Addis Ababa University
Addis Ababa Institute of Technology
School of Mechanical & Industrial Engineering

Development and Analysis of Composite Material using Honey comb Orientation of Bamboo Fiber and Epoxy Composite for Prosthetic Socket Application

A Thesis Submitted to the School of Graduate Studies of Addis Ababa Institute of Technology, Addis Ababa University in partial fulfillment for the Degree of Master of Science in Mechanical Engineering (Manufacturing Engineering)

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Declaration

I hereby declare that the work which is being presented in this thesis entitled "Development and Analysis of Composite Material using Honey comb Orientation of Bamboo Fiber and Epoxy Composite for Prosthetic Socket Application" is original work of my own, has not been presented for a degree of any other university and all the resource of materials used for this thesis have been duly acknowledged.

______________________	__________________	____/___/___
Yelshaday Regasa	Signature	Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge and belief. It has been submitted for examination with my approval.

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Advisor	Signature	Date

Acknowledgment

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List of abbreviations and acronyms

AASTU	Addis Ababa Science and Technology University
ASTM	American Society for Testing Materials
CPAF	Compliant passive ankle–foot prosthesis
TFA	Trans femoral amputations
DOF	Degree of freedom
FEA	Finite element analysis
FI	Failure index
FSM	Finite state machines
HPP	Homo polymer polypropylene
Hrs.	Hours
HS	Heel strike
KN	Kilo Newton
KPa	Kilo Pascal
Mb	Mass of bamboo fiber
Me	Mass of epoxy resin
MPa	Mega Pascal
NaOH	Sodium hydroxide
RTM	Resin transfer method
UTM	Universal Testing Machine
VARTM	Vacuum assisted resin transfer method
Vb	Volume of bamboo fiber
Vc	Volume of composite
Ve	Volume of epoxy resin
ρb	Density of bamboo fiber
ρe	Density of epoxy resin

ABSTRACT

This thesis focuses on utilizing honeycomb fiber orientation techniques to develop a prosthetic socket with enhanced mechanical properties at a lower cost. The current challenges in prosthesis production include the high cost of fibers and the inadequate strength of the composite fiber. To address these issues, this research explores the tensile characteristics, water absorption and impact strength of bamboo fiber reinforced epoxy composites with an optimized material mix ratio design.

The Finite Element Method for Numerical Analysis is employed to predict the desired properties of the composite material. Using numerical analysis software solutions, the stacking sequence is determined based on established standards. The newly designed prosthetic socket is evaluated for improved qualities, such as stance stability, speed control, multiple speed adoption, shock absorption, and reduced weight throughout the entire cycle.

By closely emulating nature, the study investigated the relationship between woven fiber orientations and honeycomb pattern fiber orientations. It examines the optimal material mix ratio design, as well as the best fiber orientation pattern and angle of fiber orientations. The obtained results include a tensile strength of 53.4 MPa, compressive strength of 57.6 MPa, flexural strength of 64.55 MPa, impact strength of 13.02 J/cm^2, and water absorption rate of 2.31%.

The findings of this research aim to contribute to the development of low-cost, high-strength composite materials for prosthetic sockets. Prosthetic socket designers can utilize these recommendations to improve the overall performance and durability of prostheses.

Keywords: Bamboo/epoxy, Honeycomb orientation, Prosthetic socket, Fiber stacking sequence, tensile characteristics, Energy absorption, Impact strength

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

When two materials with different physical and chemical properties are combined, the result is a composite material. When they are combined, a material is produced that is specially designed to carry out a certain task, such as becoming stronger, lighter, or electrically resistant. Additionally, they can increase stiffness and strength. They are chosen over traditional materials because they improve the properties of the underlying material and can be used in various settings [1], [2].

Despite having chemical or physical features that are visibly different, these constituent materials are mixed to create a material with properties that are distinct from the individual parts. Inside the finished construction, the individual components remain distinct and separate, distinguishing composites from mixes and solid solutions. Typical engineered composite materials include [3], [4]:

- Reinforced concrete and masonry
- Composite wood such as plywood
- Reinforced plastics, such as fiber-reinforced polymer or fiberglass
- Ceramic matrix composites
- Metal matrix composites and
- other advanced composite materials

Fiber reinforced materials have been increasingly popular in biomedical applications in recent years. Composites having a particularly high strength-to-weight ratio can be used in prosthetic applications due to their biocompatibility. The upper and the lower prosthetic limbs are made of composite materials with the right material mix to satisfy the need to get higher strength and superior biocompatibility [5], [6], [7]. The advancement of composite material development is currently being developed by directly copying nature. Bio inspired fiber designs are favorable due to their exceptional superior bio compatibility in orthopedics design applications.

A 3000-year-old Egyptian mummy that was discovered with a prosthetic toe constructed of wood and leather provides the earliest evidence of prosthetics [8]. Roman historians describe fighters who fashioned prosthetic arms and legs out of wood and iron. Little development was made during the Dark Ages. The devices that were developed were mostly utilized to cover up imperfections cosmetically.

Ambroise Paré, a French surgeon and army barber who lived in the 1500s, invented the modern amputation and prosthetics by creating prosthetics with knee lock controls and harnesses [8]. Paper and leather, for example, were introduced as softer, lighter, and more malleable materials. After the American Civil War, J.E. Hanger created the "Hanger Limb," which was patented in 1871 and made a significant contribution to modern prosthetics. He started Hanger Inc., which is now a pioneer in the prosthetics industry.

Contrarily, advancements in prosthetic technology lagged behind the increased attention on military technology during the two World Wars. The Artificial Limb Program was established by the National Academy of Sciences in 1945 and marked the beginning of coordinated study in the area [9]. Inventor Ysidro Martinez revolutionized prosthetics in 1975 when he created a limb that was intended to enhance balance and lessen friction. This signaled the beginning of a fresh wave of technology developments aimed at enhancing human comfort and functionality.

Under this research work, a study of the mechanical properties of the honeycomb-oriented bamboo fiber reinforced epoxy polymer composite for prosthetic socket application is performed based on ASTM standards. The finite element analysis was also performed to assess the feasibility of the material for the intended applications. Further, finite element analysis of the prosthetic socket is done on FEA software packages by taking its dimensions.

1.2 Statement of the Problem

In today's world, the demand for lightweight materials is linked to system energy usage. The lighter the material, the lower the load carrying capacity and the longer the material will last.

According to reports, most problems associated with using prosthetics are caused by the prosthetic socket. The most frequently reported issues are those related with pain or discomfort around the applied area (affected body) and skin concerns such as itching and irritation brought on by the socket's design or poor fit [10]. Prosthesis users often claim that the existing socket is uncomfortable which results to pain and irritation on affected body. The socket interface is the most important component of the prosthesis since it stabilizes the pelvis during stance,gives the user prosthetic control, and affects how the components work [11].

Prosthetics are externally applied devices and products that help individuals with physical or functional limitations to improve their functioning and increase their potential to live healthy, productive, independent, and dignified lives. However, due to their high price, lack of awareness, availability, skilled staff, policy, and finance, only one out of every ten persons in need do not always have access to assistive items like prostheses and orthoses [12], [13].

Polyethylene and polypropylene are the materials utilized in Ethiopia for prosthetic purpose [14]. However, research suggests that the majority of people who used the artificial prosthetic limb products made from these materials have skin problems such as: excessive sweating, itching, wounds, and irritation on the affected body region. These products have the following problems: higher weight, frequent buckling, lower compressive and impact properties [15]. There are also compatibility issues of the parts to the rest of the bodies. So, this research work is intended to solve the limitations of the currently applicable composite materials by developing a material with bamboo fiber in honeycomb fiber orientation with epoxy resin composites. The proposed material has the following properties: lightweight, good mechanical properties and higher degree of compatibility with the rest of the body parts.

In comparison to epoxy composites bonded with carbon and glass fibers, polypropylene has strength limitations and also experiences tiredness [16]. The reason for this is that it experiences significant heat generation upon contact with the body, whereas, carbon and glass fiber reinforced composites have a comfort limitations [17], [18]. Similarly, these fibers exhibit high electrical resistance in addition to being thermally and acoustically insulating. Due to its low rigidity features of the fibers, amputees who utilize the products experience a premature loss of comfort before its intended service life of the prosthetic products.

Amputees require a prosthetic socket that is both comfortable and affordable. In terms of loading conditions from fiber direction angles, hybrid composites have similar constraints to uni-axial and bi-axial fiber-oriented composites, notwithstanding high strength [19]. To overcome the design limits of fiber reinforced composite products and to meet the requirement for improved property composites, bio-inspired innovative composite design approaches are becoming fascinating research and development fields. Therefore, this research work investigates the physio-mechanical properties of honeycomb-oriented bamboo fiber reinforced epoxy polymer composite for prosthetic application. To validate the application of the developed composites for the prosthetic applications the experimental tests and finite element analysis were performed based on the ASTM standards.

1.3 Research Questions

- ✓ What are the effects of honeycomb orientations on the mechanical properties of bamboo fiber with epoxy composite for prosthetic socket?
- ✓ What are the effects of woven orientations on the mechanical properties of bamboo fiber with epoxy composite for prosthetic socket?
- ✓ How to validate the experimental test results and check the feasibility of the fabricated material for the prosthetic socket applications?
- ✓ What is the optimal honeycomb orientation of bamboo fiber with epoxy for the developed composites?

1.4 Objectives

1.4.1 General objective

The main purpose of this research work is to develop and analyze the composite material with honeycomb fiber orientation of bamboo fiber reinforced epoxy polymer composite for prosthetic socket applications.

1.4.2 Specific objectives

The specific objectives of this research work include:

- ✓ To develop a composite material using a honeycomb orientation of bamboo fiber with epoxy resin
- ✓ To evaluate the mechanical properties (such as: compression strength, tensile strength, impact strength, and flexural strength) of the developed composite material.
- ✓ To develop a composite material using a woven orientation of bamboo fiber with epoxy resin
- ✓ To evaluate the mechanical properties (such as: compression strength, tensile strength, impact strength, and flexural strength) of the developed composite material.
- ✓ To perform finite element analysis on the prosthetic socket using the honeycomb fiber orientation composite material to check its feasibility.

1.5 Scope and Limitations of the Research Work

This study is experimental based research that investigated the mechanical properties of the bamboo fiber in honeycomb fiber orientation and bamboo fiber in woven orientation with epoxy resin composite materials. The fabricated composite material was prepared to perform the following tests: compressive strength, flexural strength, tensile strength, impact strength, and water absorption. The experimental test results were validated with the FEA results. Finally the prosthetic socket was designed and analyzed using solidworks and Ansys software packages, respectively.

The limitations of this research study includes that the thermal and vibration characteristics of the honeycomb-oriented bamboo natural fiber reinforced epoxy polymer composite are not studied under this condition.

1.6 Significance of the Research Work

To show that honeycomb bamboo fiber arrangement with epoxy glue is feasible for prosthetic sockets. The study comprises a clinical case-controlled comparison of variable compliant wall prosthetic sockets with traditionally produced prosthetic sockets, as well as an engineering design component. The study's long term goal is to develop a technology for fabricating variable wall compliant prosthetic sockets directly from digital residual limb shape data. In comparison with the traditional socket fabrication processes, these sockets are projected to improve prosthetic socket comfort, improve tissue-loading properties, reduce skin pain (e.g. itching, sweating, irritation, e.t.c.) and breakdown, and reduce fabrication time and cost.

1.7 Organization of the Research Work

This thesis consists of five chapters, where each chapter is dedicated to a specific aspect of the research work.

Chapter 1 serves as an introduction to the study and provides background information on prosthetic socket. It highlights the importance of a well-fitting prosthetic socket for an amputee's comfort and mobility.

Chapter 2 presents a literature review of the research topic, covering various aspects related to prosthetic socket, such as its design, fabrication, and materials. It also discusses the potential use of bamboo fiber and honeycomb structure in prosthetic sockets. This chapter aims to provide a comprehensive understanding of previous studies and the existing knowledge gap in this field.

Chapter 3 is focused on research methodology, where the experimental design is outlined in detail. It explains the selection of materials, their properties, and sample preparation process. Additionally, testing methods such as mechanical testing, dynamic cushioning testing, and comfort assessment are elaborated. This chapter provides information on how the research work was conducted and how data were collected and analyzed.

Chapter 4 demonstrates the experimental findings and presents the results, interprets and analyses the findings in the context of the literature review.

Chapter 5 gives conclusion and recommendations on the research. In addition, future work is proposed.

CHAPTER TWO

Literature Review

There is a growing interest on the development of new materials based on natural resources that enhance optimal properties for biomechanical materials. In most recent technology era, high stiffness and high strength materials are the choices of modern structure designs in various fields. For these conditions, polymer materials which are composites of two or more materials or constituents which have different mechanical and chemical properties or other composites can be used. The constituents are named as reinforcement (Fiber) and matrix. The fiber reinforcement which is discontinuous in nature is a major load carrying element while the continuous matrix sticks the fiber together to ensure load distribution [20]. So, under this chapter all points important for the identified research work have been reviewed and discussed in detail.

2.1 Composite Materials

Composite materials are generally designed to have superior mechanical properties and/or superior stiffness-to-weight ratios than the individual constituent materials [21]. The combining of two or more materials, each with distinct properties, results in a composite material. The structure of composite materials consists of two or more different phases in terms of physical and chemical properties of the constituents. These are continuing phase or matrix and the discontinuous phase or fiber reinforcement [21], [22]. To produce a material with desired properties. This is often accomplished by combining relatively brittle, strong fibers with a matrix that resists cracking when subjected to high stress. The main advantage of a reinforcement fiber is to enhance strength to the composite while the matrix has a duty of binding the fibers together and distributing the load among them. Good flexibility, high strength to weight ratio, non-corrosive, good stiffness, good dumping, low electric conductivity, lightweight, low cost are the main advantages of composite materials.

Table 2.1: General constituent of Fiber Reinforced Composite

Fiber material	Matrix Material:
✓ The fibers provide the reinforcement and give the composite its strength and stiffness. ✓ The fibers classified into different categories based on their nature, such as carbon fibers, glass fibers, aramid fibers, and natural fibers like abaca. ✓ Short and random fiber orientations allow resisting load from any direction. ✓ Compared to the other types of composites fiber reinforced composites (FRC) are widely used due to their versatile orientations and lengths advantages [22].	➢ The matrix material holds the fibers together, provides protection, and transfers loads between the fibers. ➢ It is a base material that binds fiber materials together to provide shape and form that improves toughness, load distribution, stability to resist buckling, protection from damage and chemical attack [21]. ➢ The choice of matrix material is determined by factors such as desired mechanical properties, cost, and processing requirements.

The drawback of composite materials is their long fabrication time, low ductility, operating temperature limit, susceptible to moisture attack and lower maintainability after failure [23].

The apparent lack of sensitivity to fatigue when the load is applied in the fiber direction, even at pressures near to the static fracture strength, is one of the factors that make composites suitable for high-performance constructions. However, several different fatigue damage mechanisms are known to exist in composites [23], [24].

2.1.1 Fabrication of Composite Materials

The polymer composite fabrication techniques depend on the availability of manufacturing equipment's and the application for which the composite material going to be developed is used. Generally, polymer composites manufacturing process are categorized as open molding, closed molding and polymer cast molding. The hand lay-up technique is most common since no special talent is required to utilize it. This can be performed with open mold by applying the resin to the surface of the fibers with brush or can be assisted with vacuum bagging to remove air to reduce formation of voids. Further to hand lay-up the resin transfer method (RTM), spray up, vacuum assisted resin transfer method (VARTM), hot press molding, filament winding, pultrusion and autoclave are commonly used in manufacturing and research world [25, 26, 27].

I. **Hand lay-up:** it is the most used fabrication method for thermoset polymer composites. The process starts with laying prepregs plies on to the mold manually to create laminate stack with continuous application resin to the layer of plies to create wet lay-up for binding.

II. **Open Molding:** is low-cost process used for the fabrication of polymer composite materials such as fiberglass reinforced after treating the mold with release agent (gel). The resin is sprayed on the fiber strands on to the molding surface simultaneously and compact spread using rollers followed with curing.

III. **Resin Transfer molding:** this method is one of the automated fabrication techniques used for faster production rate. First the dry reinforcement is put into the mold followed with pumping of the mixture of matrix under low pressure. Here the resin used should be of low viscosity to prevent fast curing and the process produces high-quality parts without an autoclave.

IV. **Reaction Injection Molding**: unlike the resin transfer, the resin and hardener are inserted in to separate streams to the mold. The chemical reaction of the mixtures takes place in the mold instead of the dispensing head.

V. **Vacuum-Assisted Resin Transfer Molding (VARTM)**: this technique of composite fabrication differs from other resin transfer methods since it doesn't require heat or pressure. Instead of pumping with pressure, VARTM draws the resin into perform using a vacuum. It uses low-cost tools and easy to produce a considerable amount of complex and inexpensive parts.

VI. **Filament Winding**: provide low material cost with continuous and highly automated process specially for making golf club shafts. Further, this process helps to produce cylindrical parts, fishing rods and pressure vessels.

VII. **Pultrusion:** is a continuous, straightforward manufacture process for composites. In this method, the reinforcing fiber is compelled to travel through a resin bath while being molded into precise forms using a number of forming guides. When the composite is forced through a heated die, it takes on its final shape and cures. This method yields smooth results that don't require post-processing.

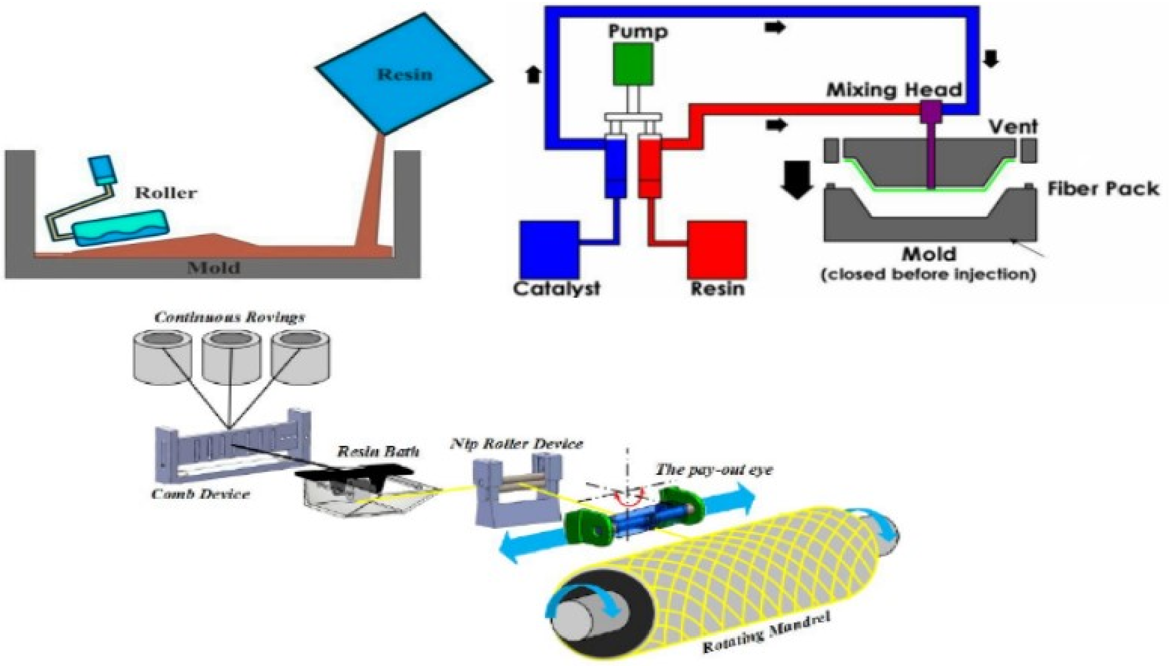
VIII. **Compression Molding:** widely used for fabrication of high-volume thermosets products. First the resin paste is placed down and added the reinforcement which is finally covered using final layer of resin paste. It is preferable for sheet molding compounds to take the advantage of the strength and stiffness to weight ratio of reinforcements.

IX. **Injection Molding**: a fast and low-pressure fabrication method widely used for fabrication of filled thermoplastics. It is the quick process for the production of high amount of small parts within short period of time.

When selecting composite materials fabrication techniques, there are some important details to be noted.

- Considering the desirable properties that make the composite suitable for applications
- Desired shape and geometry of the composite from the constituent materials
- Observing and maintaining a safe working environment of the composite
- Addressing the health and safety concerns by developing monitoring policies

(a) (b)



(c)

Figure 2.1: (a)Hand lay-up Fabrication Technique (b) RTM (c) Filament Winding [2, 27]

The increased interest in developing new materials with superior biomechanical qualities has led to the discovery of pioneer natural resources. In recent years, new structure designs in a variety of fields have favored high stiffness and high strength materials. In composite materials, the reinforcement fiber material provides strength, stiffness and support to the loads applied. It is the main constituent that determines the life of the composite material, the type and the properties of the fiber material greatly affect the desired composite properties. According to these fiber properties and types, fiber reinforced composites materials can be grouped as: structured fiber reinforced Composite, Particle Reinforced Composite, Whisker Reinforced Composite and Fiber Reinforced Composite [28].

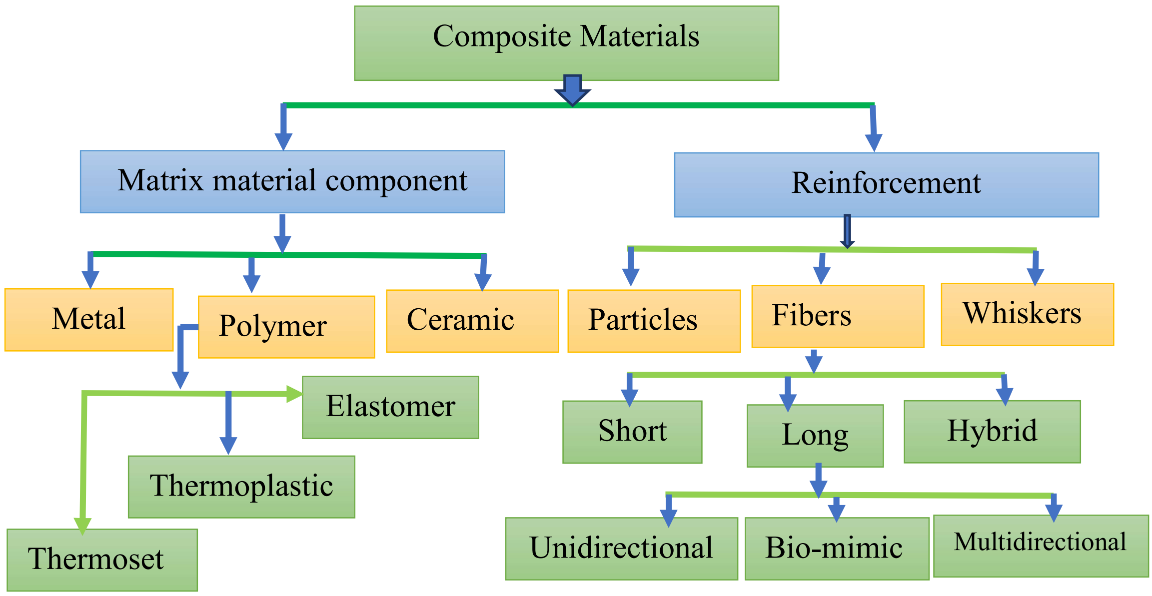


Figure 2.2: Constituent of composite material [29]

2.2 Fiber reinforced composites

The two constituents of composite material used to construct fibrous composite which is different from particle composite. Depending on the direction of interest, these composites have different properties. Fibrous composites have advantages over traditional single-component polymer films and particle composites. Compared to some metallic materials, they have high strength-to-weight and modulus-to-weight ratios [23, 28, 30].

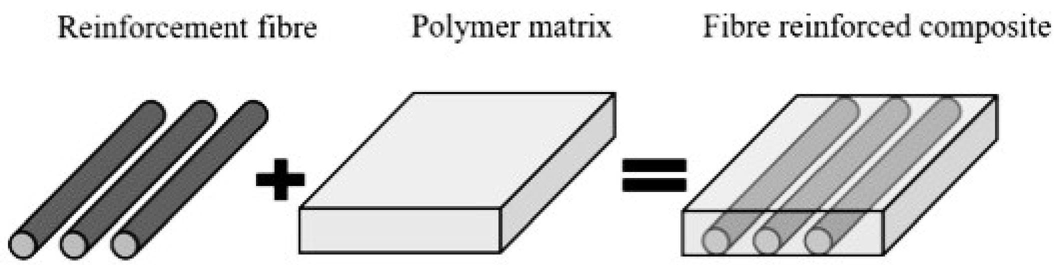


Figure 2.3: General structural assembly of fiber reinforced composite [30]

i. **Thermoplastic polymers**

Thermoplastic matrix-based composites are tougher and less brittle than thermoset composites. The energy intensive manufacturing process of thermoplastic polymer composites because it requires high pressures and heat to melt the plastic for impregnating the fibers with the matrix. The energy consuming fabrication technique required makes thermoplastic composites to be more costly than thermoset composites. [29].

ii. Thermoset polymers

These types of polymers are deformed permanently for temperature change and can be converted to a solid form when cured. Polymer composites consisting thermoset matrices are characterized with high strength and very good fatigue strength compared to others. They are characterized with brittleness and low impact -toughness than other matrix types. Because the greater viscosity liquid form of thermoset is so simple to deal with, thermoset-based polymer composites are typically less expensive and simpler to manufacture. The disadvantage of thermoset composites is that they are difficult to recycle because they cannot be reshaped or molded; only the reinforcing fiber that was employed may be recycled. [30], [31].

Epoxy resin is common thermoset type of polymer used in manufacturing different polymer composites. According to the producer of composite material [32], epoxy resins are "a group of monomeric or oligomeric substances that can undergo further reactions to produce thermoset polymers with excellent adhesion to a variety of surfaces, little shrinkage after curing, impact resistance, flexibility, and good electrical characteristics. When selecting an epoxy resin, the resin, modifiers, and cross-linking agent can all be individually chosen to provide the necessary qualities for a specific application. This makes it possible to use epoxy resins in a variety of applications.

Epoxy resins offer a number of desirable characteristics [32]:

- Resistance to chemicals, particularly alkaline environments
- Heat resistance
- Adhesion to a variety of substrates
- High tensile, compression, and bend strengths
- Low shrinkage during curing
- High electrical insulation and retention properties
- Corrosion resistance
- Cures under a wide range of temperatures
- Resistance to fatigue

2.2.1 Fibers

The major load bearing component from the constituents of composite materials are called fiber and it is bonded to the matrix. Fiber is a key load-bearing element and a reinforcing ingredient [33], [34]. The fiber material can be classified in different ways. Composite fibers can be divided into two categories: short fiber composites and continuous fiber composites. Short fiber composites consist of short fibers that are randomly oriented within the matrix material. Continuous fiber composites consist of long fibers that are aligned in a specific direction within the matrix material.

