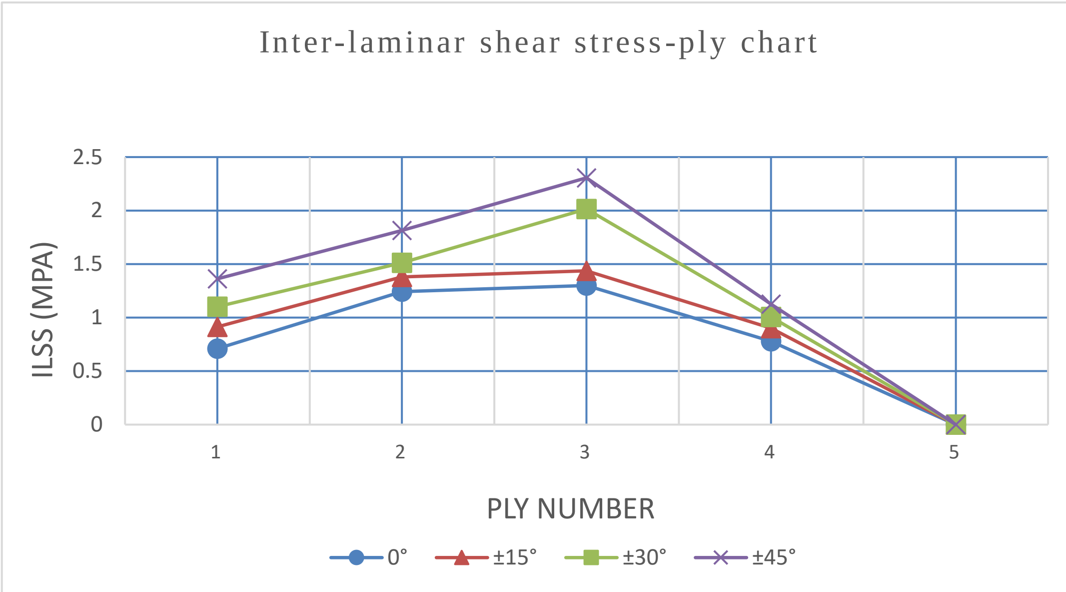


Figure 5.6. Inter-laminar shear stress for loading case 2

F. Case 3: Inter-laminar shear stress

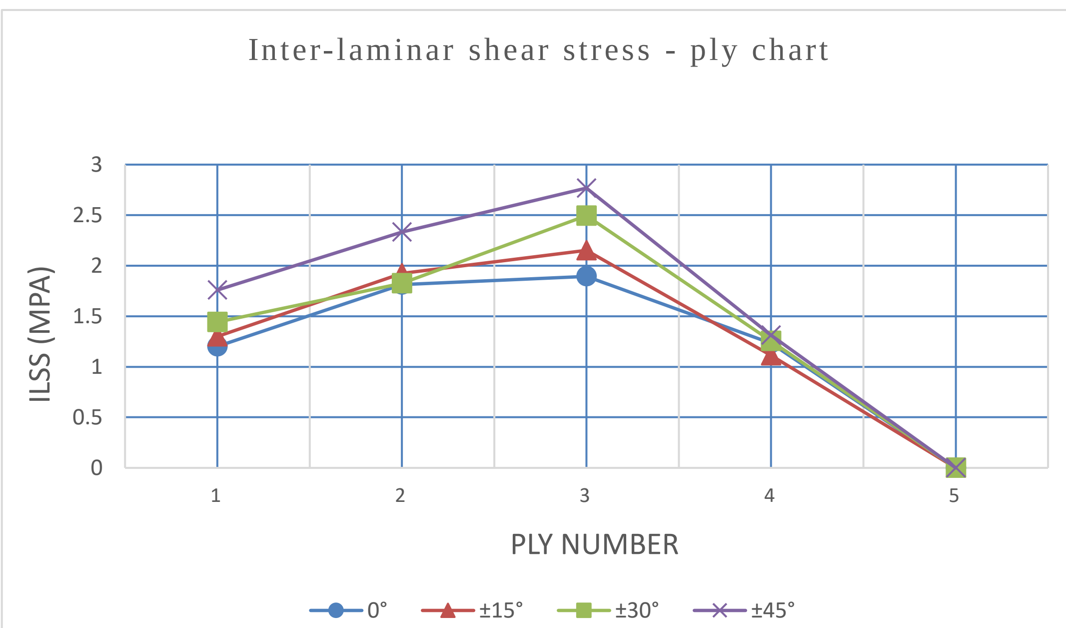


Figure 5.7. Inter-laminar shear stress for loading case 3

5.2.2 Mechanical properties across all plies

This subtopic is present the estimation of the maximum mechanical properties of the laminate for the four different fiber orientations as a response of the three loading conditions.

Table 5.5. Maximum von Mises stress

Fiber orientations	Loading cases		
	Case 1	Case 2	Case 3