Fibers can be classified based on their sources as natural and synthetic fibers.

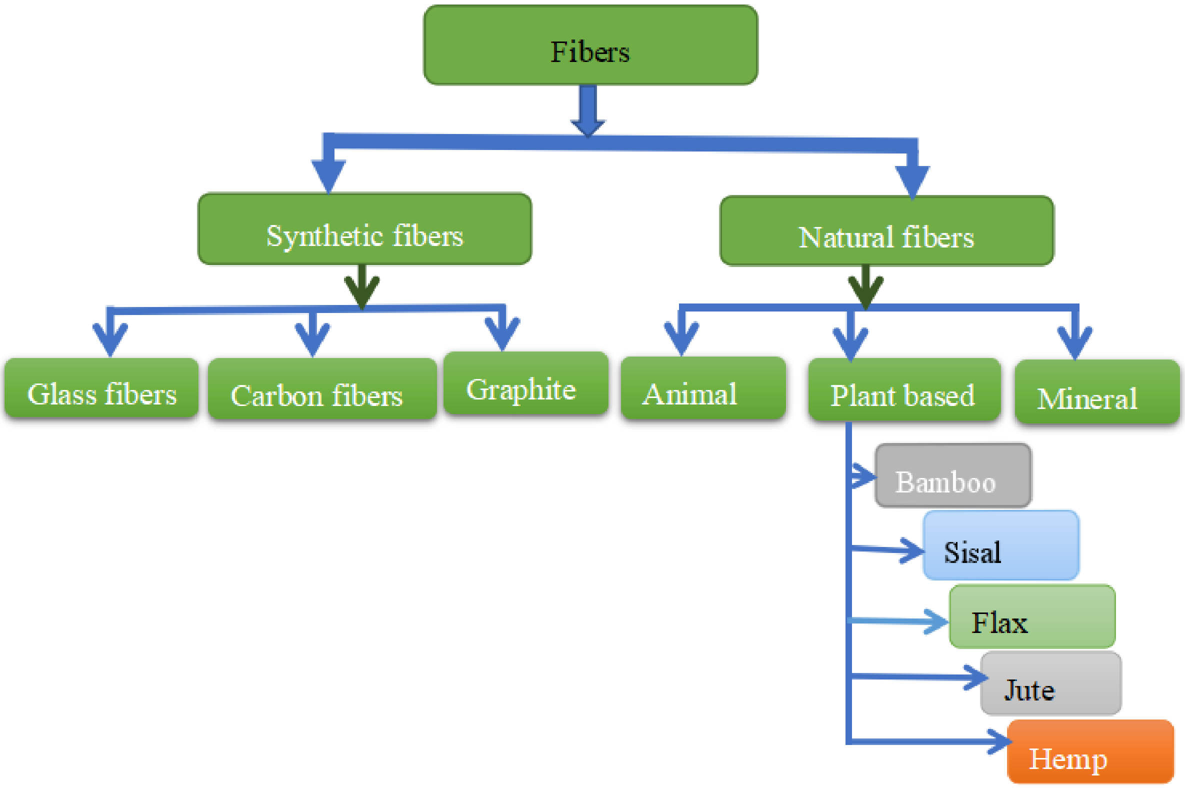


Figure 2.4: Classification of fibers, based on their sources [23]

a) **Synthetic fibers** are durable fibers derived from Chemical resources passing through certain steps of fiber fabrication which involve silk extrusion and spinning systems. Petroleum byproducts are the principal source of synthetic fibers. The most commonly used synthetic fibers as Glass fibers, Carbon fibers, graphite and Kevlar fibers [33]. Though the advantages, synthetic fibers have higher tendency to pollute the environment since they contain higher carbon percentage and not biodegradable.

b) **Natural fibers**: can be considered as naturally existing composites consisting especially of cellulose fibrils (fibers) embedded in lignin matrix (resin) [5], [7], [35]. Those cellulose fibrils are aligned alongside the direction of the fiber in the whole length, regardless of its origin. This alignment renders most tensile and flexural strengths, in addition to providing tension in that direction of the fiber as determined inside the case of bamboo. Similarly, these fibers exhibit high electrical resistance in addition to being thermally and acoustically insulating. They are easily accessible and have high specific strength although their higher water absorption capacity is the main drawback for structural applications. However, this can be mitigated by using chemical treatments to reduce the water absorption capacity [36].

Some of the major drawbacks of composite materials include their excessive price for raw materials and manufacture, extra brittleness compared to wrought metals, weak transverse properties, weak matrix, so there is very little toughness, reuse and disposal of composite material is difficult, effect of water absorption on their properties, high coefficient of thermal expansion, low impact resistance, low maximum working temperature and sensitivity to radiation [37].

2.2.1.1 Bamboo fiber

Bamboo is one of the tropical (warm temperate) growing members of grass family Gramineae belonging to the sub-family named as Bambusoideae. Bamboo abundantly grows in temperate, subtropical and tropical areas with multipurpose high local economy significance and environmental value except in Europe.

Reports show that there are more than 1,500 species of bamboo belonging to 110 genera from all over the globe. These resources are distributed from 46° north to 47° South latitude with altitudes ranging from sea level to about 4k meters in equatorial highlands. Estimation around 80% of bamboo forestland and species in the world are mainly found in Asia and Pacific regions also Latin America has a high biodiversity of bamboos with more than 400 species. Africa possesses about 43 species of bamboo under eleven genera, covering an area of over 1.5 million hectares. The Arundinaria, Oreobambos and Oxytenanthera [38] are the most known three bamboo genera under which the distribution of African bamboo are categorized.

Researchers argue that, the highland bamboo (Arundinaria alpine, Yushania alpina) and the monotypic genus lowland bamboo Oxytenanthera abyssinica [39, 40] are indigenous bamboo species in Ethiopia. These species of bamboo are indigenous to Ethiopia and endemic to African bamboo distribution. The Ethiopian bamboo forest is estimated to have been around one million hectare before the excessive deforestation begins some years ago.

It is very important to point out that Ethiopia is the only country in Africa which has over 850 thousand hectare of Oxytenanthera abyssinica natural bamboo forest [41].

Oxytenanthera abyssinica is a clumping type bamboo with solid culm at its maturing age. It has an average culm diameter of 5 cm and with total number of 5-7 internodes. This type of bamboo species grows at an elevation between 1,000 to 1,700 m above sea level and is widely distributed in the western lowland areas of the country [38]. Essentially, bamboo is a type of grass with a woody stem (culm). Some are tiny and resemble grass, while others have enormous culms that can grow up to 10" or (250mm) in diameter and span length over 100". In perfect conditions, some species can grow more than one foot each day [42].

Bamboo is any of the about 1,450 species of the Poaceae family that are cultivated in Asia, Africa, and the Americas. The majority of bamboo species are incredibly hardy, thriving in both warm tropical climates and frigid highland environments. [43], [44]. They may grow up to 60 cm in a single day, making them one of the world's fastest-growing plants.

Figure 2.5: Bamboo species

Bamboos are perennial, evergreen, blooming plants in the grass family's bambusoideae subfamily [45]. The Dutch or Portuguese languages, which likely took it from Malay, are where they get the word "bamboo." A special rhizome-dependent system makes bamboo one of the plants with the quickest growth rates in the entire planet. Some bamboo species have a 24-hour growth rate of 910 mm (36 in), or approximately 40 mm (1 12 in), every hour (a growth around 1 mm every 90 seconds, or 1 inch every 40 minutes). The largestmembers of the grass family are giant bamboos. Some kinds of bamboo can grow more than a meter each day, making it the woody plant with the quickest growth rate known to man [46, 47]. It supports hundreds of millions of people, animals, and insects.

Bamboo has historically aided in meeting the many physical demands and spiritual needs of humans with its countless uses as food, textiles, paper, shelter, and inspiration.

The chemical makeup and characteristics of lingo-cellulosic bamboo fibers are comparable to those of jute and flax. It has a cellulose content of 70–74 percent, hemicellulose of 12–14 percent, lignin of 10–12 percent, and extractive of wax, pectin, and protein of 2–3 percent [48, 49].

The advancement of composite material development technology opened wide room for natural plant like bamboo to be used as reinforcement further to the synthetic fibers with nature inspired fiber orientations such as honeycomb due to their higher specific strength and eco-friendly.

I. Advantage and application area of bamboo fiber

The bamboo fiber is one of the highly extracted natural fibers around the globe [50]. The utilization of bamboo fibers begins with the advancement of composite materials from the synthetic reinforcement to the natural fibers based one to attain biodegradability and reduce environmental pollution.

The fibers are collected after removing the nodes, weak inner portion, and/or the exoderm layer with any mechanism. The bamboo culm is composed of segments with internodes which determines the length of the fibers with natural aspect ratio between 150:1 and 250:1 [51]. The bamboo consists of around 60% cellulose which makes it preferable for fiber and higher percentage of lignin (32%) which should be removed to improve water resistance. The bamboo fibers are often brittle compared with other natural fibers since the fibers are covered with lignin. But removing these components with chemical treatment and adding softening agents can improve their flexibility. The available and biodegradable bamboo fibers' mechanical property includes high specific strength, high mechanical strength, low specific weight and high modulus of elasticity. But the properties bamboo natural fibers vary based on the growing season, age of the plant used for the fiber, geographical location of the plant source, and other environmental factors. Its extraction methods includes the steam-explosion processing, chemical processing and mechanical processing [44], [45], [52].

Table 2.2: Chemical composition of bamboo fiber [51]

S/No	Properties	Values
1	Dry tensile strength (cN/dtex)	2.33
2	Wet tensile strength (cN/dtex)	1.37
3	Dry elongation at break (%)	23.8
4	Linear density (% deviation)	1.8
5	Percentage length deviation	1.8
6	Over length staple fibres (%)	0.2
7	Whiteness (%)	69.6
8	Moisture region	13
9	Oil content	0.17

Where: cN stands for centi newton, and dtex for deci tex = 0.1 Tex

Decitex (dtex) is used to determine the linear density or fineness of fibers. It represents the weight in grams per 10,000 meters of the fiber being measured.

- **Advantages of Bamboo Fiber** [51]**:**
    - Green and eco-friendly
    - Soft & Breathable
    - Natural Anti-Bacterial Property
    - UV protection property & Biodegradable
    - Bamboo Fiber Gives Your Skin a Chance to Breathe Free

- **Applications of Bamboo Fiber:**

Common application areas of bamboo fiber include:

a. Bamboo sanitary materials: for making bandages, surgical instruments, towels, gauze masks, absorbent pads, and food packaging. Because bamboo fiber has a built-in ability to inhibit bacteria growth, completed products don't require the addition of any synthetically created antibacterial substances. As a result, bamboo fiber products won't cause skin allergies [51].

b. Bamboo clothing: It can be used to make bathing suits, mats, blankets, and towels. Bamboo fiber has a special anti-bacterial property that makes it perfect for making socks, tight-fitting t-shirts, and undergarments. Its UV-blocking properties make it ideal for use in summer clothes, especially for protecting small children and expectant mothers from the harmfuleffects of UV rays [51].

c. Series of bamboo bathrooms: Enjoys excellent moisture absorption, a soft feel, beautiful colors, and anti-bacterial properties that make them highly popular for home textiles. Bamboo bathrobes and towels feel soft and comfy in the hand and have a great ability to absorb moisture. Its built-in antibacterial function keeps bacteria at bay so that it won't stink.

d. Series of bamboo decorations: Bamboo-fiber wallpaper and curtains can absorb UV light at different wavelengths, reducing the danger to people. More importantly, dampness won't cause bamboo decor items to become moldy. Bamboo fibers can be used to make curtains, television covers, wall coverings, and sofa slipcovers.

II. Bamboo Fiber Extraction Methods

A. **Steam-explosion processing method:** to extract the fiber first the raw bamboo is cut into bamboo culms with internode length using saw machine, and put into an autoclave with over-heated steam at temperature of 175^{0}C and 0.7- 0.8 MPa pressure for an hour. Then, the steam gets released suddenly for 5 minutes and the cycles of sudden steam release continuously repeated for 8-10 times to assure the complete fracture of cell walls especially exoderm and legnin.

Finally, the fibers get washed in hot water with addition of soap at 90-95^{0}C for 15 minutes to remove ash and dried in the oven for 24 hours at 105^0C [53].

B. **Mechanical Processing**: This process can be performed with two techniques.

i. **Treating and crushing process**: the biological enzymes are used to treat the crushed or splitted bamboo. The biological process breaks the bamboo into a mushy mass to make the individual fibers easily combed out with steel comb.

ii. **Soaking and separating bamboo fibers process**: the crushed bamboo gets soaked in water for some days and gets hammered with rubber hammer by ensuring constant impact. Then the individual fibers get combed manually.

Although the mechanical extraction method is not cost effective but it is eco-friendly compared to other methods [53].

C. **Chemical Processing**: This process is basically alkalization through hydrolysis process. The crushed bamboo with crushing machine is cooked with Sodium hydroxide (NaOH) alkaline solution into regenerated desired cellulose fiber. Hydrolysis alkalization is done with carbon disulfide or other alternative chemicals combined with multi-step bleaching process. Chemical processing for fiber extraction is preferred by many manufacturers seeking to save time of bamboo fiber extraction processes [53].

Finding the right fiber material with fiber orientation for the product is always a difficult decision. There are so many materials to choose from: glass, aluminum, steel, wood, and paper to name a few. Therefore, selecting the preferable martial would require careful analysis. Bamboo fiber is an amazing material that can be used in almost any situation. With its strength and durability, this material is suitable for most type of product. Bamboo composite also has a low carbon footprint and eco-friendly.

Unidirectional, bidirectional, and multidirectional orientations are among the several fiber orientations used in fiber reinforced composites, along with random or chopped orientations. In addition to this, recently developed reinforcements inspired by nature, such as honeycomb and spider webs, are included.

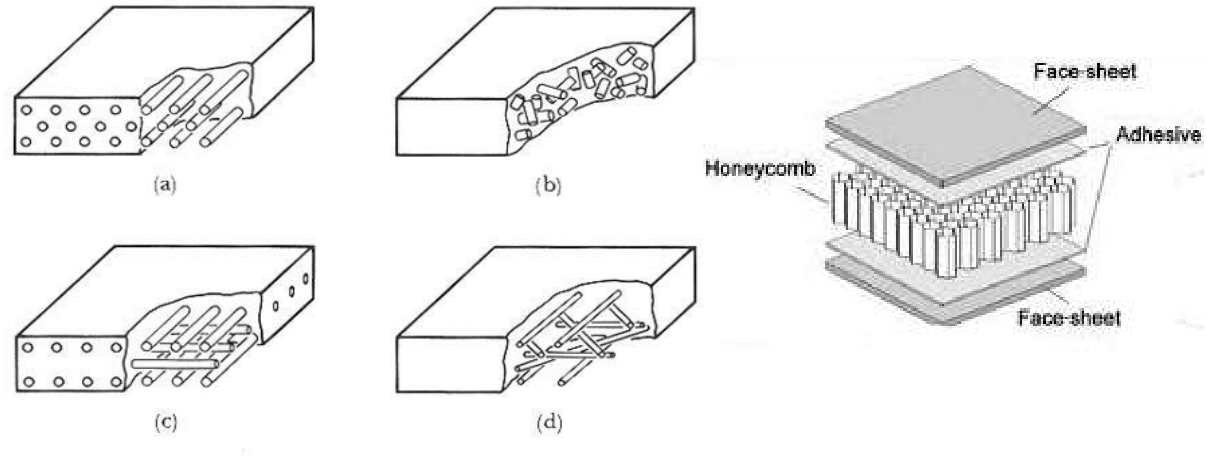


Figure 2.6: Fiber orientations for composites can be: (a) unidirectional, (b) random, (c) bidirectional, or (d) multi-directional for several planes, comparatively the honeycomb structure [37, 54]

The advantage of the fiber orientations is observed when they are fabricated based on the application requirement. Since fiber reinforced composites carry load in the fiber direction, the loading conditions for each orientation varies. Generally, the fiber reinforcements provide macroscopic stiffness and strength to the composite material. Multi directional orientation reinforced composite can carry load in more than three directions. Unlike the others, the unidirectional orientation in which all fibers run in a single and parallel direction in a flat layup with no gaps between fibers [34]. To determine the optimal fiber orientation for higher impact and bidirectional tensile loading, the fiber orientation in woven (bidirectional) and multi-directional (sandwiched honeycomb core) are optimum than the random or unidirectional orientation.

2.3: The Impact of Fiber Orientation on a Polymer Composite's Mechanical Properties

Orientations of fiber reinforcements affect the overall mechanical properties of a composite material. Nature uses and optimized fiber orientation as reinforcement in its natural structure is a way that withstands natural forces in an effective way. There are many commonly used fiber orientations in fabrication of polymer composites which can be unidirectional, bidirectional (including woven) or other nature inspired [11], [55]. In this study an inspiration for the bio inspired fiber orientation design using honeycomb orientations were considered to identify the mechanical properties for prosthetic socket structural applications.

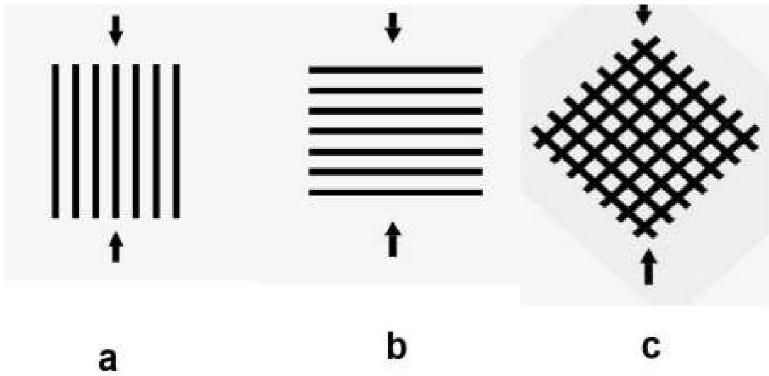


Figure 2.7: Stacking sequence and fiber loading direction (a) 0^0 (b) 90^0 (c) 45^0 [56]

2.3.1 Honeycomb Fiber Orientations

The use of honeycomb for fiber orientations in composite materials started at times when higher limitations were observed on conventional fiber orientations. It is one of the bio-inspired fiber reinforced polymer design and directly adopted from bees. An arrangement of hollow cells with columnar and hexagonal shapes that are produced between thin vertical walls is known as a honeycomb structure [57], [58].

The honeycomb structure's has empty spaces which can reduce weight while maintaining the required strength. In lightweight application areas where the structural stability of the 3D honeycomb composite has the potential to be a competitive substitute for aluminum and other metal alloys [58].

The geometry of a honeycomb cell is used in honeycomb constructions, which can be either natural or man-made, to attain the lowest weight and highest strength possible [59], [60]. The least dense material with comparatively strong compression and shear characteristics is provided by this structure. A theoretical analysis of the impact, flexural, and compression behavior of honeycomb structural composites is provided in order to comprehend the potential advantages of these materials. 3D woven honeycomb hollow structures are developed to produce lightweight, high-volume reinforcement for producing energy-absorbing structural composites [61].

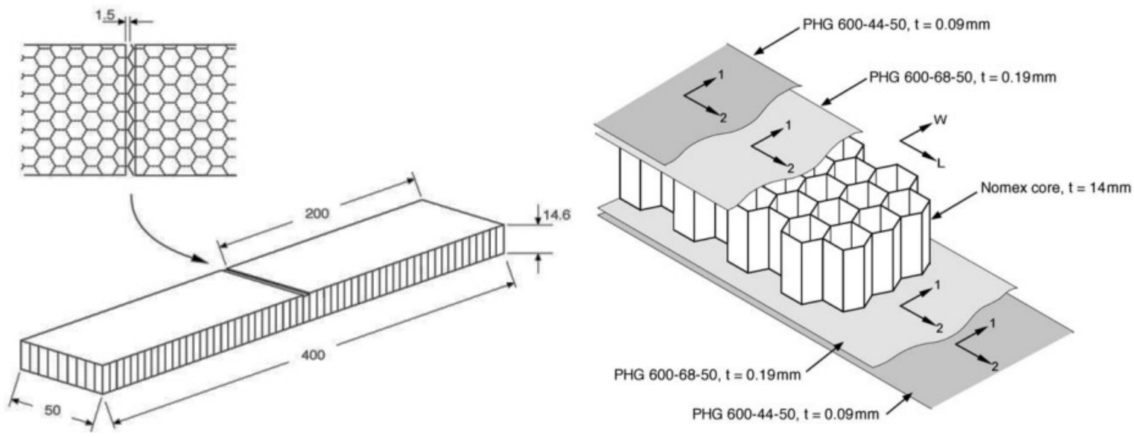
Due to their exceptional mechanical performance, honeycombs are frequently used in the aerospace industry as the core of sandwich panels and in the automotive industry as efficient impact attenuator. Several advantages of the honeycomb structure, a unique core material, include excellent fluid management, low thermal conductivity coefficients, high acoustic characteristics, outstanding mechanical capabilities, low dielectric properties, good crushing qualities, and a wide range of applications.

Honeycomb fiber orientation is the arrangement of fibers in a material such that they all point in the same direction. The parallel rows of fibers add strength to the composite material, while also providing some degree of fire resistance [62].

Honeycomb structure have been used by humans for thousands of years [63]. Honeycomb structures have mechanical qualities that are superior to most man-made fibers. Flexibility, high strength to weight ratio, non-corrosive, good stiffness, good dumping, low electric conductivity, lightweight, low cost are the main advantages of composite materials. The disadvantages of composites are long development time, low ductility, temperature limit, susceptible to moisture attack. The Greek geometers Euclid and Zenodorus [59] suggested that, effective composite materials for effective use of space and strength can be achieved with hexagon shape orientations.

Artificial honeycomb materials are made by layering materials with continuous hexagon shape between thin layers to provide strength in tension and always used were slightly curved surfaces is needed for its high specific strength. Honeycomb oriented materials in aluminum, fiber glass and other advanced composite materials are widely used in aerospace industry since 1950s [63 - 65].

Today, a variety of man-made honeycomb structures are used depending on the intended uses and necessary properties, particularly with thermosets or thermoplastics. Based on the reinforcement, the goal is to achieve low strength and stiffness with low load applications and high strength and stiffness for high performance applications. The density or quantity of the honeycomb cells used determines the composite's strength. The primary industries that make use of honeycomb composite materials include those in the aerospace, automotive, furniture, packaging, and logistics sectors.



(a) (b)

Figure 2.8: (a) The honeycomb specimen geometry and cell parameters, (b). Layup and orientation of layers of the honeycomb sandwich pane [30]

2.3.2. Woven Fiber Orientations

Woven fiber orientation is an important aspect of composite materials. For composite applications requiring more than one fiber orientation, woven fabrics can be useful. Woven fabrics are produced by the interlacing of warp (0°) fibers and weft (90°) fibers in a regular pattern or weave style. The fabric's integrity is maintained by the mechanical interlocking of the fibers. Drape (the ability of a fabric to conform to a complex surface), surface smoothness and stability of a fabric are controlled primarily by the weave style [66].

Woven orientation of bamboo fiber reinforced composites is an important factor that affects the mechanical properties and performance of the final composite product. The orientation of the fibers in the composite can be controlled by the weaving pattern used during the manufacturing process. The most common weaving patterns used for bamboo fiber reinforced composites are plain weave, twill weave, and satin weave.

- ✓ In plain weave, the fibers are woven over and under each other in a simple crisscross pattern. This pattern is easy to manufacture and results in a uniform distribution of fibers throughout the composite.
- ✓ Twill weave is a more complex pattern that results in a diagonal pattern on the surface of the composite. This pattern is stronger than plain weave and is often used in applications where strength is important [67].
- ✓ Satin weave is a more complex pattern that results in a smooth surface on the composite. This pattern is often used in applications where aesthetics are important [68].

The orientation of the fibers in the composite affects its mechanical properties such as strength, stiffness, and toughness [69].

I. Advantages of Woven Fiber Orientation:

a) **Enhanced Strength**: Woven fiber composites exhibit superior strength due to the interlocking nature of the fibers. The crisscross pattern offers high tensile and compressive strength, making them suitable for applications requiring structural integrity and load-bearing capabilities.

b) **Improved Stiffness**: The woven pattern enhances the stiffness of the composite material, providing resistance against deformation and bending. This property is particularly advantageous in industries such as aerospace and automotive, where lightweight yet rigid materials are essential for optimal performance.

c) **Damage Tolerance**: Woven fiber composites display excellent damage tolerance due to their ability to distribute stress and prevent crack propagation. The interlacing of fibers allows for energy absorption during impact events, reducing the risk of catastrophic failure.

d) **Design Flexibility**: Woven fiber orientation enables designers to tailor the mechanical properties of composites according to specific application requirements. By varying the fiber type, density, and weave pattern, it is possible to achieve desired characteristics such as strength, stiffness, and flexibility.

e) **Cost-Effective Manufacturing**: The weaving process used to create woven fiber composites is relatively simple and cost-effective compared to other techniques like filament winding or braiding. This makes it an attractive option for large-scale production, resulting in reduced manufacturing costs.

II. Disadvantages of Woven Fiber Orientation:

a. **Anisotropic Properties**: Woven fiber composites exhibit anisotropic behavior, meaning their mechanical properties vary depending on the direction of loading. This characteristic can be advantageous in some applications but may limit their use in certain situations where isotropic properties are desired.

b. **Fiber Misalignment:** During the weaving process, fibers may experience misalignment, resulting in variations in mechanical properties across the material. This can affect the overall strength and stiffness of the composite, requiring careful quality control during manufacturing.

c. **Limited Complex Shape Capability**: are primarily suited for flat or moderately curved structures due to the inherent limitations of the weaving process. Creating complex shapes with intricate geometries may be challenging and may require additional manufacturing steps or alternative techniques.

III. Manufacturing Process of Woven fiber composites:

The manufacturing process of woven fiber composites involves several steps:

Step 1: Fiber Selection

The choice of fiber material is critical and depends on the desired mechanical properties and application requirements. Commonly used fibers include carbon fiber, glass fiber, aramid fiber, and natural fibers like flax or hemp.

Step 2: Weaving

The selected fibers are woven together using specialized looms, following a specific pattern such as plain, twill, satin, or complex weaves. The weaving process interlaces the fibers in a crisscross manner, creating a fabric-like structure.

Step 3: Impregnation

Once the woven fabric is formed, it is impregnated with a matrix material, typically a polymer resin such as epoxy, polyester, or vinyl ester. This impregnation step ensures that the fibers are thoroughly wetted and bonded to the matrix, providing strength and stiffness.