Orientation (1)	5.891 MPa	8.146 MPa	10.500 MPa
Orientation (2)	10.940 MPa	12.330 MPa	13.112 MPa
Orientation (3)	11.517 MPa	12.630 MPa	13.791 MPa
Orientation (4)	12.340 MPa	13.225 MPa	14.909 MPa

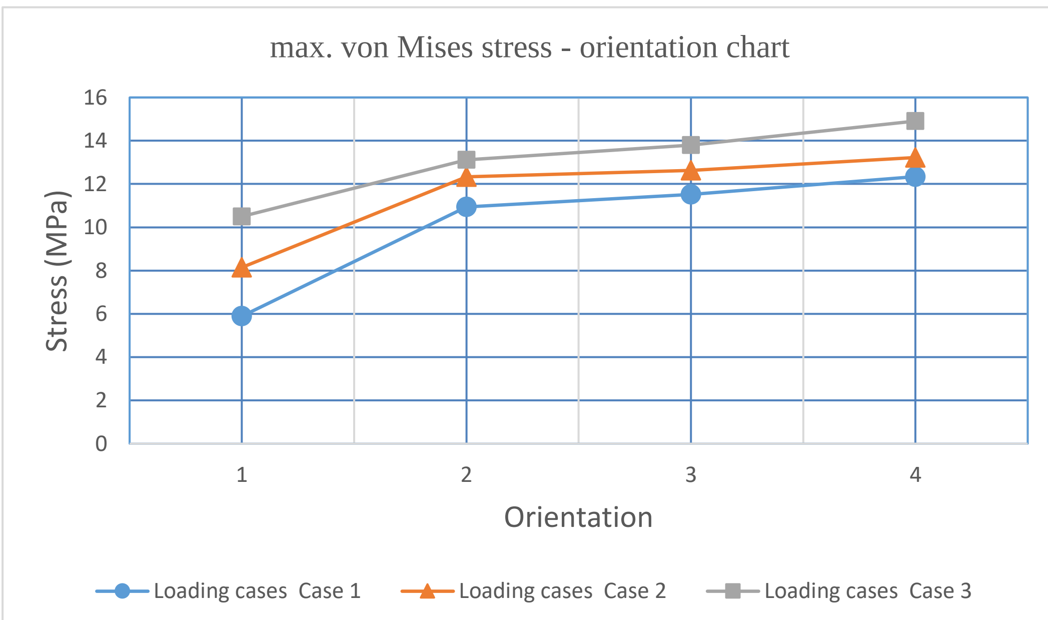


Figure 5.8. Maximum von Mises stress - orientation graph

Table 5.6. Maximum inter-laminar shear stress

Fiber orientations	Loading cases		
	Case 1	Case 2	Case 3
Orientation (1)	0.914 MPa	1.578 MPa	1.853 MPa
Orientation (2)	1.336 MPa	1.638 MPa	2.102 MPa
Orientation (3)	1.512 MPa	2.015 MPa	2.396 MPa
Orientation (4)	1.622 MPa	2.306 MPa	2.568 MPa