Step 4: Curing

The impregnated fabric is then subjected to a curing process, where heat and pressure are applied to initiate a chemical reaction in the resin. This reaction leads to the hardening of the resin, resulting in a solid composite structure.

Step 5: Finishing

After curing, the composite material may undergo additional finishing processes such as trimming, sanding, or coating to achieve the desired dimensions, surface quality, and aesthetics.

IV. Application Areas of Woven Fiber Composites:

Woven fiber orientation finds application in various industries, including:

- **Aerospace:** are extensively used in aerospace applications, such as aircraft structures, interior components, and engine parts. The high strength-to-weight ratio and excellent damage tolerance make them ideal for reducing weight while maintaining structural integrity.

- **Automotive**: woven fiber composites are employed in body panels, chassis components, and interior parts of the automobiles. The lightweight nature of these materials contributes to fuel efficiency, while their strength enhances safety and crash resistance.
- **Sports and Recreation**: Woven fiber composites are widely used in sporting goods like tennis rackets, golf clubs, bicycles, and helmets. These materials offer improved performance characteristics, such as increased power transmission, reduced weight, and enhanced impact resistance.
- **Construction**: applications in the construction industry for structural elements, reinforcement of concrete structures, and seismic retrofitting. Their high strength and stiffness properties contribute to improved durability and load-bearing capabilities.

2.4. Fiber Orientation Selection for Prosthetic Leg

The reason behind the selection of honeycomb pattern orientation is the inspiration of using the nature- based honeycomb pattern for structural applications in this case the prosthetic leg. This is due to the contribution of the honeycomb pattern in improving the mechanical properties such as impact and compressive loading while reducing the possibility of buckling [70], [71].

In medical area, the bidirectional (woven) and multidirectional (honeycomb and spider web pattern) orientations are used to fabricate prosthetic materials to replace damaged parts [66], [70]. This is because to their low weight, ability to withstand corrosion, and body-compatibility. Drug-eluting medical textiles with the aforementioned fiber orientations are preferred when the fibers are natural, like bamboo.

The honeycomb fiber orientation is a preferable option for prosthetic leg applications because it offers higher stiffness, superior flexural qualities, increased energy absorption, increased load carrying capacity, and improved aerodynamic behavior. Presently in use materials for prosthetic socket results lower compressive and impact qualities, more expensive, heavier, and often buckle. Because some sections are not as compatible as the rest of the body which may result discomfort and pain around the affected area [22], [71]. Therefore, the constraints of the currently employed composites will be solved by employing bamboo fiber in a honeycomb pattern fiber orientation. Bamboo fiber reinforced composite ensures a better degree of compatibility, good mechanical qualities, and lightweight. Bamboo fibers are a protein-based material produced under mild conditions through an intricate hierarchical process.

2.5. Related Research Works on Applying Polymer Composites for Prosthetic Socket

The polymer composite is getting for to be used for various structural and non-structural applications due to their promising properties. Due to this, many researchers conducted studies on domesticating these material types for prosthetic applications. To put a contribution, some open literature was reviewed with clarification on their limitations.

Composite materials are commonly used in manufacturing devices such as prosthetic devices and aerospaceparts [16, 27, 71, 72, 73]. They are used to make composite structures with high strength and low weight.

A composite sheet or panel is made up of a matrix of fiber material and filler. The matrix can be a thermoplastic, thermoset, thermally curable, or thermomechanical elastomer. Composite panels are usually used for making composite parts such as aircraft wings, fuselage, and structures. For example, composite panels can contain a fiberglass matrix and an epoxy resin as an adhesive. Such composites are often used where weight reduction is desired. Typical compositing processes include filament winding, compression molding, injection mold, fiber-in-plastic composite and fiber reinforced composite. [74]

There is also a gap to make the failure of one fiber will not challenge the life of other fibers in the pattern.

The tensile and flexural properties of four stacking E-glass/ Carbon fibers hybrid epoxy composite sequences for prosthetic application were characterized by [75] with ANSYS finite element software. The authors employed a computational solution with additional MATLAB verification to choose the most cost-effective stacking sequence. But the mechanical properties determined from the finite element analysis were not compared with experimental analysis. Therefore, the study lacks to determine and indicate actual properties considering the situations such as composite fabrication and testing conditions.

As indicated by [18] there are different possible materials that could provide amputees with a replacement for restoring some functions although they are not multifunctional as natural one. This means the materials only impart some improving level of patient's performance. The authors subjected that selecting a device for prosthetic feet requires much care to match the natural human feet characteristics. All physical and mechanical tests conducted were indicated from which the foot's design and composite manufacturing process. Beside this, the researchers tried to indicate how much the composite adjustment in terms of fiber, type of mixture and mass fraction of constituents affect the properties for a better prosthesis design.

Natural fibers of sisal and cotton were used to develop a prosthetic socket material by [76] for sake of substituting existing material using vacuum bagging fabrication technique. The finite element software ANSYS was employed to show the safety factor contour distribution, stress, strain and deformation of the prosthetic socket when loaded to its maximum possible load. Unlike other papers the authors tried the possibility of natural cotton fiber hybridized with others for the prosthetic application.

These composite materials have better electrical, mechanical, thermal, chemical, physical and other properties and are easily manufactured and easily accessible. The development of the composite industry brought, the requirements of the materials and processes have been increased to meet the needs of larger scale production and the increase in the number of composite applications [15], [16], [19], [20], [27], [74]. A portion of this can be attributed to the growing acceptance of lightweight composite parts. In order to improve manufacturing efficiency and lower production costs, it is necessary to minimize the weight and size of equipment used in the fabrication of these composite materials. However, controlling the characteristics of the materials utilized is critical part. Weight, stiffness, strength, ductility, impact resistance, transparency, color, and other characteristics are crucial for the manufacture of different parts and composite products.

Carbon fibers are extremely stiff, strong, light weight materials that can be used in many processes to create excellent structural products. Oscar Pistorius, formerly known as "Blade Runner," was the first person with double-leg amputees to compete in a summer Olympic Games in 2012. The advent of 3D printing has also ushered in a new era of collaborative design [14].

Figure 2.9: Oscar Pistorius huge carbon footprint [75]

Losing a limb is still a serious problem, but thanks to technological solutions, people can now live regular lives like never before. A few of the advancements produced during the Industrial Revolution include non-locking below-knee prostheses, the "Anglesey leg" supported by catgut tendons, limb-conserving operations, and the use of lighter materials like aluminum instead of steel.

Taylor's data suggest that the results might have been greatly impacted by this difference in orientation [13]. In the case of normal fibers, in addition to being parallel, these angles are all close to 180° because the normal orientation has a very low ratio.

A prosthetic socket refers to the component of an artificial limb that covers an amputee's residual limb (the part of their body from which they lost their arm or leg). Prosthesesproperty must incorporate comfortable to wear, easy to put on and take off, durable, lightweight, well-functioning, and require proper maintenance [33]. Smit.et.al. introduced the concepts of either reducing the strain softening or increasing the strain hardening to improve toughness of the material [76]. There are several types of materials which are used in the production of prosthetics. One of the important types is the elastomeric materials used for hip joints andother orthopedic implants.

The first prosthetic was used in ancient Egypt in 15th BC for the fabrication of big toe prosthetic. It is a big toe prosthetic made of car tonnage a material made of layers of papyrus covered in plaster and it is strapped onto the foot in a fashion similar to an Egyptian sandal [77].

Figure 2.10: Ancient Egypt prosthetic toe [77]

For the construction of many orthodontic appliances and orthoses, a composite that is composed of polymethyl methacrylate, nylon, andpolyethylene is used. This type of material gives the patient much better results. Another material used is silicone rubber. It is made from polydimethylsiloxane and is widely used as a dental material. In order to emulate the design operation as traditionally made by orthopedic technicians who use their hands to shape the socket [10].

2.6. Mobility and kinematic of prosthetic leg

Haohua Xiu proposed the schematic design of 2 DOF which have 1.05 kg weight and it also have a height from the bottom of female adapter 157mm and top of the male adapter have 93mm. This paper presents compliant passive ankle–foot prosthesis (CPAF) capable of 2-DOF rotation during locomotion. The CPAF uses a 2-DOF parallel mechanism to support the bodyweight and offer limited rotation during movement, and it incorporates a compliant component to facilitate and generate torque to conform to uneven terrains.

The kinematics of the parallel mechanism, including the workspace and singularities was investigated. Then, a prototype was developed, and the performance evaluations showed that sufficient torque could be generated with an appropriate range of motion for the ankle [78].

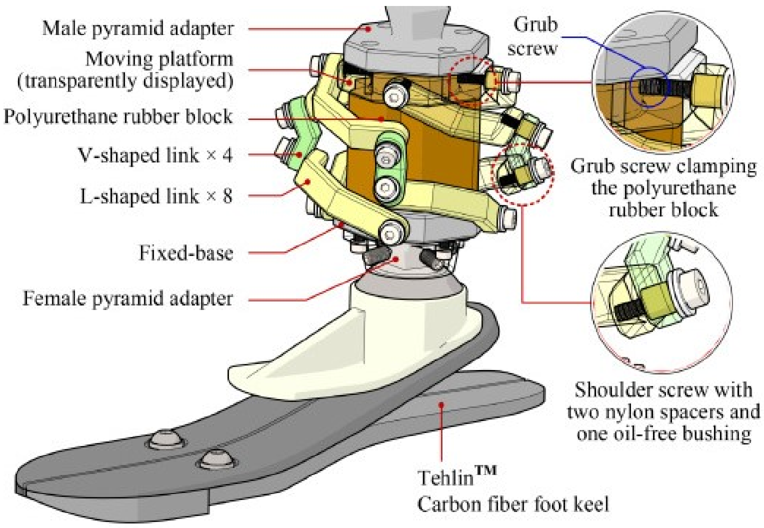


Figure 2.11: The schematic design of ankle –foot prosthetic [78]

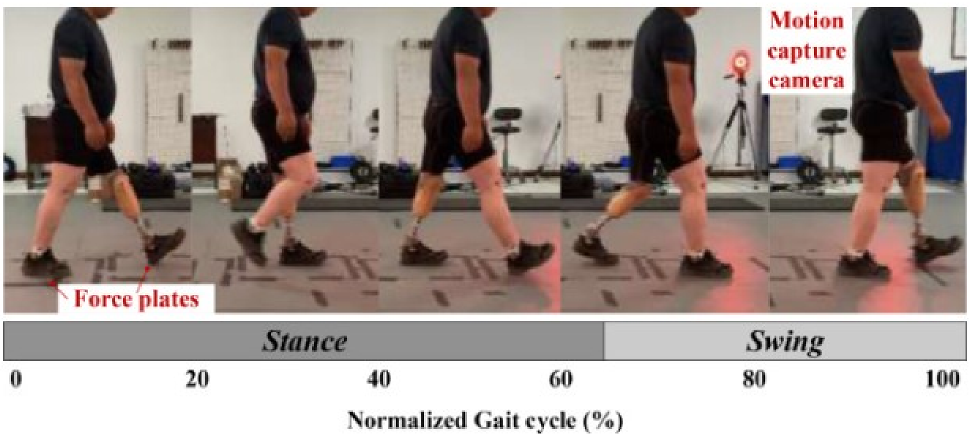


Figure 2.12: Level ground walk test by an amputee wearing 2 DOF [78]

An amputee testing the proposed 2-DOF CPAF on level ground sing a motion capture system and force-plate system, the kinematics was measured. From heel strike (HS) to HS of one leg, along with the stance and swing phases of both legs make up an intact limb gait cycle. A simple gait cycle divides the movements into periods when the foot is on the ground (the stance phase), which accounts for 62% of the entire gait cycle, and periods when the foot is off the ground (38% of one full gait).

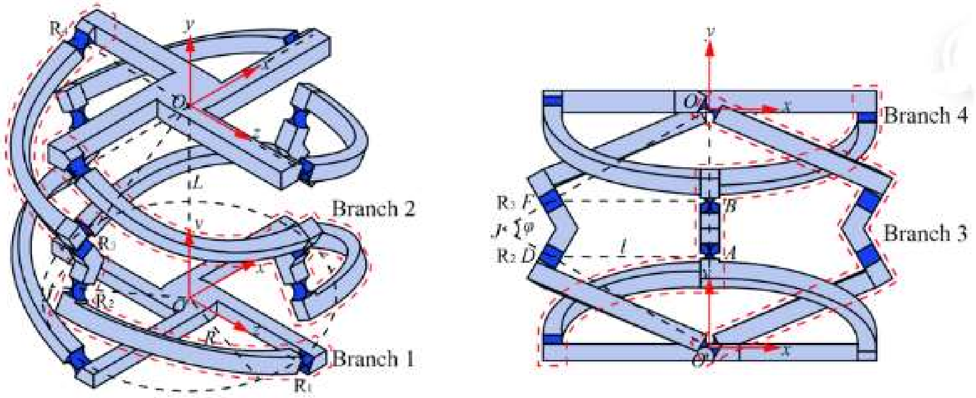


Figure 2.13: structural parameter of 4-4R compliant parallel point mechanism [79]

From different papers, the above points can be summarized as:

- Powered prosthetic legs can improve the quality of life for individuals with transfemoral amputations.
- Controllers for prosthetic legs currently use finite state machines (FSMs), which limit their use to predefined tasks.
- A continuous parameterization of joint kinematics over walking speeds and inclines provides more accurate predictions of reference kinematics than an FSM.
- Speed, incline, and phase measurements are essential inputs for accurate predictions.
- Errors in speed, incline, and phase measurements, as well as model fitting and subject-specific differences, contribute to the overall prediction accuracy.
- The continuous parameterization method provides statistically significantly better predictions than an FSM.
- Subject individuality is the most critical factor in determining predictive accuracy.
- Future work could focus on individualizing kinematics for each user to further improve accuracy.
- Other potential future work includes modeling other ambulation modes and utilizing expert clinical tuning and task propagation to improve gait performance.

2.7. Identified Research Gaps

Based on the open literature, natural fibers reinforced composite materials are becoming favorable for structural application although some drawbacks due to high water absorption, mechanical property variation based on harvesting season, age and growing area geography.

The gaps identified for the review on prosthetic socket are:

- ✓ Many researchers who work on prosthetic socket give least attention for compatibility of the selected material with natural body beside the better requirement of mechanical properties.
- ✓ Although many natural fiber-based composites are developed for prosthetic application, the development of Bamboo/epoxy composite with honeycomb fiber orientation is not observed on the open literature.
- ✓ Insignificant number of researches on the nature inspired fiber orientation composites
- ✓ Wide room of polymer composite preparation just varying fabrication technique, fiber-matrix percentages and developing effective fiber orientations.
- ✓ Less attention should be given to the consecutive comparison of effective property testing machines with numerical results

CHAPTER THREE

Research Methods and Materials

3.1 Methodology

To perform the research work, procedures were followed starting with surveying open literature to conclusion and recommendations based on results gained through whole study.

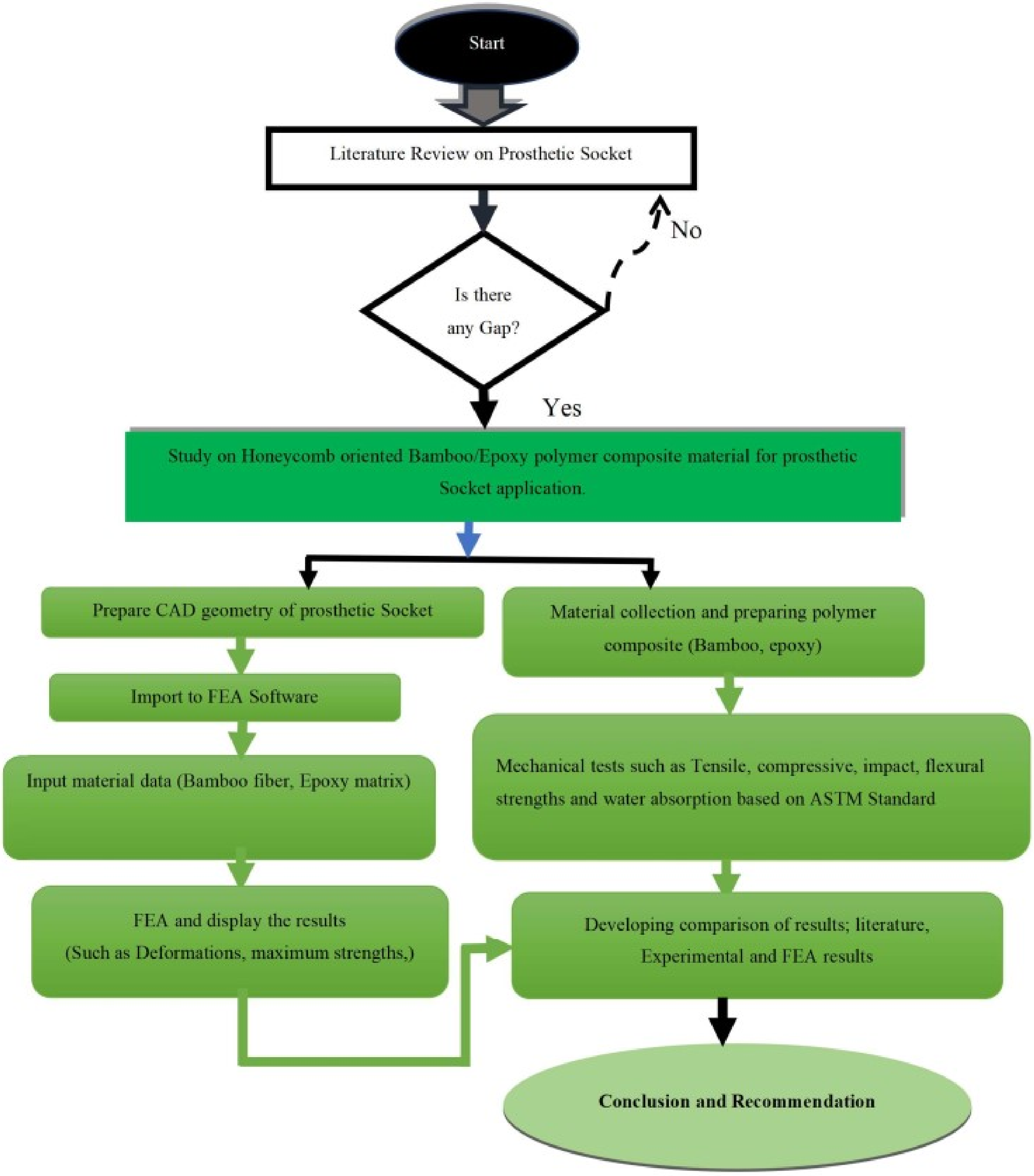


Figure 3.1 Methodology of the study

As indicated in figure 3.1 different methods of analysis and data collection were used to approach the solution for the identified problem.

Reviewing Literature include gathering and reviewing many articles, journals, and books on composites, natural fibers, hybrid fibers, prostheses, and prosthetic socket in order to have a better grasp of the problem and possible solutions for achieving the research's goal. Fiber matrix composition is designed based on literature, and the best fiber matrix composition is chosen. In addition, the fiber-fiber loading is investigated and chosen.

Next modeling of the prosthetic socket is worked. The solid works 2021 used to model the prosthetic socket. After modeling the prosthetic socket, the bamboo fiber and epoxy material is collected and prepare the mold for making honeycomb fiber orientation of prosthetic socket. By exporting the prosthetic socket design model to the FEA software, the simulation and numerical analysis of the prosthetic socket is prepared. Which is numerically examined using the ANSYS 2023 workbench program. The composition with the best attributes among the research is chosen. The findings of the Numerical test, as well as prosthetic socket loads collected from the literature, were inserted into the ANSYS software andanalyzed to determine deformation and von-misses stress. After that, prepare the samples for testing compressive strength, flexural strength, impact strength, tensile strength and water absorption using the hand lay-up technique. Finally, the comparison of the mechanical test results and Ansys software analysis result with the earlier prosthetic socket material results.

3.2 Materials Used

3.2.1 Fiber Material

Under this study the bamboo fiber collected from local farmers and extracted manually were used to prepare the honeycomb-oriented reinforcement. The matrix utilized to develop the composite material was epoxy purchased from local market.

Bamboo Fiber

The growing interest in bamboo fibers is due to their anatomical properties, ultra-structure and plant fracture mechanism, allowing bamboo fibers to provide higher specific strength and stiffness in plastic materials compared to other known natural fibers like jute, coir, sisal, straw and banana. Both in Ethiopia and throughout the world, bamboo is a naturally occurring resource that is widely accessible. The largest bamboo forest on the African continent, according to estimates, can be found in Ethiopia. Although bamboo has a diverse resource base and is used in advanced ways on a worldwide scale, Ethiopia has not yet taken use of its enormous potential to boost socioeconomic and ecological development.

Bamboo shows the mechanical properties which are analogous to that of wood. Bamboo shows better mechanical properties as compared to fibers such as sisal, banana, coir etc. Different forms of bamboo can be utilized to create composite products. These come in a variety of shapes, including whole bamboo, small bamboo fibers, long strips, and sections.

Depending on the age, height, season, species and layer, the chemical composition of bamboo varies and also aging of a bamboo culm influences physical, chemical, and mechanical properties, and consequently its processing and utilization. Such variation can lead to physical and mechanical properties changes during the growth and maturation of bamboo which brings variability in its characterization for fiber reinforced materials. On this research work a bamboo culm collected from **Ambo** with three years old highland bamboo (Yushania Alpina) species plant was used.

Figure 3.2: Bamboo species used for the research

Extraction of Bamboo fiber

The highland bamboo collected was cut on its nodes where discontinuity of fiber is observed in order to extract the long fibers. The culms were splitted into smaller sections with a splitter machine after applying load on the one end forcing to pass through the specified cross-sections which is mechanical extraction. Then the bamboo strips were soaked in water for one day to facilitate the extraction of individual fibers. A rubber made hammer was used to soften the strips and finally combed with a metal comb. The individual fibers collected were then treated with chemical to reduce the water absorption properties and ensure fiber-matrix adhesion.

Figure 3.3: Extracted bamboo fibers manually

Bamboo fiber treatment

After extraction of the bamboo fiber with desired thickness and length, Sodium hydroxide (NaOH) also known as lye, caustic soda and sodium hydrate which is a caustic metallic base was used for the surface treatment. When caustic soda is dissolved in a solvent like water, a strong alkaline solution is created. The white solid form of pure sodium hydroxide employed in this study comes as pellets, flakes, granules, and a 50% saturated solution. It should be kept in an airtight container because it is deliquescent and easily absorbs carbon dioxide from the atmosphere. With the release of heat, it is highly soluble in water. Although its solubility is decreased in ethanol and methanol, it can also dissolve in both of these. Although molten sodium hydroxide has qualities that are comparable to those of the other forms, its high temperature often restricts its use. In this work, NaOH pellet purchased from local market named atomic educational materials supplier. The bamboo fibers were soaked in 5% alkaline solution for five hours to modify the fiber surface based on previous researches.

Figure 3.4: Bamboo fiber alkaline treatment

3.2.2 Matrix Material

Resins are of at most importance within the composite markets since they bind the fibers together and help to create the material's strength and stiffness characteristics. Matrix materials as being found in different types, polymer matrices are dominantly used due to their cost efficiency, ease of fabricating complex parts with less tooling cost and they also have excellent room temperature properties. The matrix dominates the composite's shape, surface appearance, environmental tolerance, and overall durability. Many materials when they are in a fibrous form exhibit very good strength property but to achieve these distributed properties the fibers should be bonded by a suitable matrix. The matrix serves as a bridge to hold the fibers in place and isolates them from one another to avoid abrasion and the development of new surface defects. A good matrix should be able to quickly deform when under load, transfer the load to the fibers, and concentrate stress uniformly.

There are two types of resin systems: thermoset and thermoplastic. In a thermoset, the resin molecules are locked together in an irreversible way after a thermal cure.
In a thermoplastic resin the chemical link which is bonding the molecules together can be broken again and again by increasing the temperature steadily which causes the matrix to go from solid to liquid. In the same way, when cooled down the thermoplastic matrix solidifies. Thermoset resins that are playing a key role in the composite industry include Polyester, Vinyl Ester, Epoxy, and Phenolic Resin. Among them, the epoxy resins are being extensively used for many advanced composites due to their good performance at elevated temperatures, outstanding adhesion to wide variety of fibers, superior mechanical and electrical properties etc. In addition, they have low shrinkage upon curing and good chemical resistance. Epoxy (LY 556) is chosen as a matrix material for the present research work.

Polyester

Polyester resins are one of the most common resins used in the composite industry. The success of Polyester is mainly based on the low cost that makes it more attractive than some higher performing resins like epoxies. Polyester resins require a catalyzer or hardener, which functions as an initiator of the chemical reaction to solidify and cure. The quantity of catalyzer has an effect on the speed of the reaction and is responsible for the solidification. During the curing, the polyester resins shrink significantly.

Polyester resins have numerous advantages over other resins.

- The most well-known benefit of polyester is the price; the resin is relatively cheap in comparison to other types of resin.
- Polyester has the ability to accept a broad variety of fillers which makes them applicable to a wide range of projects.
- Polyester is demolded and the part can be sanded and finished resulting in an optically clear surface.
- Polyester is not impacted by UV radiation like other resins which is essentials for applications exposed to the sun.

Epoxy

Previously it was mentioned that matrix determines the working conditions of the composite. Among many thermoset polymer matrices, Epoxy resins are the most commonly used. This is because; they have excellent adhesion, good performance at elevated temperature, better mechanical and electrical properties, low shrinkage, great working time, good chemical resistance, good corrosion resistance, cost efficiency, low viscosity, long pot life at room temperature and ease of fabrication. In this thesis, epoxy resin which is LY556 purchased from local market was used.

Table 3.1 Epoxy matrix general properties

Description	Specifications
Epoxy Resin	LY556
Model	Herebna
Color	Clear
Viscosity @25^{0}C	10,000 – 12000 Mpa
Density @25^{0}C	1.10-1.2g/cm^3
Flash Point	>200^{0}C
Curing Time	10-20min
Shelf Time	2 Years

Hardener

In order to ensure effectiveness of the resin, adding a catalyst is needed to facilitate curing. The catalyst cures the resin by initiating chemical reaction and changes it from liquid to solid. To obtain better mechanical properties appropriate amount of hardener should be used.

The hardener catalyst used for this study was HY951 that is purchased from local market.

3.3 Composite preparation

3.3.1 Preparation of honeycomb fiber orientation

Firstly, the honey comb orientation is prepared on a flat plate using 1.5mm diameter nails to guide the fibers. Then the fibers were soaked in alkaline solution to get softened and become flexible. Next the fibers were arranged on the honey-comb oriented structure prepared by the nails to fabricate the ply orientation. The composite can be prepared by the hand lying composite manufacturing method. The specimen preparations are based on ASTM standards for the intended mechanical tests such as compressive, tensile, impact and flexural test. Based on the Mechanical properties of each constituent of the composite mixture for composite preparation were designed. The Epoxy resin LY556 can mixed with Hardener HY 951 with 100:10 mix ratio were stirred with a bowl thoroughly until fully mix gained and roller brush was used to avoid air bubbles. The types of composite mechanical characteristics are influenced by the volume fraction of fibers, their orientation, and the strength of the link between the fibers and matrix.

.

Figure 3.5: Honeycomb preparation

3.3.1 Preparation of woven fiber orientation

To achieve a woven fiber orientation, the following steps are taken:

1. **Preparation of the Woven Structure**: A flat plate is used as a base, and managing the distance and distribution of bamboo fiber. This creates a framework for the woven structure.

2. **Fiber Treatment**: The fibers are soaked in an alkaline solution to soften and increase flexibility, making them more manageable during the weaving process.

3. **Weaving Process**: The softened fibers are then carefully arranged and woven together on the framework created by the wood box. This process ensures the desired woven fiber orientation in the composite material.

4. **Application and Air Bubble Prevention**: During the application of the composite mixture, a roller brush is used to ensure an even distribution of the mixture and to minimize the formation of air bubbles.

5. **Composite Manufacturing**: The composite material can be prepared using the hand laying composite manufacturing method, where the woven fiber structure is combined with the matrix material.

6. **Specimen Preparation**: The specimen preparations adhere to the relevant ASTM standards for mechanical testing, such as compressive, tensile, impact, and flexural tests. This ensures consistency and comparability of results.

3.3.2 Preparation of Mold and Fabrication

The mold to fabricate the bamboo fiber-based honey-comb oriented polymer composite was prepared in open type with dimensions of 50cm square shape to hold the laminate with 30x30cm cross-section. Same to this cover plate were also prepared on which the pressing load of curing and binding were applied. Total of 200Kg load were applied to compress the five-layer honey-comb oriented bamboo/epoxy composite to ensure compact structure with 5mm overall thickness, remove excess resin, and void formation due to air gaps at the inter-phase level.

The surface of the mold plates was cleaned to remove dust and lubricated with wax material to eliminate the adhesion between the composite and plates. Then the epoxy resin and hardener were mixed with 100:10 to facilitate the curing of the composite.

Next the matrix was applied to the mold surface followed by fiber ply configuration step by step for five plies. Finally, the composition was covered with the cover plate and a load around 200 Kg were applied on the surface for 24 hours to cure at room temperature.

Figure 3.6 mold preparation

Figure 3.7: Honeycomb-oriented bamboo fiber with epoxy composite preparation

3.3.3. Lamina preparation for single ply

The preparation single ply needed to cover sufficient dimension for all specimens. The effective area of the ply given by drawing of all test specimens are used in test orientation. Compound specimen prepared in the moulding section should be cooked efficiently to minimize energy utilization.

Figure 3.8 Single ply preparations

3.3.4 Methods of Design of Experiment

The sample to be fabricated was prepared based on the number of the specimens for each test and the composition was based on the higher property achievement for previous studies. Then the prepared polymer composite samples were cut to the size requirement based on the predetermined data.

3.3.4.1. Rule of Mixture

The most accurate method for calculating a unidirectional composite's elastic characteristics is the rule of mixture. A weight proportion of 35 % exists in the unidirectional bamboo epoxy composite when mechanical bamboo fiber extraction is followed by manual fiber extraction. The multi-directional fiber-reinforced composite can be identified from the unidirectional evaluation.

According to the rule of mixtures, the elastic modulus of a composite is proportional to the fiber volume fraction and the fiber to matrix module ratio. The fiber to matrix module ratio is the ratio of the elastic modulus of the fiber to the elastic modulus of the matrix. A high fiber to matrix module ratio means that the fiber is much stiffer than the matrix, which can also enhance the mechanical properties of the composite.

Therefore, using 65/35 fiber to matrix ratio for composite materials can result in a high fiber volume fraction and a high fiber to matrix module ratio, which can make the composite more resistant to deformation and failure under external loads [80]. Therefore, the optimal fiber to matrix ratio for a composite material depends on the specific application and performance requirements.

$$Mb = \frac{mass\ of\ Bamboo\ fibers}{Total\ mass} \quad (1)$$

$$Me = \frac{Mass\ of\ epoxy\ matrix}{Total\ mass} \quad (2)$$

$$vb = \frac{Volume\ of\ bamboo\ fiber}{Total\ volume} \quad (3)$$

$$v_e = \frac{Volume\ of\ epoxy\ matrix}{Total\ volume} \quad (4)$$

Where: M_b = Bamboo Fiber mass fraction, M_e= Epoxy Matrix mass fraction, v_b = Bamboo Fiber volume fraction, and v_e = Epoxy Matrix volume fraction

Note that mass fraction can be obtained from volume fraction (eq.1 and eq.3):

$$v_b = \frac{\frac{M_b}{\rho_b}}{\frac{M_b}{\rho_b} + \frac{M_e}{\rho_e}}$$

$$M_b = \frac{\rho_b v_b}{\rho_b v_b + \rho_e v_e}$$

$$v_b + v_e + v_p = 1$$

The density of the lamina (ply) defined as:

$$\rho_c = \rho_b v_b + \rho_e v_e \quad (5)$$

The length of the necessary specimens, the thickness of the plies, the number of plies, and the volume of a single ply can all be used to define the volume of the honeycomb-oriented fiber ply. Therefore, the volume of a single hexagon honey comb ply is:

$$V_{hp} = 3\sqrt{3}a^2\ h/2 \quad (6)$$

Where V_{hp} =is the volume of a single hexagon ply, a=the length of a single honey comb structure and h=thickness of a single ply

The volume of the composite is defined by the diameter of the composite and the depth (thickness) of the composite given by the equation below

$$Vc = Vhp * Th \quad (7)$$

Where *VC is volume of the composite*, and *Th is the total number of honeycomb hexagons in the ply of the composite*

The volume of the composite also calculated from rule of mixture:

$$Vc = Ve + Vb \quad (8)$$

Where: V_c is volume of the composite, V_e is volume of matrix, and V_b is volume of bamboo fiber

$$Vm = Vep + Vh \quad (9)$$

Where *V_{ep} is volume of epoxy and V_h is Volume of Hardener (the curing agent)*

The low temperature curing agent (HY951) mixed with the corresponding epoxy resin in the ratio of 1:10 by weight. The mixing was done thoroughly and then the fiber mats were reinforced in the matrix body.

3.4 Procedures and experimental design Conditions

According to the methodology all possible procedures for the experiments were followed in order to gather the mechanical properties for the honey-comb oriented polymer composite material for prosthetic application. The procedure followed was the material collection, composite preparation and finally test sample preparation and then followed to experimental procedures. The experimental tests was performed on universal testing machines according to ASTM standards for tensile, compressive and flexural tests, while the impact test was performed using computer controlled charpy impact testing machine. Based on the experimental results the modeling and Simulations was performed using high performance computers on the specified analysis software.

3.4.1. Lamina and Laminate Design Theoretical Analysis

Lamina is a single layer or plate that can be laminated by stacking it up and placing it in the right order. Lamina, in general, is a thin layer of a composite material with a thickness of around 0.125 mm. By stacking several of this lamina in the direction of the lamina thickness, a laminate is created. Using a hand layup process, bamboo fibers with a honeycomb orientation were woven in a 350 mm-long mold formed from a square cage frame. .

Laminate: - is layered composite with an assembly of plies bonded together in the plane normal to the principal direction

Lamina: - is a single ply panel used as a building block of laminate with the thickness less than 0.5mm and stacked together in thickness direction to produce a laminate.

The low temperature curing agent **(HY951)** mixed with the corresponding epoxy resin in the ratio of 1:10 by weight. The mixing was done thoroughly and then the fiber mats were reinforced in the matrix body [21]. The mix ratio was 20 mL of hardener for 1 kg of resin. TTe weight fraction of 40% and Volume fraction 35% of bamboo fiber was taken from the unidirectional bamboo epoxy composite [2].

$Density\ of\ bamboo,\ \rho_b = 0.974\ g/cm^3$

$Density\ of\ epoxy, \rho_{ep} = 1.17\ g/cm^3$

$Density\ of\ hardener, \rho_h = 1.1\ g/cm^3$

Volume fraction of bamboo (v_f) =0.35

$$Vb + ve = 1$$

Volume fraction of matrix (ve) =0.65

Weight fraction of bamboo (Wb) =0.40

$$Vb = VC * vb$$

Where *Vb is Volume of fiber, vb is volume fraction of fiber and Vc is volume of composite*

$$(Ve) = Ve \times ve \qquad (10)$$

$$Mb = \rho bVb \qquad (11)$$

$$Me = \rho e \times Ve \qquad (12)$$

$$Mc = Me + Mb \qquad (13)$$

$$\rho c = \rho_b v_b + \rho_e \qquad (14)$$

Where: Ve is for volume of matrix, Mb is for mass of fiber, Me for mass of matrix, Mc for mass of composite, and ρ_c for density of the composite.

The stressed applied to the composite is shared by both the fiber and the matrix proportionally according to the constituency.

The average strain in the composite is the same in the longitudinal direction:

$$E1 = Ee\varphi e + Eb\varphi b \qquad (15)$$

The Elastic modulus of treated Bamboo fiber can be taken as 23 GPa and the modulus for the pure epoxy resin LY556 measured to be 3.81GPa from [46] , from this E1 becomes 10 GPa

The major Poisson's Ratio:

$$v12 = Vb\varphi b + Ve\varphi b \qquad (16)$$

Composite property in Transverse direction:

$$\frac{1}{E2} = \frac{\varphi b}{Eb} + \frac{\varphi e}{Ee}$$

$$E2 = \frac{EbEe}{Ee\varphi f + Eb\varphi me} \quad (17)$$

The miner Poisson's Ratio:

$$\frac{v21}{E2} = \frac{v12}{E1}$$

$$v21 = v12\frac{E2}{E1} \quad (18)$$

Shear Modulus:

$$G = \frac{E}{2(1+v)}$$

$$Gf = \frac{Ef}{2(1+vf)}$$

$$Gm = \frac{Em}{2(1+vm)}$$

$$G12 = \frac{GfGm}{Gf\varphi m + Gm\varphi f} \quad (19)$$

In orthotropic lamina based on material symmetries mechanical properties of a composite can be related by:

$$\frac{v12}{E1} = \frac{v21}{E2}, \frac{v13}{E1} = \frac{v31}{E3} \, and \, \frac{v23}{E2} = \frac{v32}{E3} \quad (20)$$

The lamina properties **E1, E2, E3, G12, G13, G23, v12, v21, v23**, can be found using appropriate experimental test. The longitudinal and transverse characteristics of the tested lamina can be transformed to determine the shear modulus.an orthotropic fiber reinforced composite has five independent elastic constants these are:

E1, E2=E3, v12=v13, v23=v32, G12=G13, G2. According to the given scientific formulations results are calculated empirically using the relations below:

- Vc=612.5 cm3(Volume of composite)
- Vb=215.6 cm3 (Volume of fiber)
- Ve=396.9 cm3 (Volume of matrix)
- E1 = 10 GPa (Young's modulus along grain)
- E2 = 10 GPa (Young's modulus perpendicular to grain)
- E3 = 1 GPa (Young's modulus in radial direction)
- v12 = 0.2 (Poisson's ratio)
- v13 = 0.2 (Poisson's ratio)
- v23 = 0.4 (Poisson's ratio)
- G12 = 1 GPa (Shear modulus)
- G13 = 0.5 GPa (Shear modulus)

- G23 = 0.5 GPa (Shear modulus)

3.5 Preparation of Test Specimens and Testing Procedures

3.5.1. Preparation of Test Specimens

The specimens for physical and mechanical tests are prepared based ASTM standard for testing. The specimens were prepared for tensile test, flexural test, impact test and water absorption test.

A Jig Saw cutting machine was utilized to cut the test specimens for the mechanical test according to Code of standard (ASTM D638 for tensile, ASTM D790 for flexural, ASTM D3410 for compressive, ASTM D256 for Charpy impact and ASTM D570 for water absorption) from the composite sample with five layers. The dimensions for each specimen are listed in the figure below.

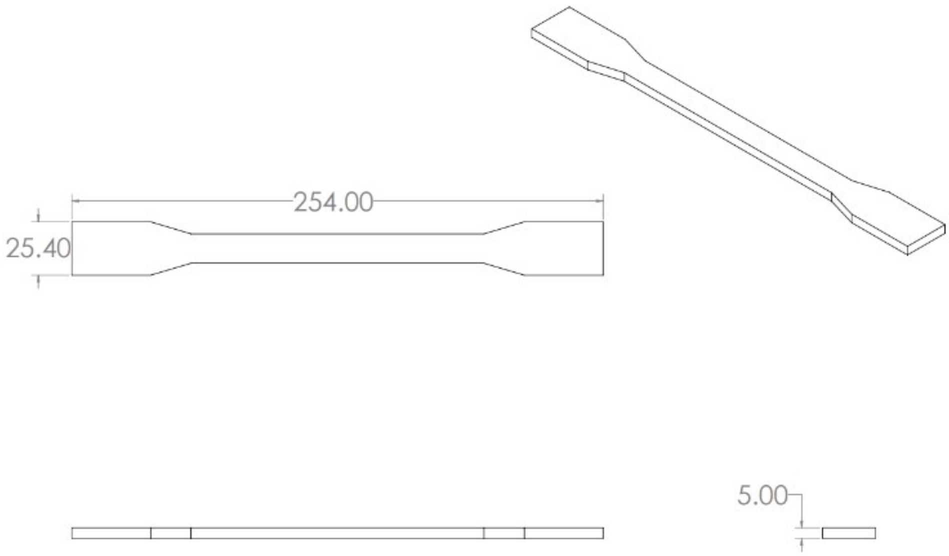


Figure 3.9: Tensile Test Specimen [81]

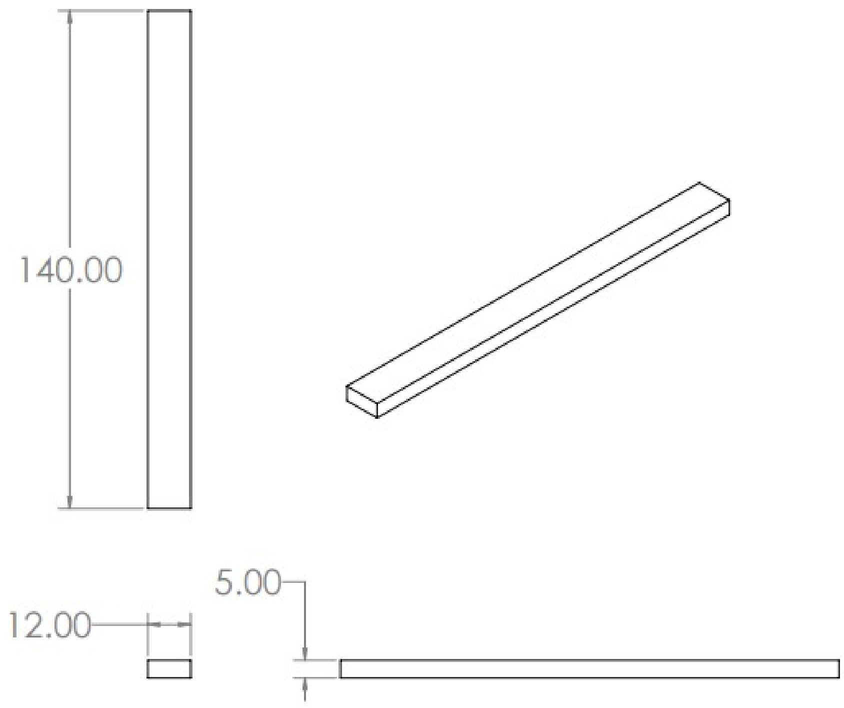


Figure 3.10: Compressive Test Specimen [82]

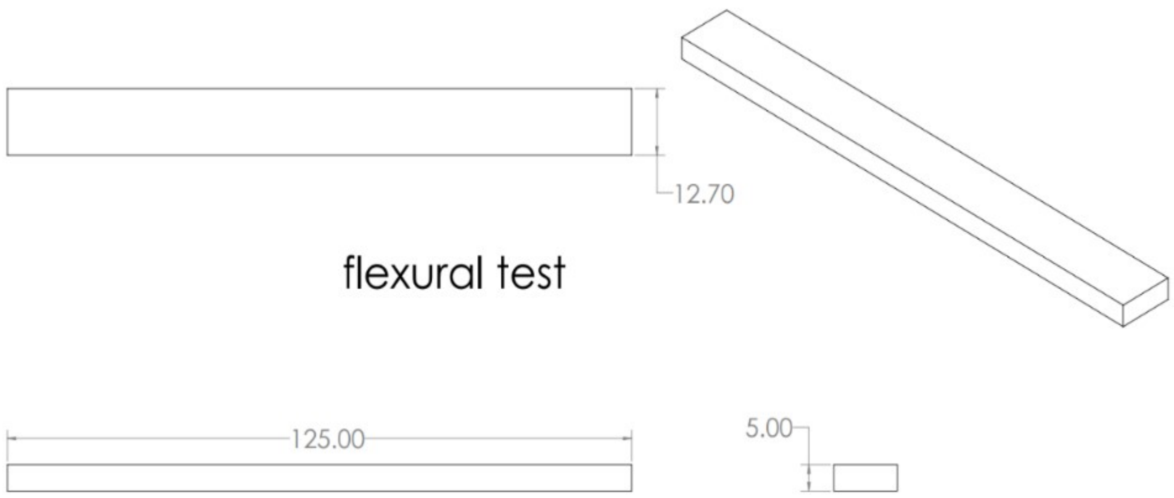


Figure 3.11: Flexural Test Specimen [83]

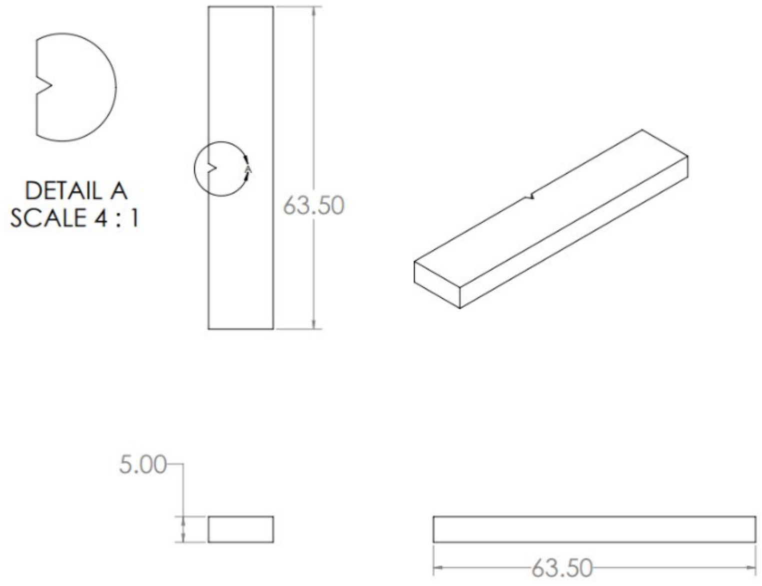


Figure 3.12: Charpy Impact Test Specimen [84]

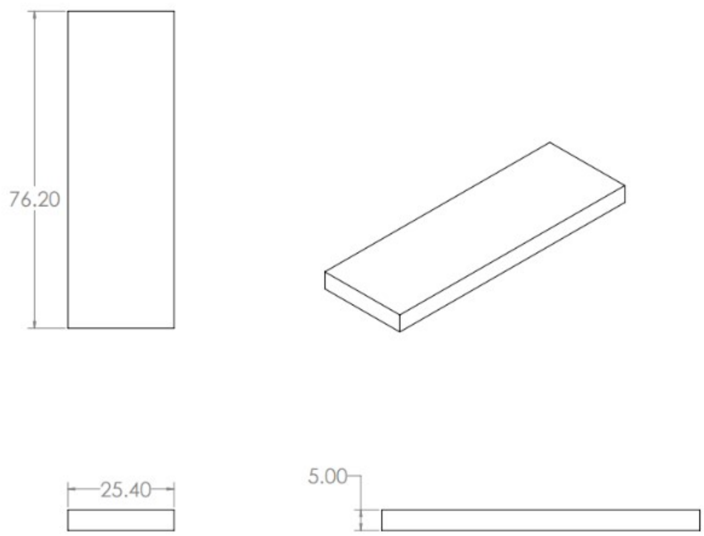


Figure 3.13: Water Absorption Test Specimen [85]

3.6 Experimental Test Procedure

From the literature review the composite material preparation would take a long period until testing. In section 2.4, the fabrication mechanism used for specimen preparation for test procedure was stated on the literature review. The specimen created for this thesis adhered to the standards of the American Society for Testing Materials. Compression, flexural, impact, Tensile, and water absorption tests were performed on the specimens. Computer controlled Electromechanical Universal Testing Machine (UTM) with a 100KN capacity was used to conduct the tensile and flexural tests after the test specimens had been prepared. The Pendulum Charpy Impact Testing machine was used to carry out the impact test.

Figure 3.14: Universal Testing Machine (UTM) setup

3.6.1 Tensile test of honeycomb orientation of bamboo fiber composite

Tensile strength is the measurement of the force required to pull a material such as wire, a structural beam or test specimen to the point where it fractures. The greatest tensile stress that a material can withstand before failing is known as its tensile strength. The greatest tensile stress that a material can withstand before failing is known as its tensile strength.

The tensile test is executed by following the ASTM standard using a universal testing machine [86]. Three samples of bamboo fiber with honeycomb orientation were prepared and subjected to tensile loading until failure. The tensile strength, modulus of elasticity, and elongation at break points were recorded for each sample.

Figure 3.15: Tensile test specimen using honeycomb fiber orientation

3.6.2 Tensile test of woven orientation of bamboo fiber composite

The bamboo fiber under investigation was woven, thereby enhancing its inherent strength and rigidity. The tensile test was conducted using a standard testing machine, adhering strictly to the relevant ISO standards. The parameters include dimensions of the specimen, testing speed, and atmospheric conditions.

Figure 3.16: Tensile test specimen using woven orientation

3.6.3 Compressive test of honeycomb orientation of bamboo fiber composite material

The bamboo fibers were processed into a honeycomb orientation, a structure that provides superior strength and flexibility. The compressive tests involved the use of a Universal Testing Machine (UTM) following ASTM standards [82]. The bamboo samples were prepared in multiple dimensions to analyze the difference in compressive strength across various sizes.

The specimens prepared for this mechanical test were loaded with axial compression until it fractures under the electromechanical UTM which records result of the force data and compressive stress-strain graphs. Compressive test specimens were fabricated with the dimension of $140 \times 12 \times$5 mm.

Figure 3.17: Compressive test specimen using honey comb fiber orientation

3.6.4 Compressive test of woven orientation of bamboo fiber composite material

The primary goal of the study was to evaluate the mechanical properties, predominantly the compressive strength, of bamboo fibers alongside the impact of woven orientation. To understand the compressive strength of bamboo fiber, the compressive test was performed using a modern universal testing machine. Pieces of bamboo fiber in woven orientation were tested under controlled environmental conditions. They were subjected to a fixed load rate until failure or breakage occurred. The various aspects focused on the orientation of the woven structures.

Figure 3.18: Compressive Test Specimen using woven orientation

3.6.5 Flexural test of honeycomb orientation of bamboo fiber composite material

A flexural test specimen fabricated according to ASTM standard guidelines [83]. The honeycomb-oriented bamboo fiber was designed and produced for this test. The samples for the test were extracted in different orientations to affirm the effectiveness of the honeycomb design in manipulating the material's mechanical properties. To conduct the flexural test of the developed polymer composite a three-point bending fixture mode was used under the electromechanical UTM machine with feed speed of 2mm/min. The flexural test specimen was fabricated with $125 \times 12.7 \times 5\ mm$ dimensions. The section modulus data extracted from the machine depend on the width and thickness of specimen for flat specimen. The greatest load placed on the bar with the radius of the moment from a given point can be used to compute the maximum bending moment.

Flexural strength ($\sigma bmax$): $$\sigma bmax = \frac{Mbmax}{section\ modulus} \qquad (21)$$

Figure 3.19: Flexural strength test specimen using honey comb orientation

3.6.6 Flexural test of woven orientation of bamboo fiber composite material

This flexural test is to ascertain the flexural properties of woven orientation bamboo fiber. The properties include flexural stiffness, elastic limit, and strength. Using a mechanical testing machine, the bamboo fiber is subjected to a three-spot bending test. The samples' thickness and width measurements were carefully taken, and the span length was set accordingly.

Figure 3.20: Flexural Strength Test Specimen using woven orientation

3.6.7 Impact test of honeycomb orientation of bamboo fiber composite material

Bamboo fiber's unique honeycomb orientation makes it a material of significant interest in the manufacturing and construction industries. The impact strength test of the bamboo fiber honeycomb orientation aims to examine the resilience, durability, and strength of this material upon impact. The test samples were fabricated following the ASTM standards [84].

The samples were set up on the positioning surface at the impact position at which the pendulum attains maximum kinetic energy under the Charpy impact testing machine in order to measure the energy absorption capacity of the composite. The computer provides individual results with some statistical information, such as minimum, maximum, mean, etc., for each specimen that was coded in a batch. The specimens had 25.4- and 2-mm deep notches placed in the middle of them.

The impact strength test involves applying a sudden strike or shock over a short period to the bamboo fiber and observing the fiber's resistance to impact. The material is introduced to a pendulum releasing a known amount of kinetic energy.

Figure 3.21: Impact strength test specimen using honey comb orientations

3.6.8 Impact test of woven orientation of bamboo fiber composite material

The impact strength test of the woven orientation of bamboo fiber is crucial in understanding its ability to resist high imposed loads. This paper tells the results and observations from the impact strength test of woven bamboo fibers.

The impact tests were conducted using the Charpy methods. The woven bamboo fiber was cut into standard test samples and then subjected to an impact load to determine the absorbed energy and the subsequent behavioral patterns

Figure 3.22: Impact Strength Test Specimen using woven orientation

3.6.9 Water absorption test of honeycomb orientation of bamboo fiber composite material

The water absorption capability of bamboo fiber with a honeycomb configuration was assessed in a controlled environment in this study. This inquiry aimed to enhance our understanding of the bamboo fiber's dimensional stability and establish a foundation for future use in product of prosthetic socket.