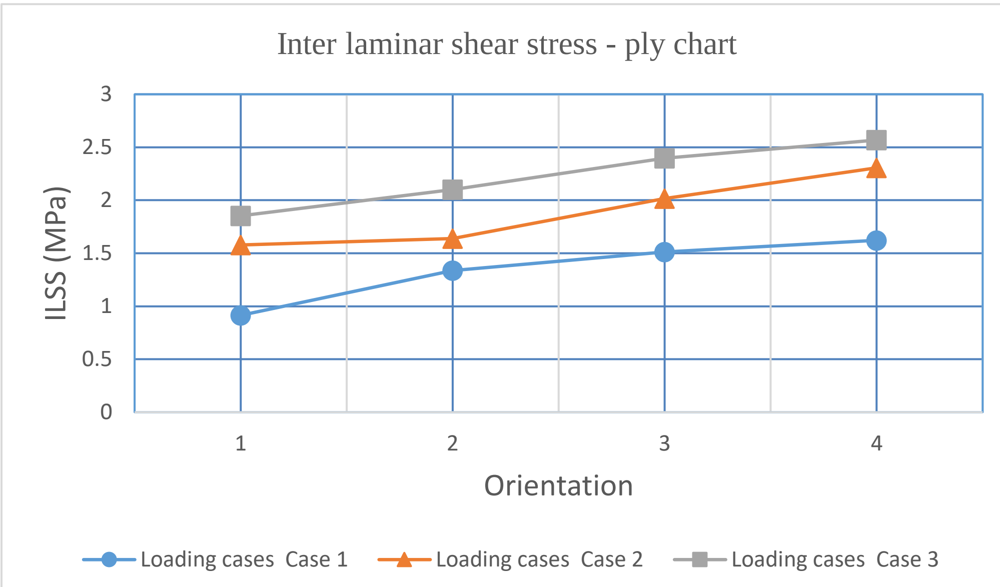


Figure 5.9. Maximum inter-laminar shear stress - orientation graph

Table 5.7. Displacement output

Fiber orientations	Loading cases		
	Case 1	Case 2	Case 3
Orientation (1)	2.188 mm	2.390 mm	3.102 mm
Orientation (2)	2.027 mm	2.301 mm	2.912 mm
Orientation (3)	1.920 mm	2.150 mm	2.652 mm
Orientation (4)	1.911 mm	2.060 mm	2.513 mm