Following the measurement of their dry weight, the specimens selected for water resistance testing were prepared in accordance with ASTM standard and submerged in water for 24 hours [85]. The specimen was fabricated with $76.2 \times 25.4 \times 5\ mm$ dimensions. Following immersion, each composite's mass (wet weight) was measured, and the percentage of absorption was determined as follows.

$$(H_2O)Asorption\% = \frac{(\text{Wet Weight} - \text{Dry Weight})}{\text{Dry Weight}}\ x\ 100\% \quad (22)$$

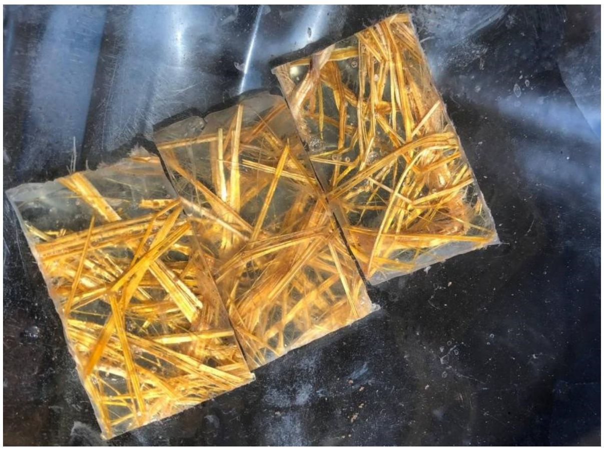


Figure 3.23: Water Absorption Test Specimen using honeycomb orientations

3.6.10 Water absorption test of woven orientation of bamboo fiber composite material

The water absorption capacity of the woven orientation of the bamboo fiber was investigated over a span of 24 hours. Bamboo fiber has been identified as crucial in several applications due to its unique properties, such as high specific strength, renew-ability, and biodegradability; therefore, understanding its absorption of water over time is valuable for its utility.
The test started by submerging samples of woven oriented bamboo fiber in distilled water at room temperature. The samples' weight was documented before the immersion, after which they were weighed at hourly intervals for 24-hour mark.

Figure 3.24: Water Absorption Test Specimen using woven orientation

3.7 Finite Element Analysis and Modeling

It is possible to assess the mechanical properties of the composite by computational and experimental analysis. The ANSYS Workbench 2023 R1 application has been used to develop the numerical analysis by describing the material parameters and boundary conditions.

3.7.1. Preparing the Composite Material in ANSYS

Using ANSYS software and a variety of workbench disciplines, including ACP (for orientation, stacking sequence), Static Structural for analysis, and Space Claim to model the geometry, the honeycomb-oriented Bamboo/epoxy composite was created. The 105 hexagons of the 20mm long hexagon ply are formed by fiber knitting in a honeycomb pattern using an ANSYS Space claim modeler.

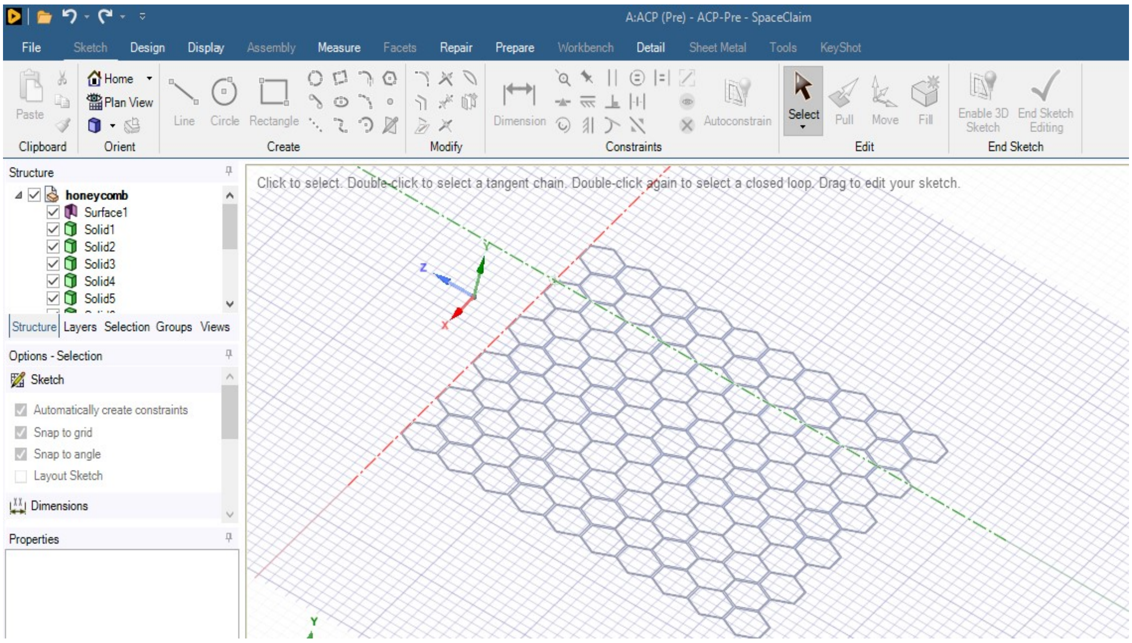


Figure 3.25: Honeycomb Pattern using an ANSYS Space claim model

3.7.2 Developing the plies Stacking Sequence and Modeling

A finite element analysis model using the developed ANSYS 2023 R1 was used to evaluate the properties of honeycomb-oriented bamboo epoxy composites with a stacking order of [0/72/144/216/288] layer orientation, Compression, and bending tests. Composite analysis involves modeling geometry, defining material properties, applying boundary conditions, and defining stacking sequences.

The stacking sequence of 0/72/144/216/288 in honeycomb orientation of bamboo fiber with epoxy for making composite material can be justified based on several factors:

Fiber Orientation: The chosen sequence of 0/72/144/216/288 represents different orientations of the bamboo fibers within the composite material. This particular stacking sequence is known as a quasi-isotropic layup [87], which means that the fibers are arranged in a manner that provides balanced mechanical properties in multiple directions. It helps to distribute the load evenly and enhances the overall strength and stiffness of the composite.

Balanced Mechanical Properties: The quasi-isotropic layup ensures that the composite material exhibits similar mechanical properties in all directions. The 0° orientation provides high tensile strength along the fiber direction, while the ±45° orientations contribute to enhanced shear strength. The 90° orientation helps to resist compressive forces. By combining these orientations in a specific sequence, the composite material can achieve a more balanced response to various loading conditions.

Reduction of Anisotropy: Anisotropy refers to the directional dependence of material properties. By incorporating multiple fiber orientations in the stacking sequence, the anisotropic behavior of the bamboo fiber composite can be minimized. This is particularly beneficial in applications where the material needs to withstand loads from different directions or exhibit consistent behavior in all orientations.

Results in improved Damage Resistance: The stacking of honeycomb allows for the creation of interlaminar shear paths, which can enhance the damage resistance of the composite material. When subjected to external loads, the different fiber orientations provide alternate paths for crack propagation, thus reducing the likelihood of catastrophic failure. This can lead to improved toughness and durability of the composite structure.

Manufacturing Considerations: The chosen stacking sequence might also be influenced by manufacturing considerations. Certain fabrication techniques, such as automated fiber placement or hand layup, may require specific sequences to ensure proper fiber alignment and ease of manufacturing. Therefore, the stacking sequence you used could be the result of a combination of design requirements and manufacturing constraints.

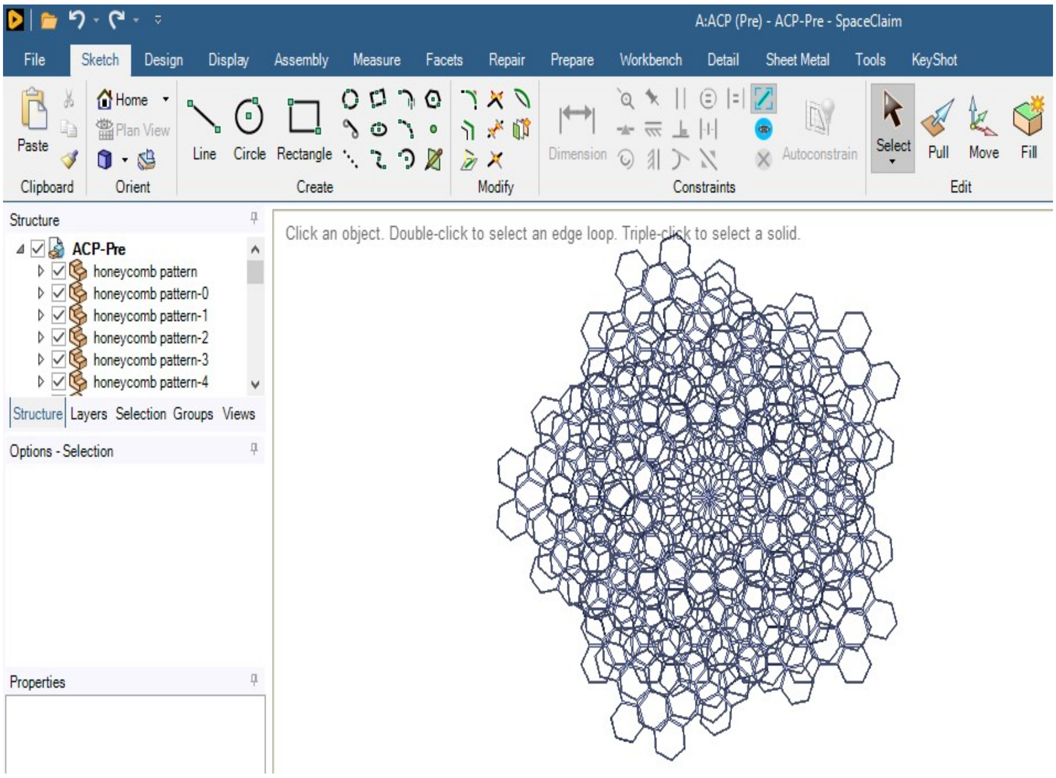


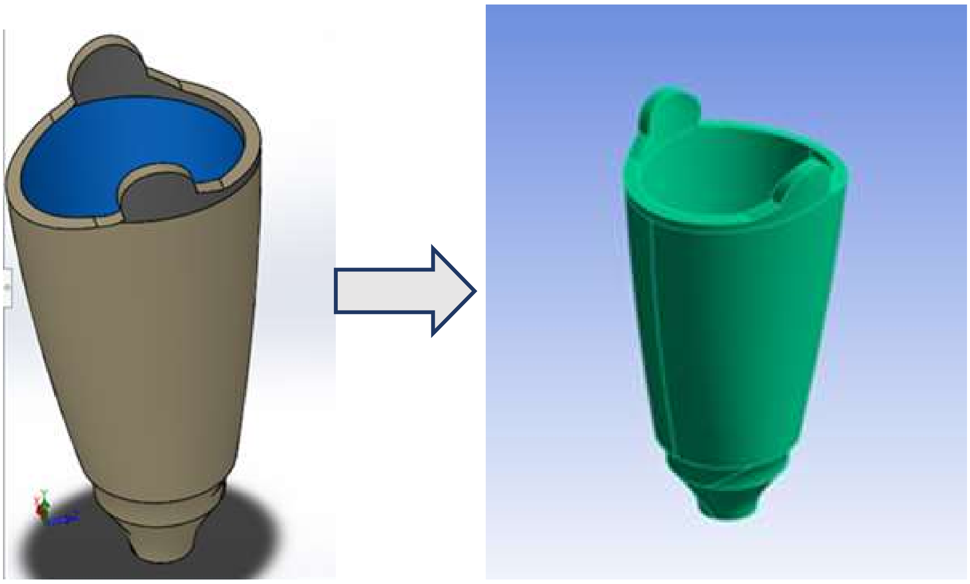
Figure 3.26: Stacking Sequences of Bamboo Fiber in Honeycomb Orientation

A total of five polar orthotropic layers are analyzed under tensile, compressive and bending loads using ANSYS ACP (before) and static structural analysis solutions are observed in ANSYS ACP (after).

Modeling a honeycomb layer, found that the longitudinal and transverse fiber orientations and loading situations are different. Loads can be lifted from any direction. Material properties are added to the Ansys materials library as technical data for analysis.

3.8 Modeling of the prosthetic socket

After developing the design of prostatic leg, the next step was importing the 3D modeling into simulation software. The probable dimensions are taken from literature review and from actual medical equipment inspection.



(a)SOLIDWORK modeling (b) Imported to ANSYS 2023 R1

Figure 3.27: 3D Model of Prosthetic socket

The Mesh element type is Fiber elements. These are special-purpose elements used to model the behavior of individual bamboo reinforcing fibers within honey comb orientation of composite materials. They are often used in micromechanical analyses to study the stress transfer between bamboo fibers and epoxy resin matrix.

Element number and node of the prosthetic socket model

Details of "Mesh"	
Mesh Defeaturing	Yes
Defeature Size	Default
Transition	Fast
Span Angle Center	Coarse
Initial Size Seed	Assembly
Bounding Box Di...	255.32 mm
Average Surface ...	862.99 mm^2
Minimum Edge L...	5.0 mm
Quality	
Check Mesh Qua...	Yes, Errors
Error Limits	Aggressive Mechanical
Target Element Q...	Default (5.e-002)
Smoothing	Medium
Mesh Metric	None
Inflation	
Use Automatic In...	None
Inflation Option	Smooth Transition
Transition Ratio	0.272
Maximum Layers	5
Growth Rate	1.2
Inflation Algorit...	Pre
View Advanced ...	No
Advanced	
Number of CPUs ...	Program Controlled
Straight Sided El...	No
Rigid Body Behav...	Dimensionally Reduced
Triangle Surface ...	Program Controlled
Topology Checki...	Yes
Pinch Tolerance	Please Define
Generate Pinch o...	No
Statistics	
Nodes	26930
Elements	5070
Show Detailed St...	No

Figure 3.28: Element and Node number of the prosthetic socket model

Aspect ratio of the composite element

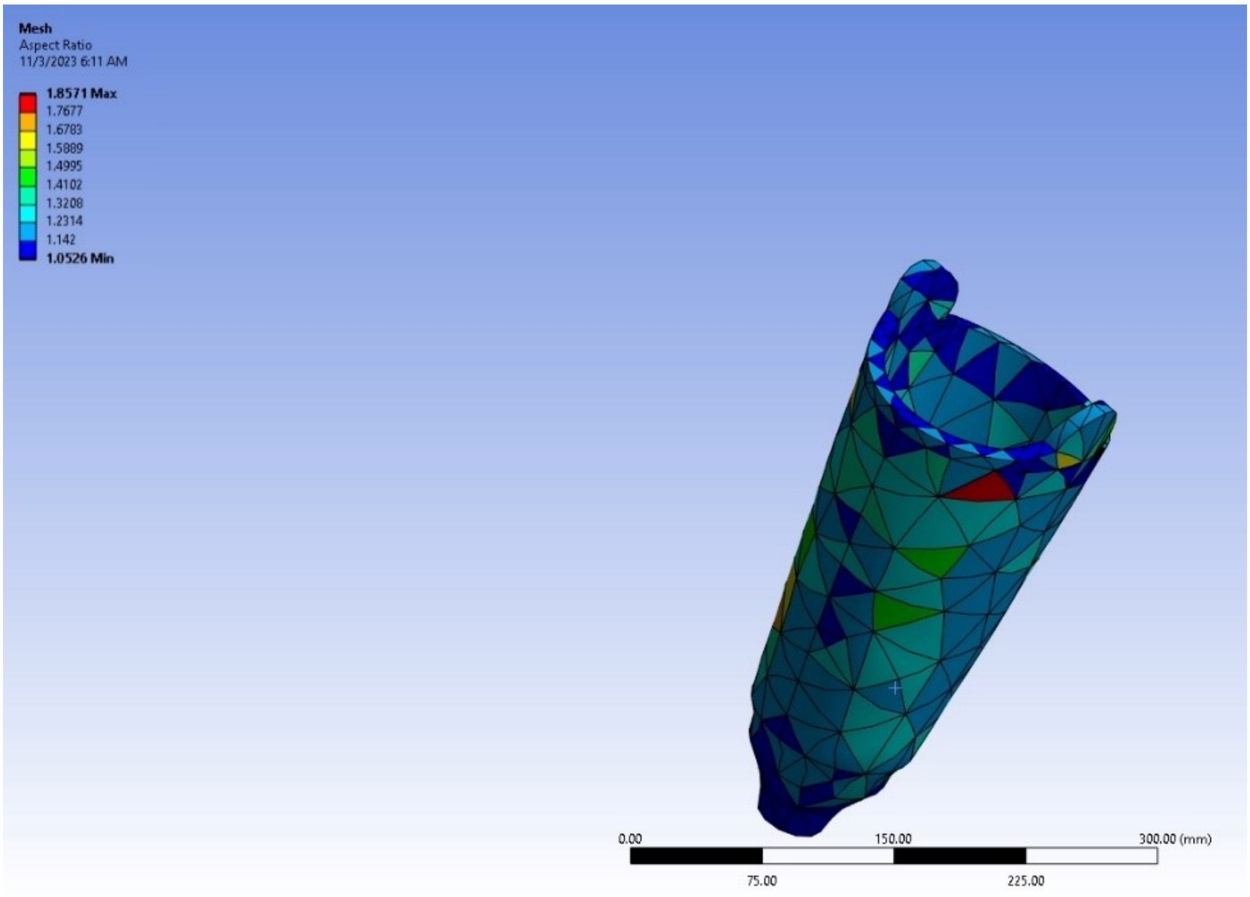
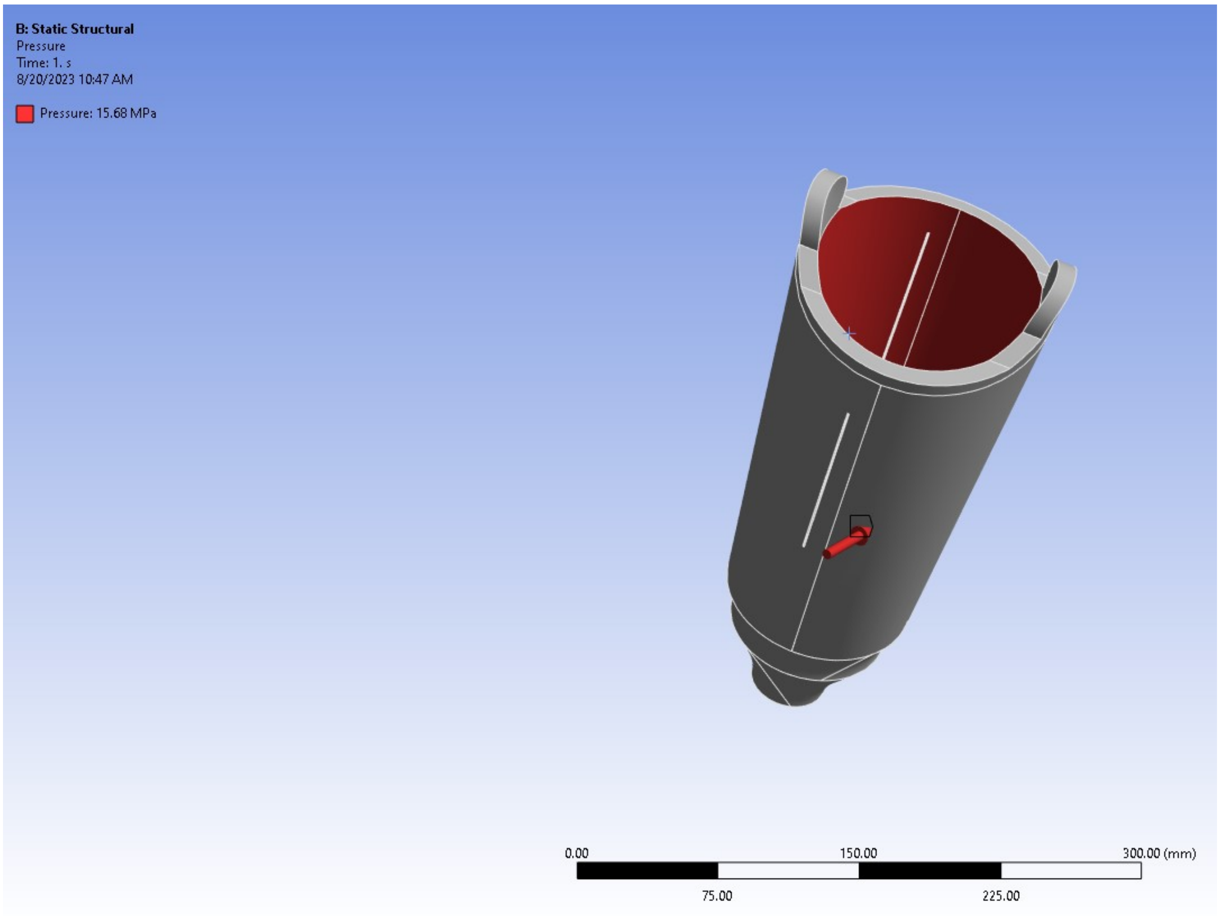


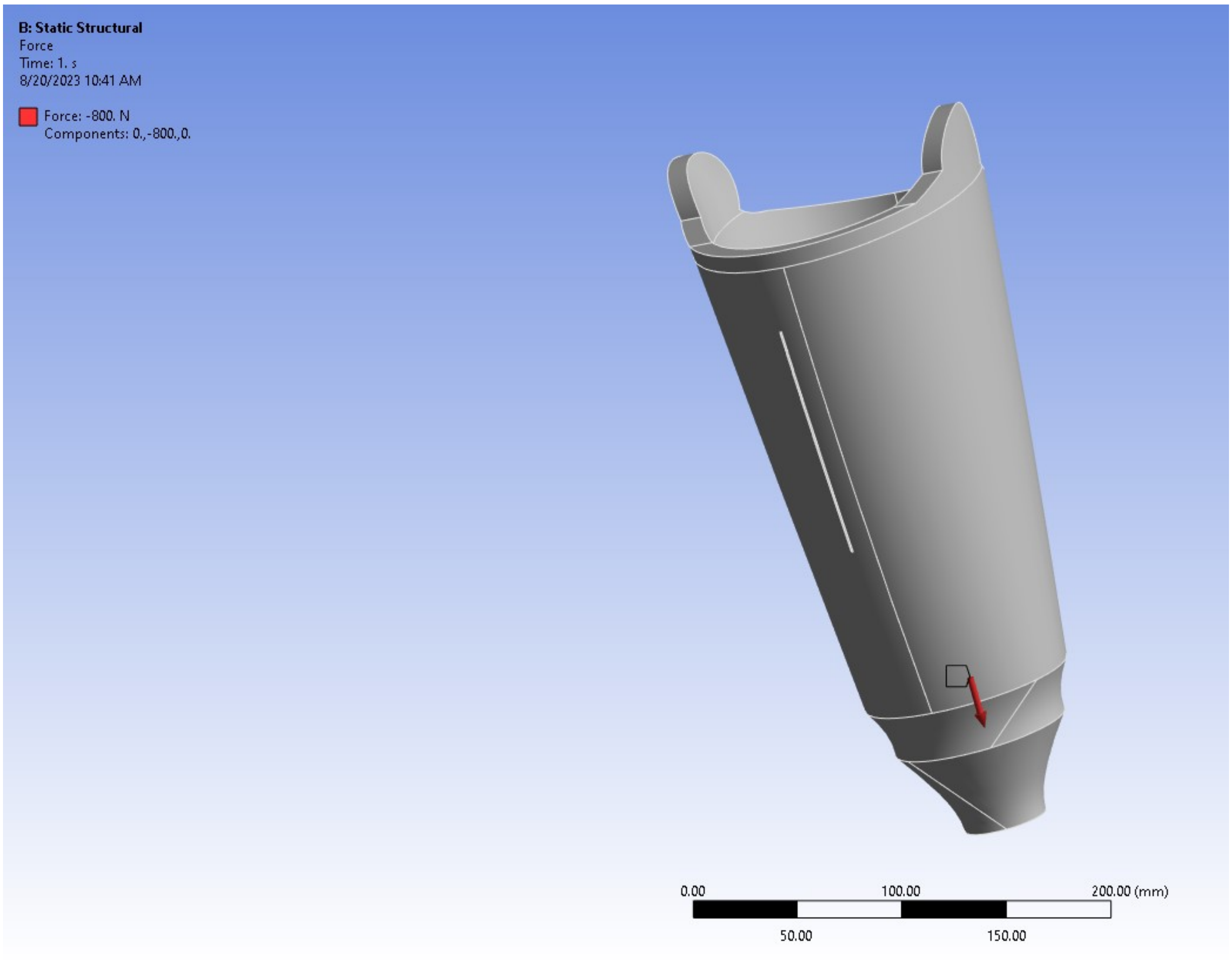
Figure 3.29: Aspect ratio of the prosthetic socket model composite material

Aspect ratio of 1.8 composite materials that are made up of bamboo fiber with epoxy in honeycomb orientation for prosthetic socket means that the composite materials have a structure that resembles a honeycomb, with hexagonal cells filled with bamboo fiber and epoxy resin. The bamboo fibers have a length that is 1.8 times their diameter. The bamboo fiber has a length of 32.5 mm and a diameter of 17 mm, then its aspect ratio is 32.5/17 = 1.85. This structure is intended to create a lightweight, strong, and flexible material that can be used to make prosthetic sockets for amputees.

Loading conditions: According to a study [88] that assessed the satisfaction and associated factors among lower limb prosthesis and orthosis users in Amhara National Regional State Rehabilitation Center, Ethiopia, the mean weight and height of the participants were 60.5 kg and 165.8 cm, respectively. The study included 207 participants, of which 131 (63.3%) were prosthesis users and 76 (36.7%) were orthosis users. The study also reported the standard deviations of the weight and height, which were 10.9 kg and 8.2 cm, respectively. This means that most of the participants had weights and heights within one standard deviation from the mean, which gives a range of 49.6-71.4 kg for weight and 157.6-174 cm for height.


B: Static Structural
Pressure
Time: 1. s
8/20/2023 10:47 AM
Pressure: 15.68 MPa
0.00
150.00
300.00 (mm)
75.00
225.00

(a)



(b)

Figure 3.30: (a) and (b) Loading condition of prosthetic socket

Boundary conditions

Fixed Constraints:

Fix the base of the socket where it attaches to the residual limb and apply fixed constraints (zero displacement) to the relevant surfaces. After that the Load Conditions will simulate the load applied during walking or other activities.

Apply forces or pressure loads on the inner surface of the socket where the residual limb contacts. The study considered both static and dynamic loads. Then define contact between the socket and the residual limb. Use frictional or frictionless contact formulations.

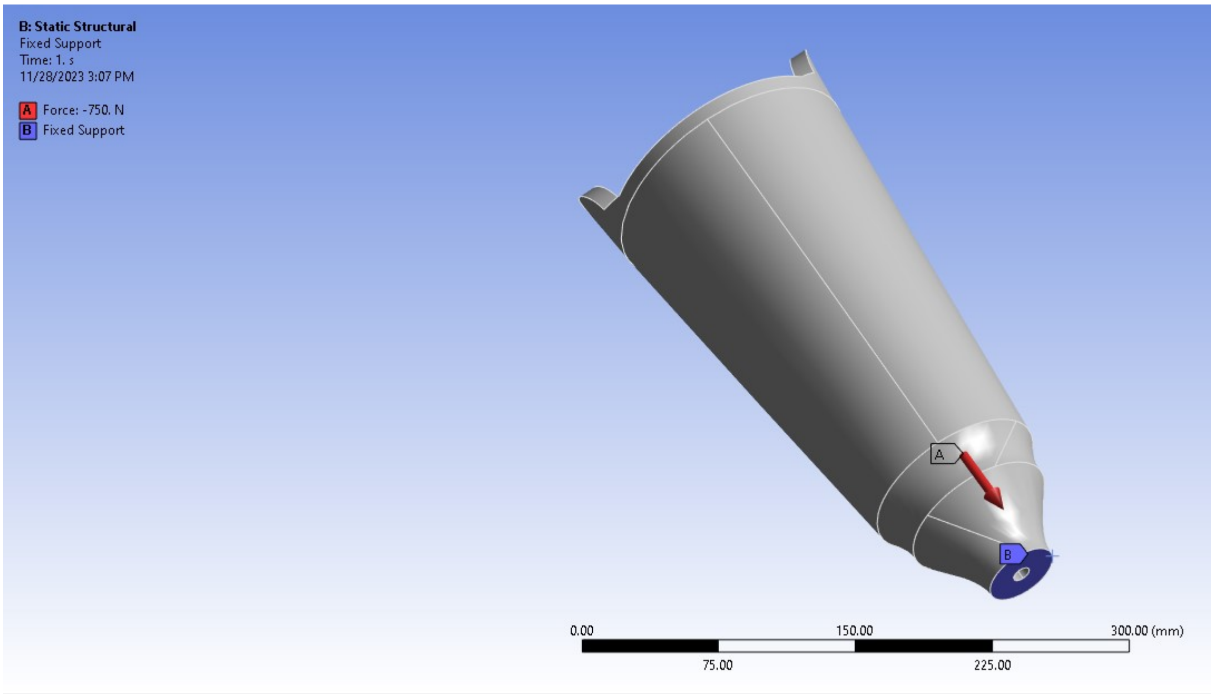
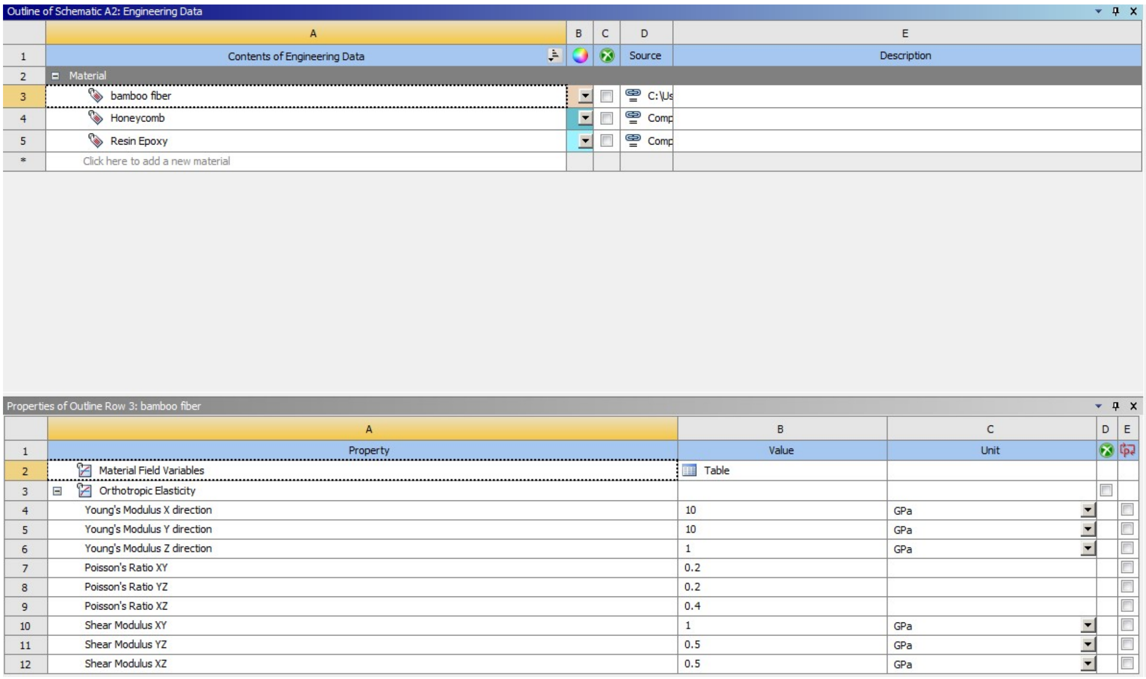


Figure 3.31: Boundary conditions

3.9 Numerical Tensile test FEA ANSYS

Create geometry based on ASTM tensile specimen standards and model in Solid Works 2023 software. Surfaces created in Solid Works are imported into ANSYS and material selection is done in the ANSYS design data pane. The properties of bamboo epoxy honeycomb fiber orientation materials were studied and analyzed. The imported geometry is discretized into the number of elements and nodes.

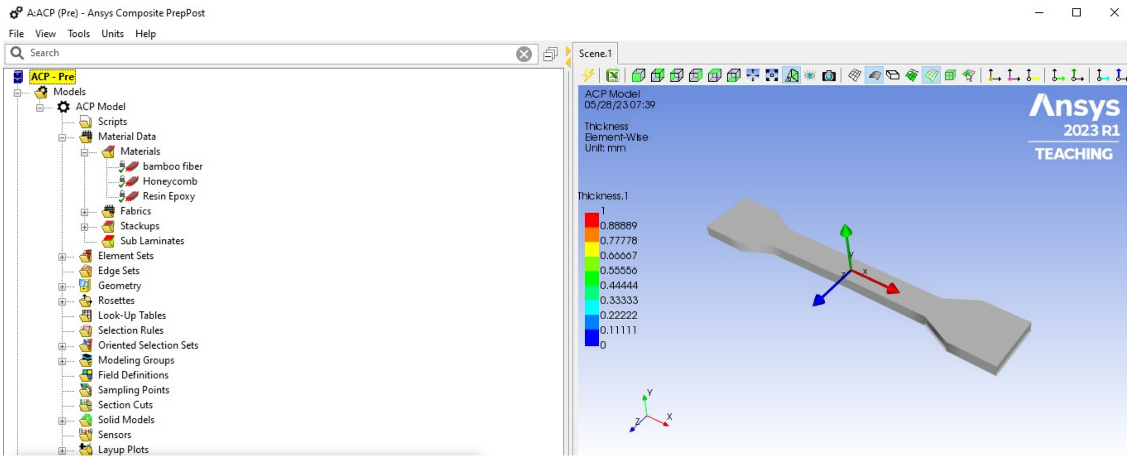

Outline of Schematic A2: Engineering Data

	A	B	C	D	E
1	Contents of Engineering Data			Source	Description
2	Material				
3	bamboo fiber			C:\Us	
4	Honeycomb			Comp	
5	Resin Epoxy			Comp	
*	Click here to add a new material				

Properties of Outline Row 3: bamboo fiber

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Orthotropic Elasticity				
4	Young's Modulus X direction	10	GPa		
5	Young's Modulus Y direction	10	GPa		
6	Young's Modulus Z direction	1	GPa		
7	Poisson's Ratio XY	0.2			
8	Poisson's Ratio YZ	0.2			
9	Poisson's Ratio XZ	0.4			
10	Shear Modulus XY	1	GPa		
11	Shear Modulus YZ	0.5	GPa		
12	Shear Modulus XZ	0.5	GPa		

(a) Engineering data provided for bamboo fiber



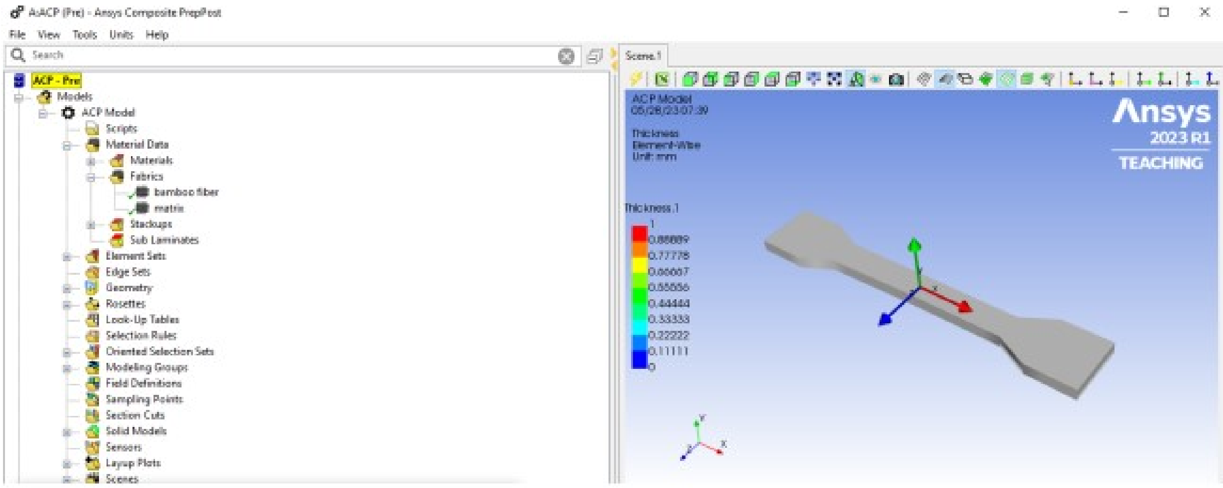
(b) The pre-inserted ANSYS composite Datum and material arrangement in the mode before meshing

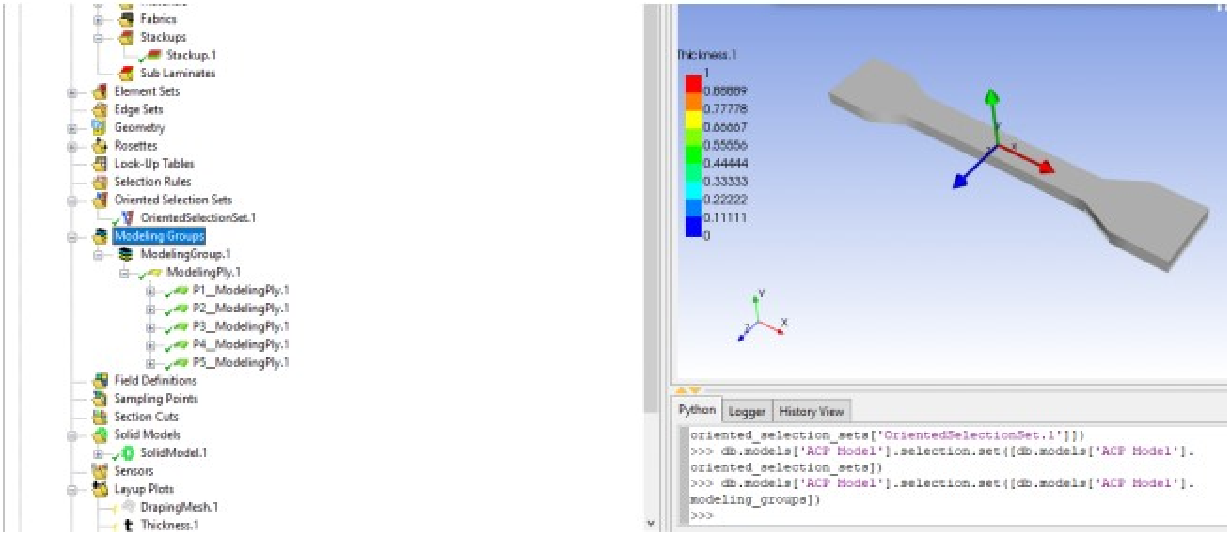
Figure 3.32: The pre-process and mesh preparation stage (a) application of engineering data for bamboo (b) the reinserted ANSYS composite Datum and material arrangement in the mode before meshing

The imported geometry would require having complete information in the engineering data. But the preparation of the finite element model can cover the selection of the type of analysis as well as material characterization. The discretization stage of the process needed to identify the type of meshing including the size which would be dividing the body into an equivalent system of finite elements with associated nodes and choosing the most appropriate element type to Model most closely the actual physical behavior.

ANSYS Composite Datum Pre-inserted into the static structural definition containing four boundary and load case definitions. A fixed boundary condition is applied to one end and a bending force is applied to the other end until the maximum breaking load is reached.

(a)





(b)

Figure 3.33: (a) composite fabric material (b) stacking sequence validation to the software

The stacking sequence arrangement in the design of composite materials in ANSYS is optimized using a finite element design optimization algorithm that uses the sub problem approximation method. The hierarchy presented on the workbench would be compared with the analytical result and the input data applied in the engineering data. The data provided to the model analyzed to construct the mesh result.

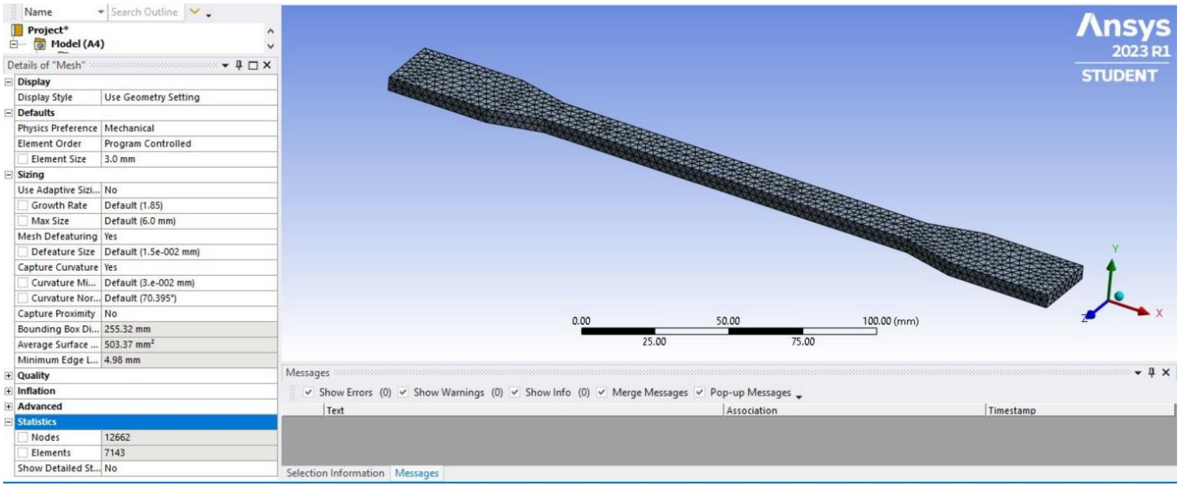


Figure 3.34: Final Mesh result of the model

The final meshing result of the composite material for the determined on the above figure contains an element size with a global mesh element of 1mm.

3.10 Three-point Bending (Flexural) Test: Numerical Analysis

Flexural stress, flexural strain, and flexural modulus are characterized using a 3-point bending test in finite element analysis according to ASTM standards. A flexural specimen geometry created in the ANSYS Space Claim workspace and imported for failure analysis in 5-ply honeycomb composite made of epoxy and bamboo fibers and ANSYS ACP. A rigid three-point load is applied to an element fabricated from a composite of honeycomb-patterned bamboo fiber and epoxy. A stack made with a layer thickness of 1 mm is pressed onto a setting element consisting of a three-point bending test support and a slider. For static structures, bearing elements are combined by drawing composite samples in ANSYS ACP (Pre).

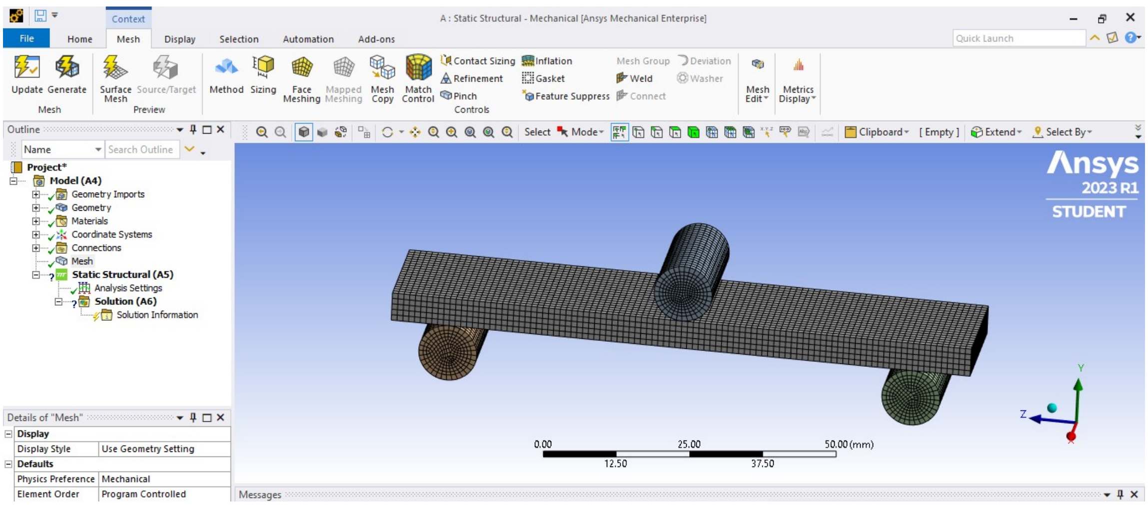


Figure 3.35: Simulation of 3-point bending test

3.11 Numerical analysis of compressive test

Compressive test ASTM standard geometrical setup in the Ansys pre work space has been used to investigate compressive strength and compressive modulus. Ansys post tools are used to build solutions for the boundary conditions that are evaluated using static structural methods.

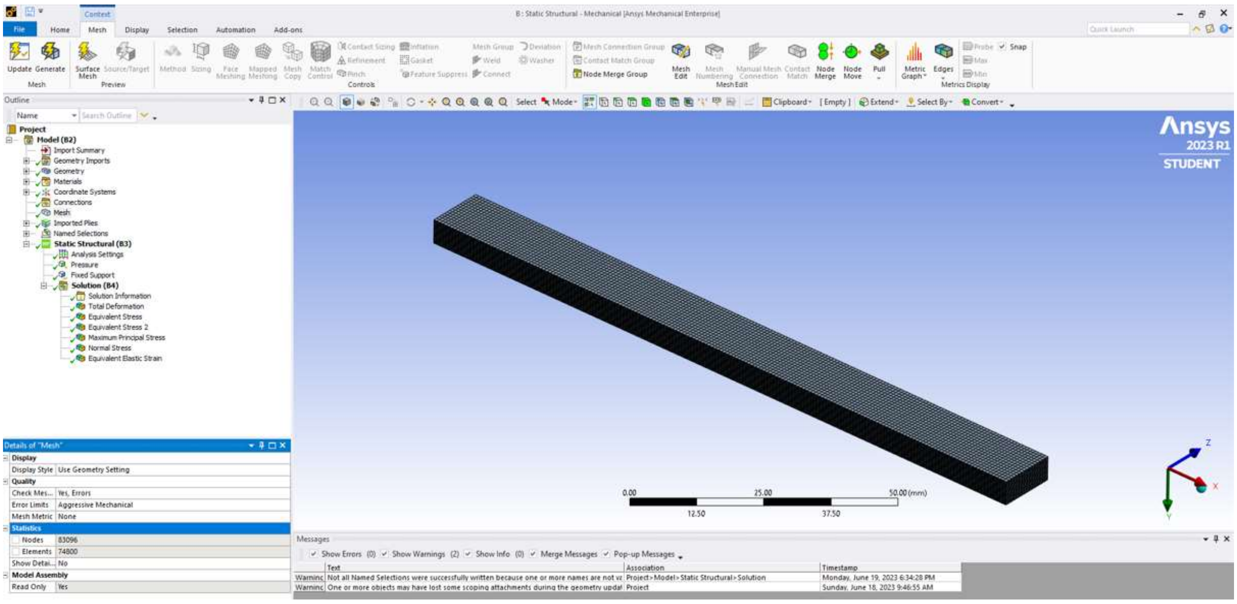


Figure 3.36: Compressive Test Specimen meshing

In the figure 3.36, the amount of node used in the meshing result was given by general meshing of 1mm size of element. Based on the discretization and the stress strain constitutive law the final result of total deformation, equivalent von-mises stress and strain would be described in the result section.

3.12 Numerical analysis of impact test

To assess product integrity and identify crucial areas in the assembly, numerical analysis impact test on ANSYS is used to model drop and impact simulation. Sudden load applied on the 5mm thick specimen.

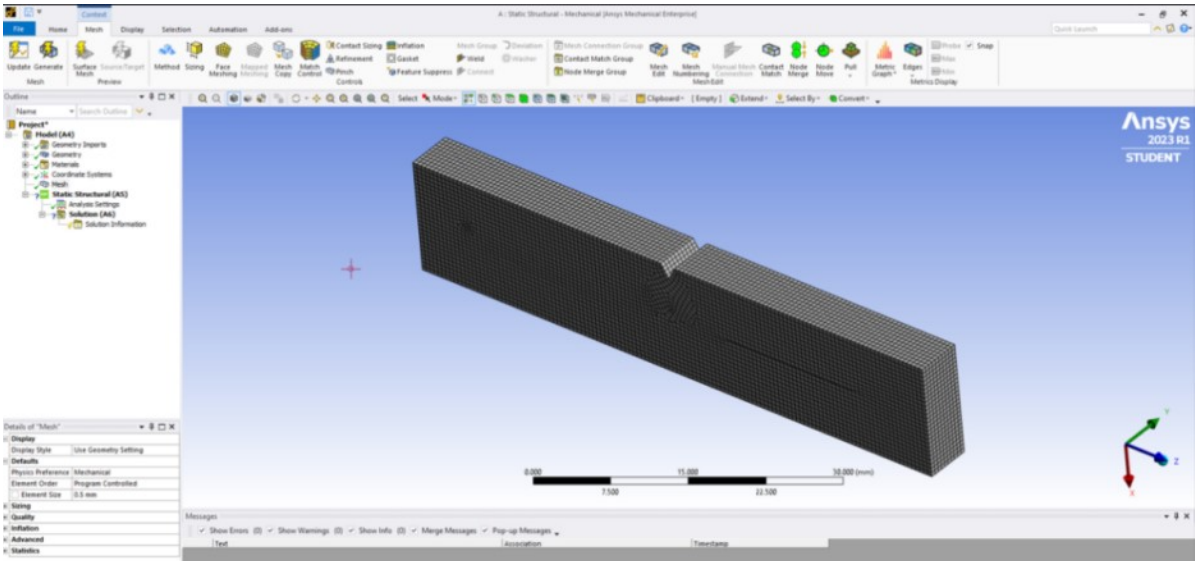


Figure 3.37: Impact Test Specimen meshing

The study determines the impact failure of the material when it is tested with the simulation of a **Charpy impact test** using the finite element method. The meshing contains the minimum size of an element of 0.5mm which is a medium element grain discretization, shown figure 3.37.

3.13 Modeling and Finite Element Analysis the Prosthetic

The prosthetic socket was modeled in Solid Works and imported into ANSYS Workbench for structural analysis and characterization. In the Ethiopian Prosthesis and Orthopedic Center, prosthesis sockets are made of homo polymer polypropylene (HPP) imported in sheets of SIMONA products with material dimensions of $2000 \times 2000 \times 5\ \mathrm{mm}$. The composite material developed this time is an epoxy resin composite material reinforced with a 5mm-thick honeycomb bamboo fiber, and has higher tensile strength, bending strength, and impact strength. A prosthesis modeled from a bamboo-epoxy composite with honeycomb fiber orientation is simulated and the results are compared with materials from the HPP model described in the literature.

Steps in the solution process in ANSYS prosthetic leg analysis

- Geometry and modeling developed in SOLIDWORKS 2021 in step file format
- The material properties of a honeycomb pattern bamboo fiber with epoxy composite have been selected and specified.
- Import the 3D prosthetic leg model into the ANSYS workspace and apply mesh generation
- Applied boundaries and load conditions
- Generate solutions

Analysis at ANSYS: The prosthesis has a solid upper support and is directly acted upon by reaction forces from the knee and the ground.

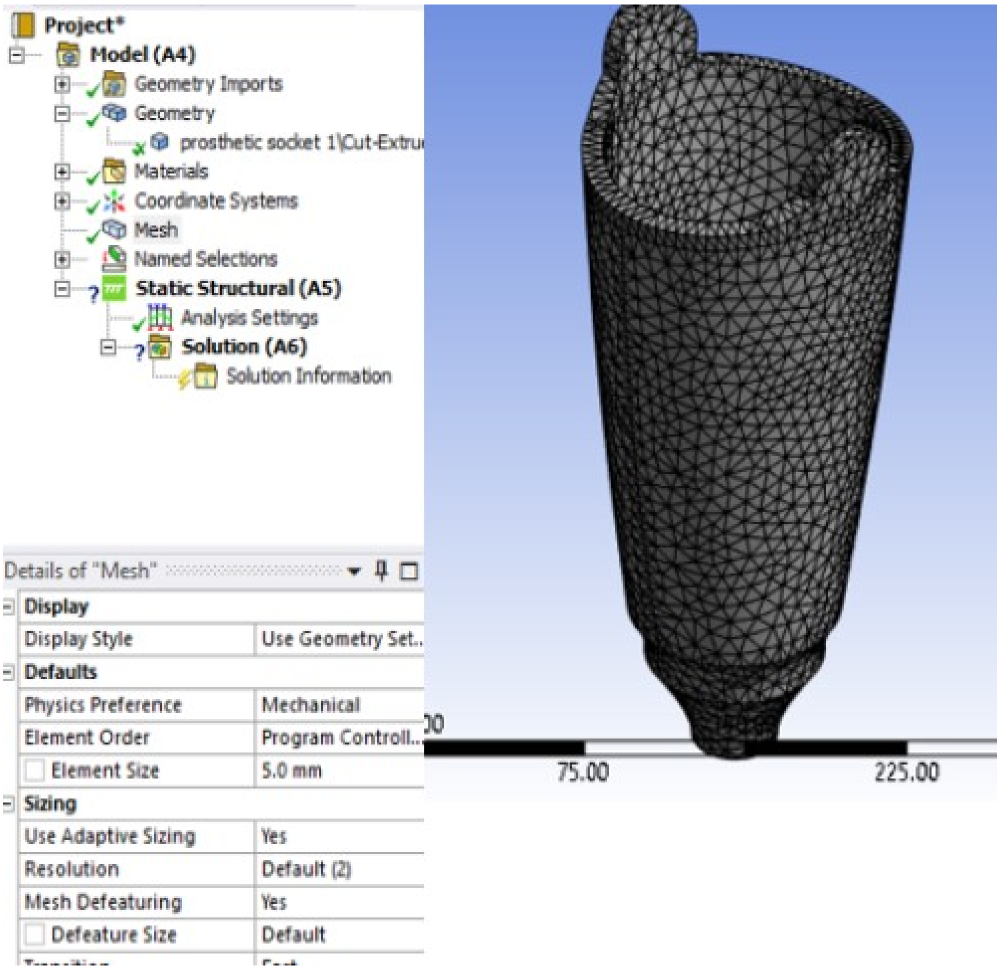


Figure 3.38: Prosthetic Socket Mesh Generation

The total mesh result extracted from the component can be effectively utilized when it would be summed up with tensile, compressive, flexural and impact test. In the figure 3.27, the geometry imported from SOLIDWORK 2021 put under simulation and got an element size of 5mm.based on the figure 3.38 the material used in the structural construction of each lamina have a honeycomb fiber material with the size of 2.43 mm.