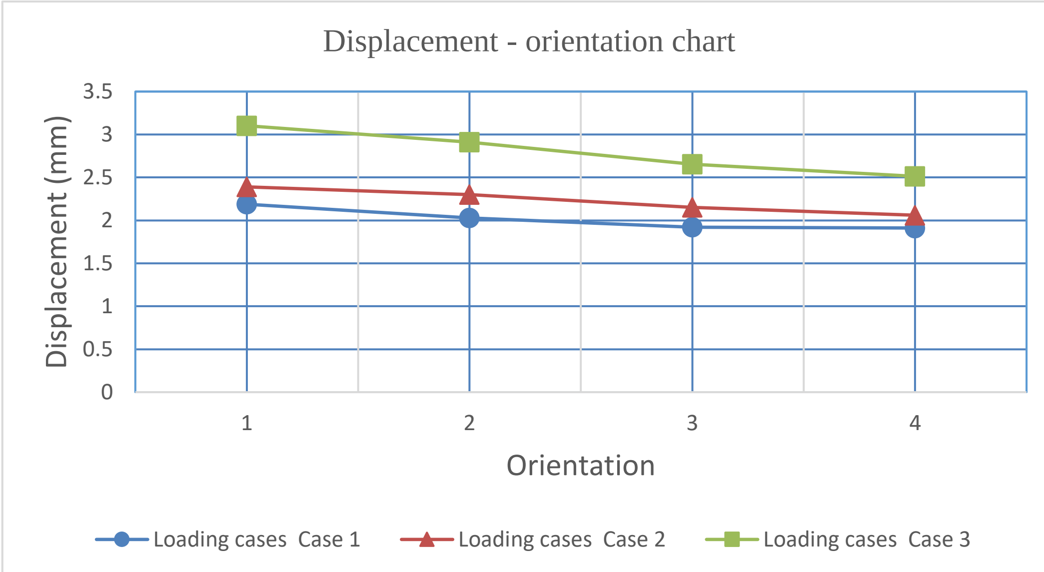
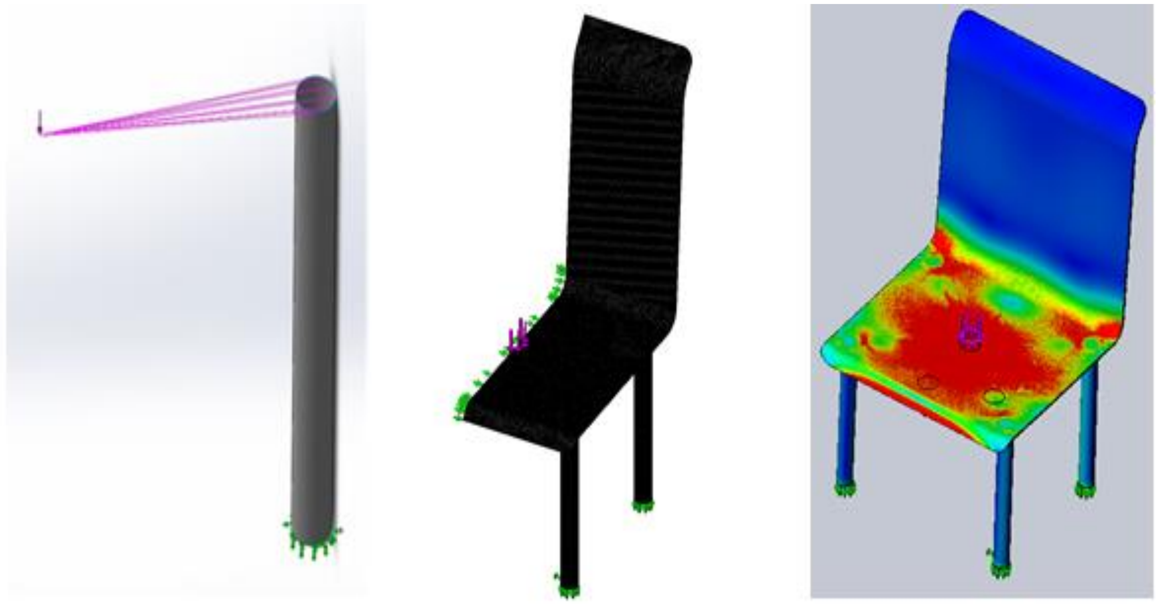


Figure 5.10. Displacement - orientation graph

5.3 Discussion on the results

The main goal of this research work was to analyze the mechanical properties of bamboo fiber based composite material with different fiber arrangement. The proposed case study to analyze the mechanical property of bamboo fiber composite was cylindrical hollow chair leg. Actually the product can be applied for other products within the allowable strength.

The load that is used to estimate the mechanical properties of bamboo fiber/ epoxy composite is 1962N (200kg). It is applied on three different points which are selected by using Gaussian point method, to predict the mechanical properties of the bamboo composite chair leg. There is three different methods for solving this kind of problems in SolidWorks Simulation software. The first method is remote load application, this can be done by modeling only one cylindrical chair leg and apply a faraway load on the given coordinate, see Figure 5.11(a). The second method is done by modeling the half section of the chair and fixing the sectioned face of the seat plate also the bottom surface of one chair leg, see Figure 5.11(b). The third method is done by modeling the whole body of the chair then fixing the bottom surface of one leg from the front two legs and giving sliding condition for the other three legs, see Figure 5.11(C).



(a) Remote load method (b) Half section method (c) Full section method

Figure 5.11. Solving methods in SolidWorks Simulation

From those three methods the full section method is better than the remaining two methods. Because its virtual working condition is much similar to the actual working condition. This helps us to predict the more accurate mechanical properties of the composite chair leg.

The result of this static analysis for each plies reveal that maximum von Mises stress is decreased when the ply number is increased from outside to the inside. But the inter-laminar shear stress is increased up to ply 3 then the value is decreasing up to ply 5; for the whole loading case and fiber orientation. The inner ply, ply 5, has zero inter-laminar shear stress for the whole cases. Also the results suggest that the first ply, outer ply, of each orientation poses a high stress value for every loading cases. The results are summarized in Figure 5.2 – 5.7.