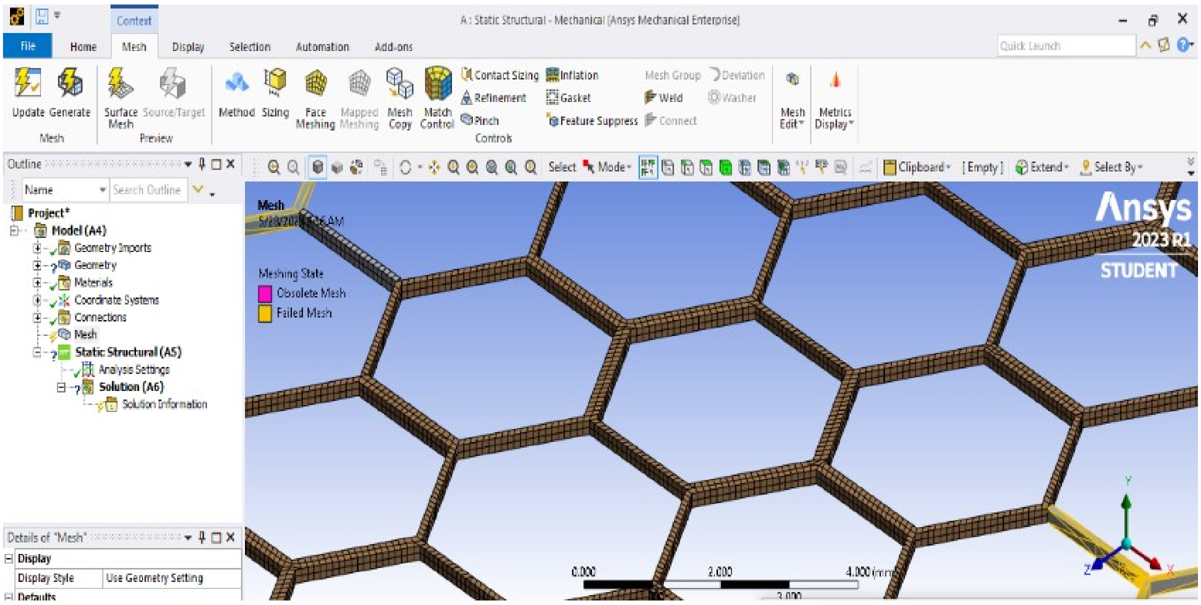


Figure 3.39: Single Lamina Honeycomb Hexagonal Fiber Orientation Meshing

3.14 Failure and failure mode analysis

A variety of failure analysis tools are available in Ansys Mechanical Workbench. Tsai-Wu Error Criterion is a tool used for ply error analysis in stacking order. According to this criterion, if the "inverse factor" or failure index (FI) is greater than or equal to 1, there is a failure of the entire ply or laminate. Since the finite element model calculates the failure zone and stiffness of the degraded material, the observed material properties degrade quickly. The first damaged ply becomes less rigid, reducing the stress in the damaged area. Stress and strain of each ply or the whole laminate is solved in the static structural according to composite failure tools in each loading steps. The simulation of five layup plies maximum deformation and maximum failure load is recorded in table form from solution report, to draw stress strain graphs.

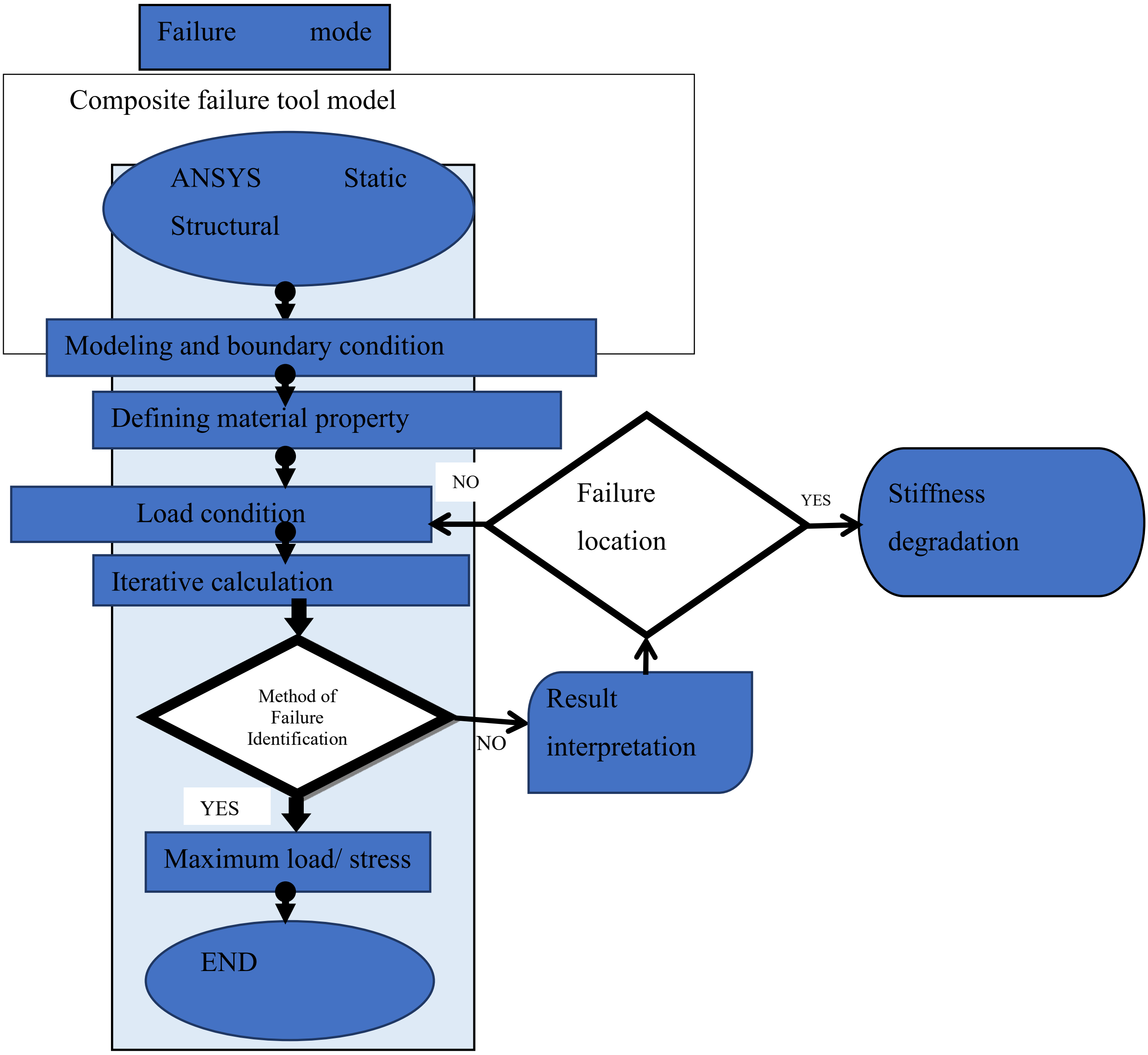


Figure 3.40: Failure analysis procedures of composite in ANSYS ACP

CHAPTER FOUR

RESULTS AND DISCUSSION

The characterization of the material for prosthesis use, the finite element simulation was numerically applied to the honeycomb-oriented bamboo fiber epoxy polymer composite using the ANSYS Workbench 2023 software. The outcomes of the FE analysis were contrasted with those of the experiments and earlier published publications.

4.1. Tensile test FEA Results and Discussion

The model is imported into the Static structural domain of ANSYS Workbench for the test of tensile analysis, after arranging all the steps necessary for creating honey comb-oriented bamboo fiber epoxy composite and uploading the layers with the right stacking sequence from ACP (Pre). After this, loads and boundary conditions were restricted. Maximum von-Mises stress of 54.58 MPa, maximum total deformation of 0.038 millimeters, and maximum elastic strain of 0.000538mm/mm were all produced by the analysis. the results of the numerical analysis for the tensile test are similar with those of the experimental findings reported in the preceding section. The center of the span length in the specimen prepared was where the tensile test failed.

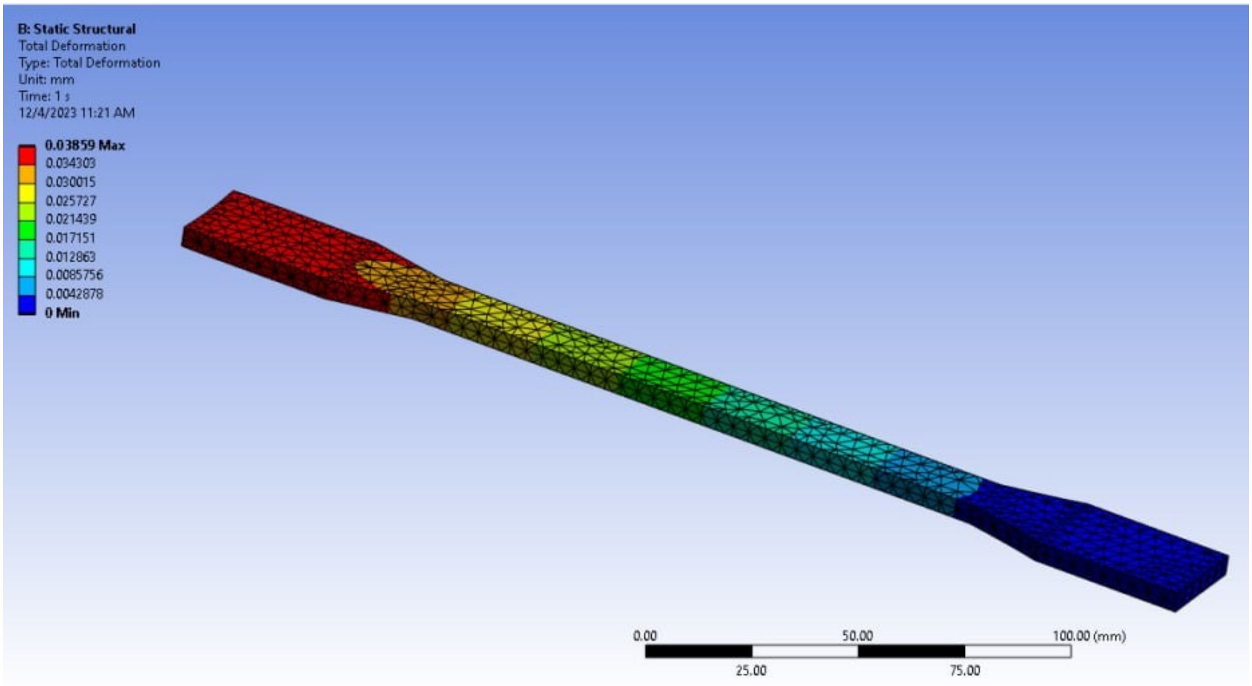


Figure 4.1: Maximum deformation result for tensile test specimen form ANSYS static structural analysis

In the figure 4.1, the maximum deformation resulted from the simulation was 0.038mm. This amount of deformation found at one end of the specimen. This result used for the derivation of constituent formula of stress. Actually, the deformation is as small as element size of FEM.

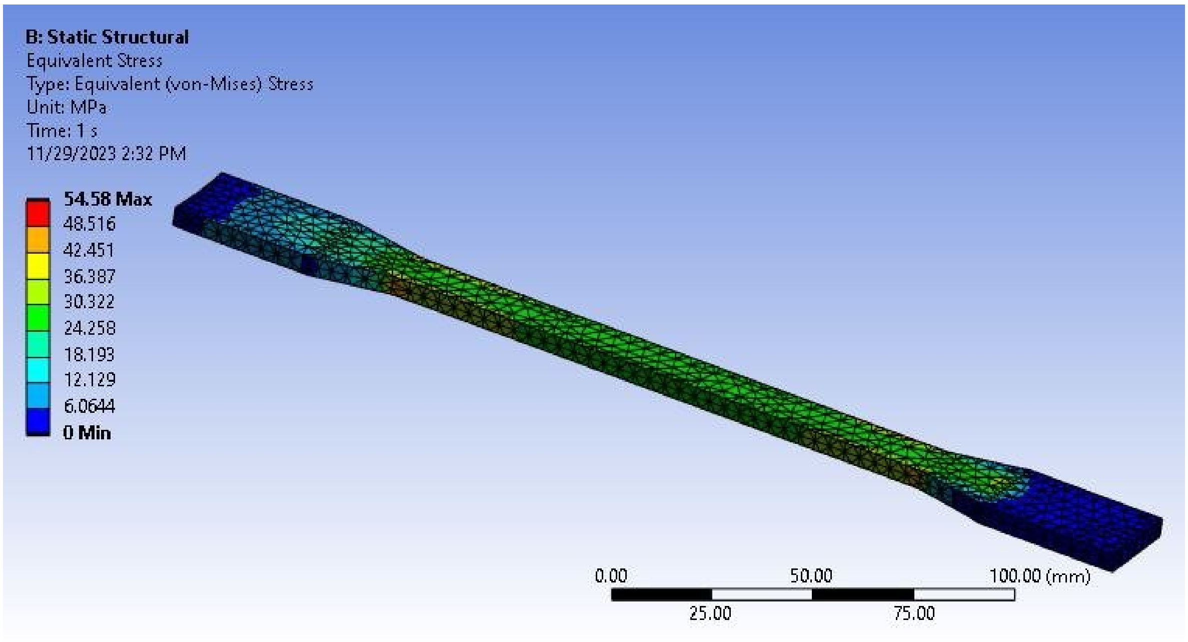


Figure 4.2: Von-Mises stress results of tensile test

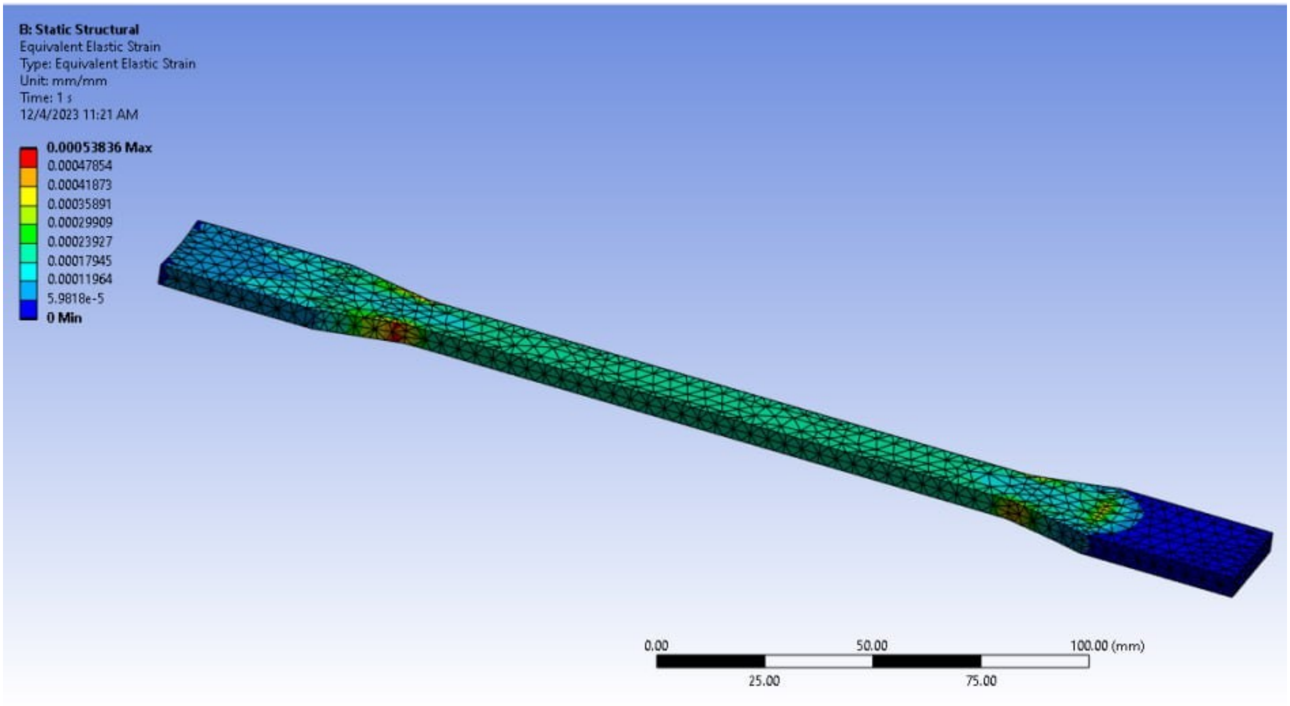


Figure 4.3: Equivalent strain results of tensile test

It is feasible to ascertain the mechanical properties of the material based on the previously mentioned figures (figures 4.1, 4.2, and 4.3). When a maximum stress of 54.58 Mpa was applied to the specimen, the largest deformation occurred at one end of the fixture, indicating that the deformation distribution was minimal at the other end of the material. In brittle materials, the area of the specimen where the load is applied will deform more quickly than adjacent areas. The specimen's center exhibits extremely high strength and stiffness values. As a result, it had a significantly smaller distribution of strain and could therefore absorb much more strain energy.

4.2. Flexural Test FEA Results and Discussion

All the tensile test protocols were followed in order to create the FE analysis for the created composite's flexural testing specimen. At the deformation of 2.75 mm, a bending stress of 65.9 MPa and a strain of 0.0015 were measured. This number is more than the experimental results owing the software examines a specimen without internal error, which might occur in experiments as a result of various processes used in manufacturing. In addition, the study's control parameters possess an effect on mechanical characteristics of their own.

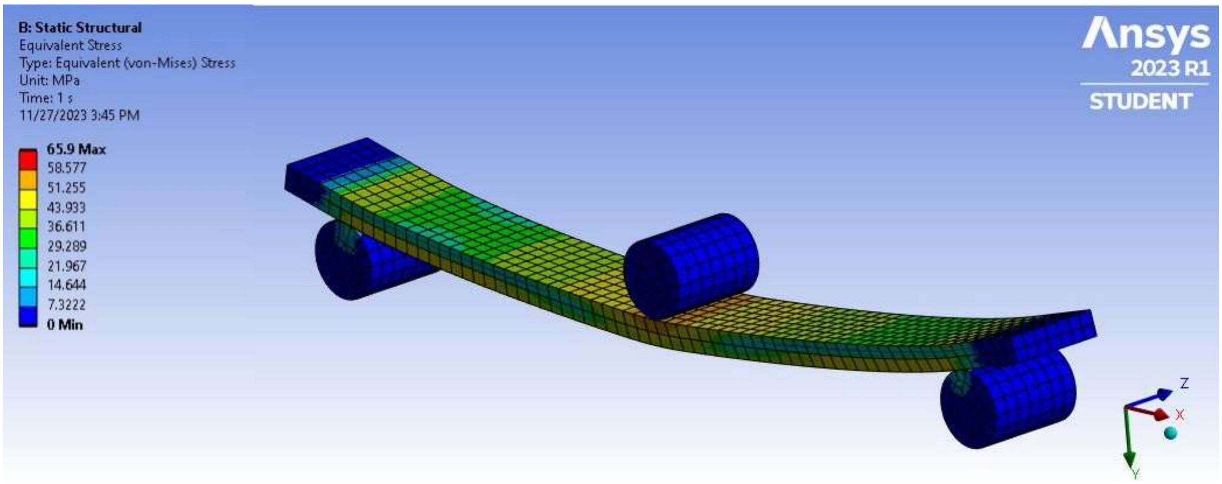


Figure 4.4: Von-Mises stress results of the bending test

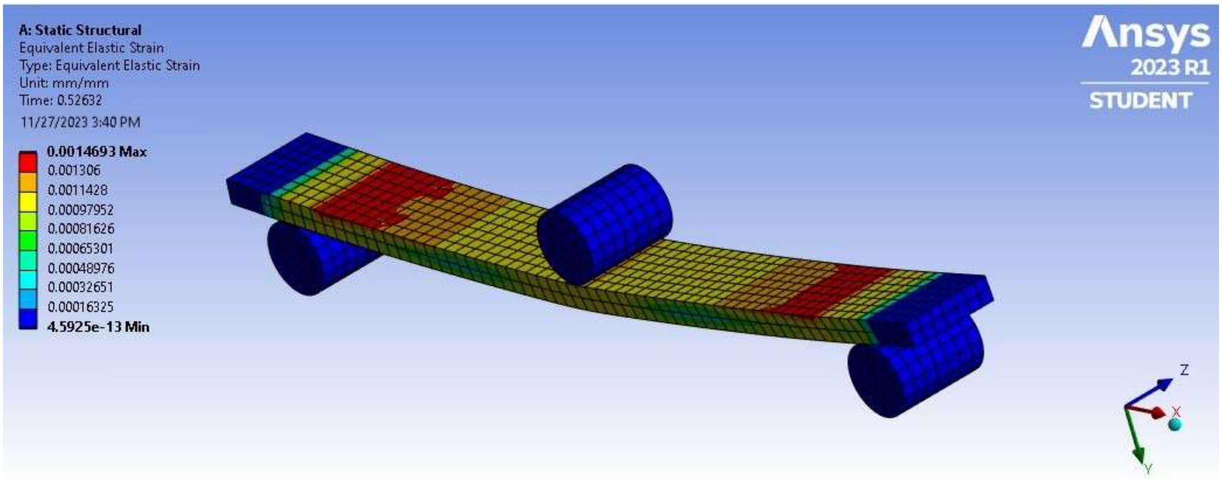


Figure 4.5: Equivalent strain results of the flexural test

4.3. Compressive Test FEA Results and Discussion

By modifying the material data, composite layer development method, stacking sequence, orientation, and ply modelling necessary to simulate the honeycomb-oriented bamboo/epoxy polymer composite modeled for the compressive test with the numerical analysis software is established.

The structural data was compiled to be compared after all the procedures had been developed for additional analysis. The maximum von-mises stress being 58.79 MPa and the total deformation was 0.05 millimeters. This value is greater than the experimental results due to the software algorithm assesses the numerical test specimen without intrinsic error, which could happen in experiments because of different errors happen. Additionally, the analysis's control parameters have an effect on the mechanical properties of the material being studied.

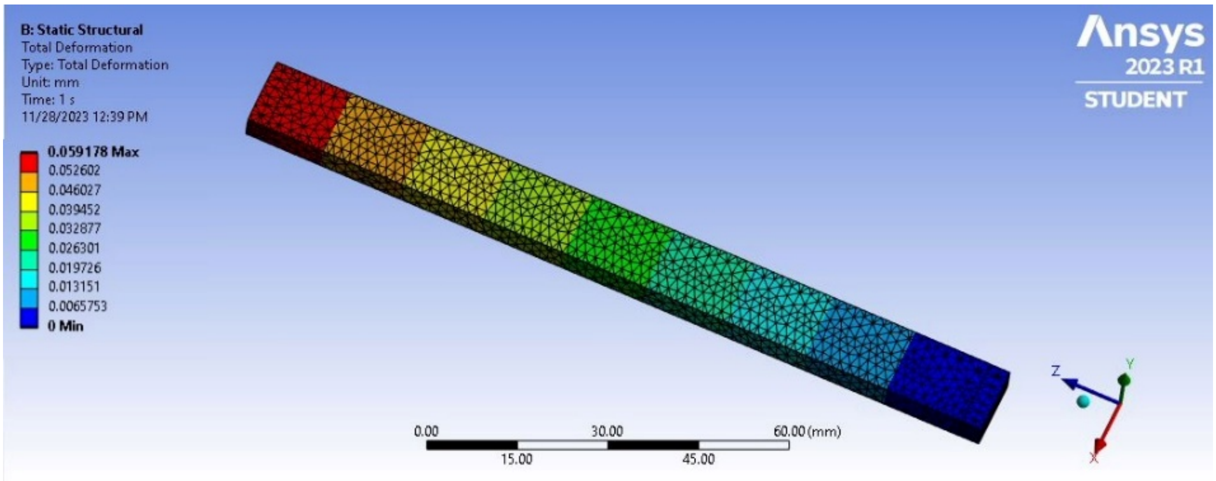


Figure 4.6: Total deformation results of the compressive test

The compression specimen simulation result shown in Fig. 4.6 largely demonstrated the emergence of structural damages close to the plotting zone, brought on by the compressive overload associated with delamination events and followed by unstable buckling behavior because of the high loads in the restricted zone. Under increasing stress, these localized problems spread gradually until the entire building collapsed. The collapsed end part showed asymmetric deformation slit tilt from the one side. The maximum compressive deformation of 1mm can be given from the tip and this phenomenon would be expected from the experimental result.

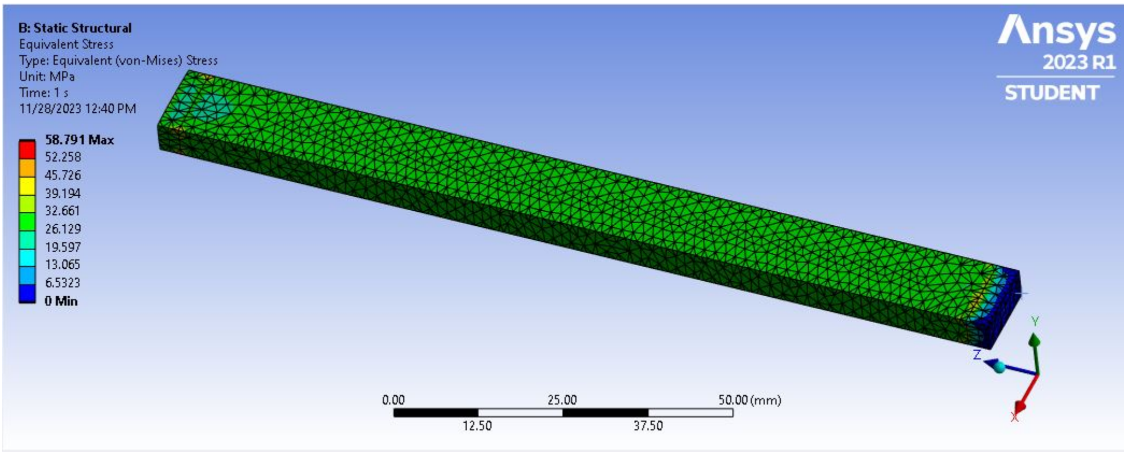


Figure 4.7: Von-Mises stress results of the compressive test

The maximum stress induced at the potting zone that used to apply compressive load to one end. And also, the strain developed at the maximum stress application. When compared to the tensile testing specimen, it has more compressive strength than tensile strength. But the above explanation could be affected by matrix strength ply orientation, binding resin, thickness of specimen and etc.