5.3.1 Comparison of loading conditions and fiber orientations

The study result reveal that, the worst loading case from the three cases is case 3, (350, 110, 110) mm, it exhibits the higher von Mises and inter-laminar shear stress values as shown on the above figures (see Figure 5.8 and 5.9). Loading case 2 is the worst case when it is compared to loading case 1 for the proposed fiber orientations. The graphs show that loading case 1 is the safest case from the remaining cases for the whole orientations.

The relations, which is presented on the above figures, Figure 5.8 – 5.10, shows a linear relation. Stress – orientation chart, Figure 5.8, shows that when the fiber orientation are increased from 0° to 45° the maximum von Mises stress also increased for each loading case. This relation also similar for inter-laminar shear stress – orientation chart, see Figure 5.9. But for the displacement – orientation chart the graph shows a decreasing linear relation. The displacement is decreasing by increasing fiber orientation by 15° from 0° to 45° for each loading cases.

Orientation (1) shows a minimum and orientation (4) shows a maximum von-Mises stress and inter-laminar shear stress for the three loading cases. Figure 5.10 presents that orientation (1) and (4) exhibit maximum and minimum displacement values simultaneously. The displacement graphs also show that loading case 1 and case 2 have very close value on each fiber orientation angles.

5.3.2 Discussion on the selection of the best fiber orientation

The result of this research work indicates that orientation (1), 0°, is a better fiber orientation from the remaining orientations. Figure 5.8 show that between orientations (1) and (2), there is a big difference in maximum von Mises stress. Orientation (1) has the lower maximum von Mises stress than the other orientations and the remaining orientations has a closer maximum von Mises stress. But in orientation (4), loading case 3 shows a large value of von Mises stress than the two loading cases, those two loading cases has a close von Mises stress. For the inter-laminar shear stress, orientation (1) has the smallest value than the other two cases.

The above paragraph is summarized as, figure 5.8 and 5.9, orientation (1) is a better orientation for the proposed case study, because it has a small maximum von Mises stress and inter-laminar shear stress.

5.3.3 Comparison of different materials with bamboo fiber composite

In today's world, light and strong materials are more preferable than a material with high weight and strong properties. The weight comparison of bamboo fiber, plastic, wood and metals are presented in Table 5.8.

Table 5.8. Weight properties of bamboo fiber, plastic, wood and metal

Materials	Specific gravity	Density, kg/m^3	Specific weight, kg/m^3	Weight of the product, kg
Bamboo composite	0.952	1516	1444	0.277
Plastic (high density polyethylene)	0.970	965	936	0.178
Wood	1.500	1300	1950	0.380
Metal (aluminum)	3.500	2712	9492	1.825

The table shows that plastic products has a small weight than the remaining products and bamboo fiber is the second material with small weight. But, plastic materials has a high degree of environmental pollution than the bamboo fiber. Also, using woods has an environmental impact by facilitating the deforestation. Metal materials has a larger weight than the others, it is also the most costly material because it is imported from foreign countries.

The comparison of environmental, economical and weight properties of the four materials shows that bamboo fiber is a better material to use as a structural material.

6. Conclusion

In this paper, the mechanical properties of bamboo fiber based composite chair leg depending on fiber orientation and different load application position were analyzed by SolidWorks software. The analysis was performed on two major sections, the first one is the mechanical properties of each plies and the second one is the mechanical properties of the laminate. The analysis result of the first section show that, the first ply is under higher stress value than the other plies in the laminate. Depending on this result, I suggest that to improve the strength of the laminate for the advanced works, further research works must be done on the improvement of the outer ply and the fiber arrangement of the plies. The overall result of the second part of the analysis highlighted that when the fiber orientation angle approach to zero degree, 0°, its ability to resist the applied load would be increased. Based on the result of this research, I concluded that $[0°]_5$ arrangement is the best case among those different orientation angles for the proposed application and for other applications within the allowable strength of the product. Also $[\pm 15°]_5$ is the second choice for the proposed and related applications.

I recommend that, for future work one can make an experiment to get a better result on bamboo fiber composite. To do this one have to consider the limitations of this research work, which is stated under section 3.7.

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