4.4. Impact Test FEA Results and Discussion

The ability of a material to withstand an abruptly applied load or force is known as impact strength. It is often represented as the amount of mechanical energy lost per unit of thickness and represents the amount of energy absorbed during the process of deformation under the applied impact loading. The thickness was taken as 5mm. The created bamboo/epoxy composite material performed with an impact test evaluation by using finite element model then the results of the total deformation, strain, and stress are shown in the figures 4.9, 4.10&4.11.

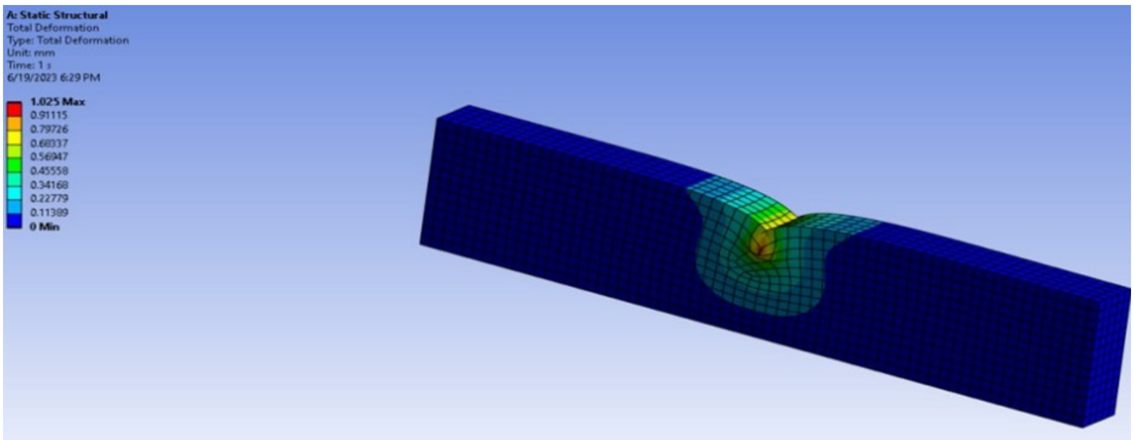


Figure 4.8: Total deformation result of impact test specimen simulation

From the figure 4.9 the maximum deformation given by 1.025mm found at the charpy necking position. The deformation is very small and concentrated at minimum thickness area. In that case the strain energy distributed around the stress concentration area which is low.

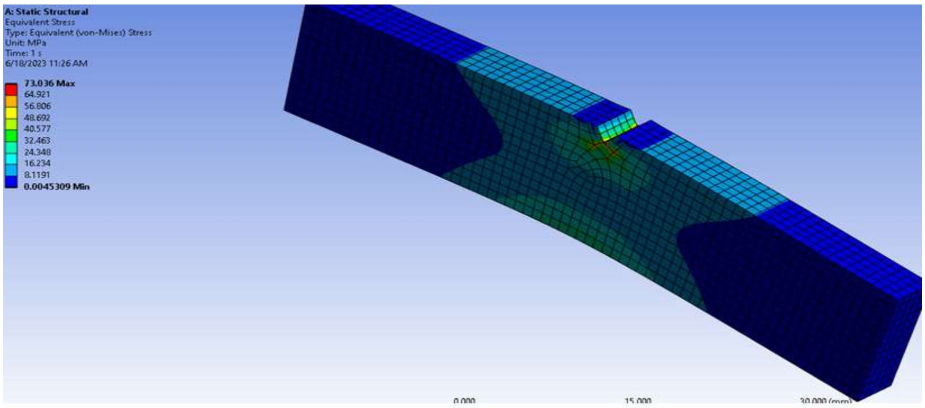


Figure 4.9: Equivalent Von-Mises stress distribution for impact test specimen

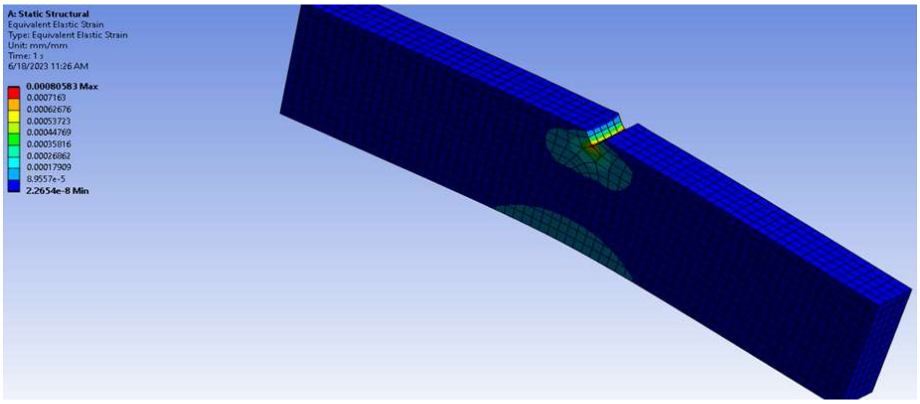


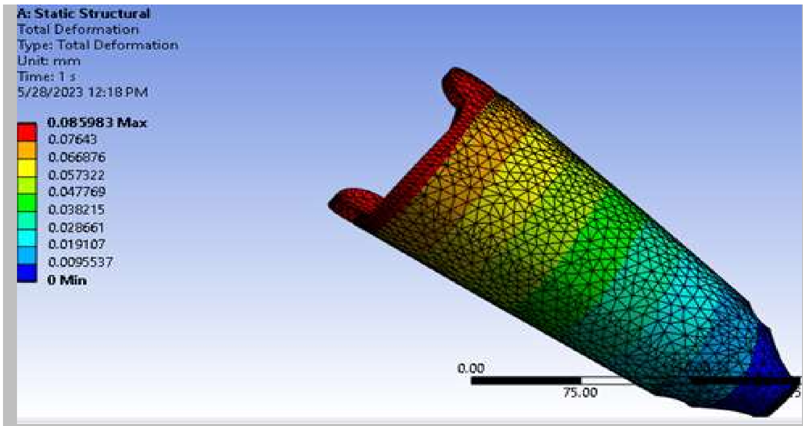
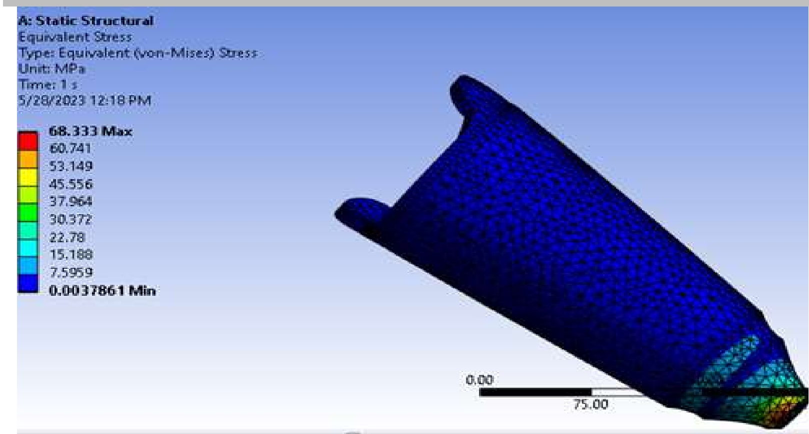
Figure 4.10: Equivalent strain result for impact test specimen

In the above two results the equivalent strain was given as 0.0008 which is too small for 5mm thickness. In that case the ability of the material to absorb strain energy is very high. The system can with stand large distortion energy still without significant damage to the system. The equivalent stress of 73.04 MPa is demonstrated by the final result of simulation.

4.5. Prosthetic leg finite element analysis result

The result developed from finite element model could a good incite about the test specimen result comparatively to the actual model. It also give important information on the application of the model strength characterization from the test. The load applied at the one end of the prosthetic leg which is directly connected with human body and the lower fixture point have small hole used to connect the shaft.

Table 4.1: ANSYS result for prosthetic leg composite

<table>
<tr><th>ANSYS result</th><th>Result summary</th></tr>
<tr><td>
</td><td>Maximum total deformation 0.0859mm</td></tr>
<tr><td>
</td><td>Equivalent maximum stress 68.333Mpa</td></tr>
</table>

From the table 4.1, the total deformation result showed that the maximum deformation of the component was found at free end point which connected to the human body and it became 0.0859mm. In the section 4.3 the compressive load applied to the specimen and it have the same manner with this analysis. The maximum Von-Mises stress was induced to the lower tip and it was 68.33Mpa.

4.6. Experimental Test Results

To create samples for testing, a bamboo/epoxy honeycomb fiber-oriented composite was designed and manufactured using hand layup technique. Then, each test was performed on its corresponding test machine in AASTU using three specimens per test with the right ASTM standard size. Each examination findings have been listed numerically discussed and interpreted.

4.6.1. Experimental Tensile Test Results

The tensile test results for bamboo fiber samples with two different orientations – honeycomb and woven – show distinct differences in tensile stress and force.

The honeycomb orientation of bamboo fiber yielded higher tensile stress results. The first specimen produced a tensile stress of 53.65 MPa under a tensile force of 6.7KN. The second honeycomb-oriented sample displayed a slightly higher tensile stress of 55.21 MPa, with a tensile force of 6.9KN. However, the third and final specimen for this particular orientation resulted in a marginally lower tensile stress of 51.35 MPa, under a tensile force of 6.42 KN. From these results, it can be deduced that the strength of bamboo fiber in a honeycomb orientation remains relatively constant at higher levels of tensile stress.

On the other hand, specimens tested with a woven orientation of the bamboo fiber showed lower readings. The first woven-oriented sample yielded a tensile stress of 48.16 MPa under a tensile force of 4.82KN. The second woven sample reflected a further lowered tensile stress of 46.46 MPa, under a tensile force of 4.67 KN. Surprisingly, the third woven sample indicated a tensile stress increase to 50.07 MPa under a tensile force of 5.08 KN. This indicates that the woven orientation of bamboo fiber may exhibit more variable tensile stress results compared to its honeycomb-oriented counterpart.

The experimental data suggest that the orientation of the bamboo fiber plays a significant role in determining its tensile strength. The honeycomb orientation appears to provide a higher tensile stress output and is less impacted by the tensile forces compared to the woven orientation. However, further experiments would be necessary to fully understand and validate these conclusions.

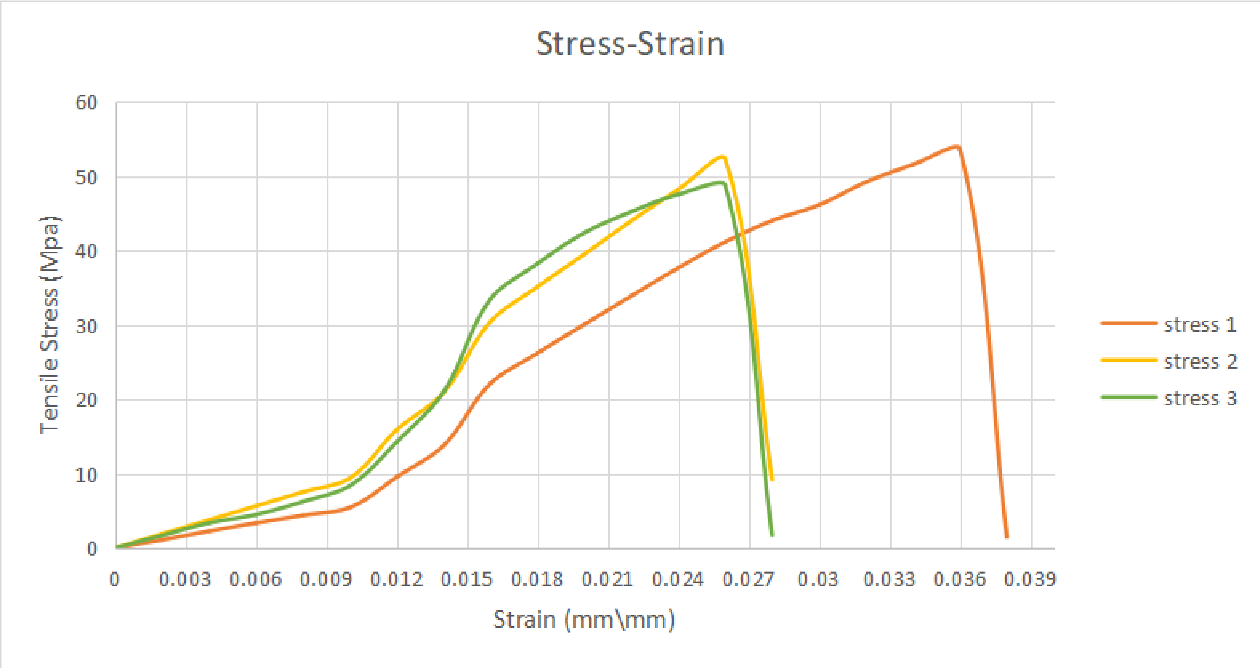


Figure 4.11: Stress-Strain curve of three tensile tests of the Bamboo/epoxy composite in honeycomb orientation

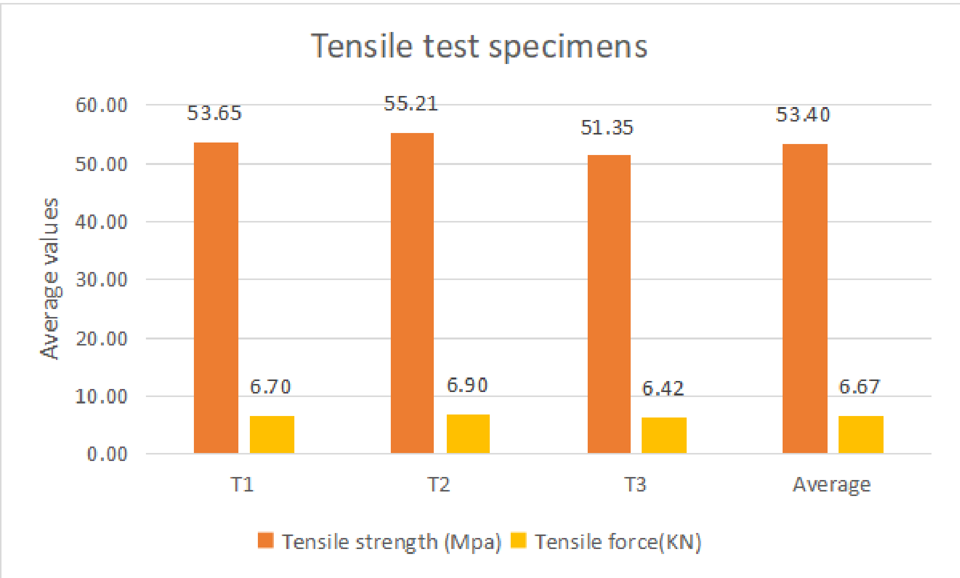


Figure 4.12: Tensile test results of three specimens and their average of the honeycomb orientation of Bamboo/Epoxy composite

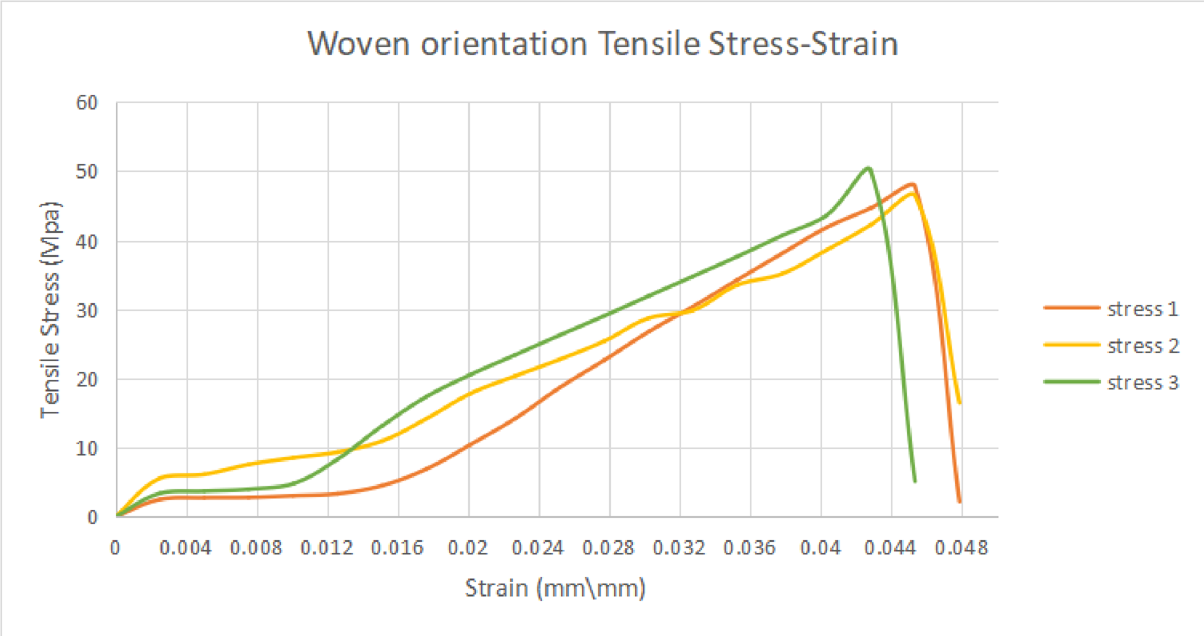


Figure 4.13: Stress-Strain curve of three tensile tests of the Bamboo/epoxy composite in woven orientation

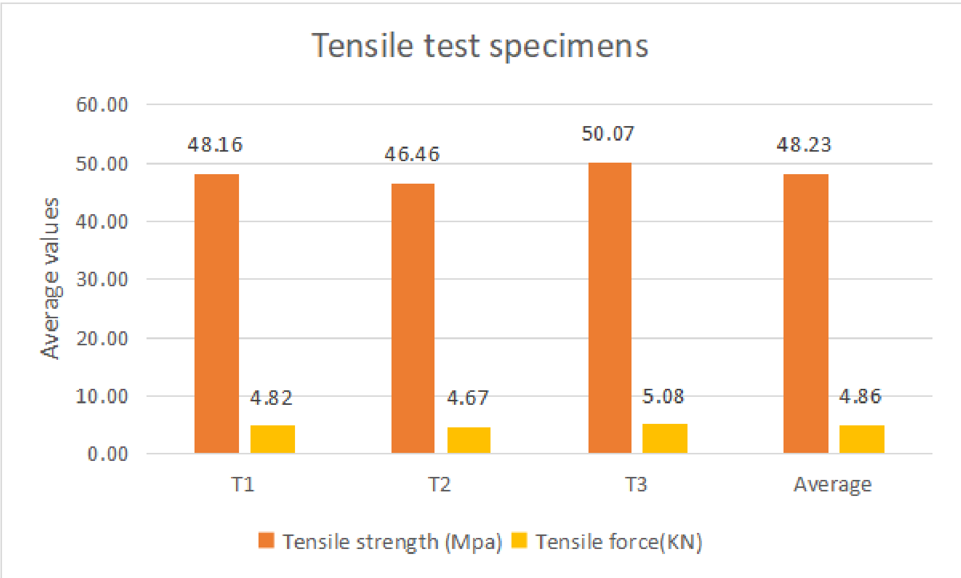


Figure 4.14: Tensile test results of three specimens and their average of the woven orientation of Bamboo/Epoxy composite

4.6.2. Discussion and Comparison of Experimental tensile test Results

The tensile test results on both honeycomb and woven orientations of bamboo fiber have been examined and compared. For the honeycomb-oriented bamboo fiber, the test results with three different specimens yielded tensile stress results of 53.65 Mpa (at a tensile force of 6.7KN), 55.21 Mpa (at 6.9KN), and 51.35 Mpa (at 6.42 KN).

On the other hand, the tensile test results for the woven-oriented bamboo fiber generated tensile stress results of 48.16 Mpa (at a tensile force of 4.82KN), 46.46 Mpa (at 4.67 KN), and 50.07 Mpa (at 5.08 KN).

Comparing the two sets of data, the tensile stress of bamboo fibers was consistently higher with the honeycomb orientation compared to the woven orientation, given the same range of tensile force. The highest stress value was attained at 55.21 Mpa (using honeycomb) whereas, for the woven orientation, the peak stress capped at 50.07 Mpa. These findings suggest that the orientation of bamboo fiber significantly impacts the material's tensile properties.

In Table 4.2, the average results for the tensile test were calculated and evaluated against earlier research studies on the available literature. Tensile results are compared to other composites with different manufacturing methods or fiber to matrix combinations to determine how much the created material is preferred for structural applications. Because of the fabrication process and the presence of cavities on the specimens, some values in the comparison are greater than the results of the current investigation.

Table 4.2: Tensile Test Result Comparison

Fiber + Matrix (reference)	**Orientation**	**Fiber to matrix %**	**Fabrication method**	**Type of treatment**	**Tensile Strength (MPa)**	**Additional remark**
Bamboo + Epoxy (Current work)	Honeycomb	35/65	Hand lay-up	NaOH 5%	53.4	Current work
Bamboo + Epoxy (Current work)	Woven	35/65	Hand lay-up	NaOH 5%	48.23	Current work
Bamboo + Epoxy [89]	Random		Hand lay-up	NaOH 5 %	25.171	550 gm of matrix, unknown fiber matrix %
Bamboo/ sisal + Epoxy [90]	Random	40/60	Hand lay-up	NaOH 5%	19.8	Tensile strength of bamboo fiber 74Mpa
Bamboo and sisal + Epoxy [86]	Bi-woven mat	35/65	Hand layup	NaOH 5%	26.41	40% of wood sawdust contents
Water hyacinth + Epoxy [91]	Random	16/84	Hand lay up	Not supported	48.06	2% resin homogeneous mixture

4.6.3 Experimental Compressive Test Results

The experimental compaction test results, exploring both honeycomb and woven orientations of bamboo fiber, indicated significant variations in compression stress and force between these two orientations.

Utilizing the honeycomb orientation of bamboo fiber, the average compressive stress was recorded to be approximately 57.6Mpa. This result was observed when the compressive force exerted to achieve this figure was around 7.22KN. These figures collectively highlight the strength characteristics of bamboo when oriented in a honeycomb pattern. The denser and organized structure of the honeycomb likely results in stronger compression resistance and higher compressive stress figures.

The test results of woven pattern oriented bamboo fiber showed a lower average compressive stress of about 50.86Mpa. This stress level was achieved at a slightly reduced compressive force of 6.35KN. Although lower than the honeycomb orientation, these results nonetheless demonstrate that the woven pattern possesses considerable strength properties.

It can be inferred from the results that the honeycomb orientation of bamboo fibers offers a higher compressive stress resistance under a larger compressive force. This suggests that the honeycomb orientation might be superior in function that requires significant strength-bearing capabilities.

However, the woven orientation still maintains fairly considerable compressive capabilities, suggesting it might be more suitable for applications requiring balance between strength and flexibility. Further testing and investigation are recommended to explore the potential applications of both orientations in various fields.

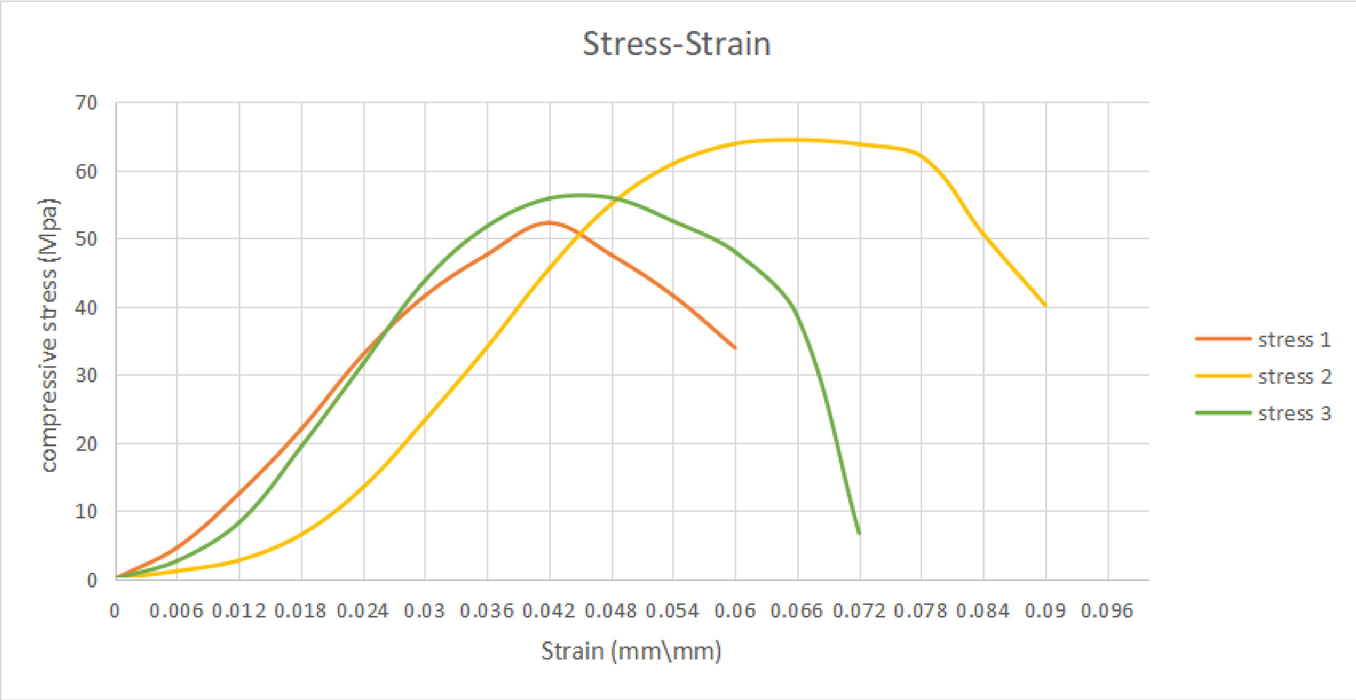


Figure 4.15: Stress-Strain curve of compressive test of honeycomb orientation Bamboo/epoxy composite

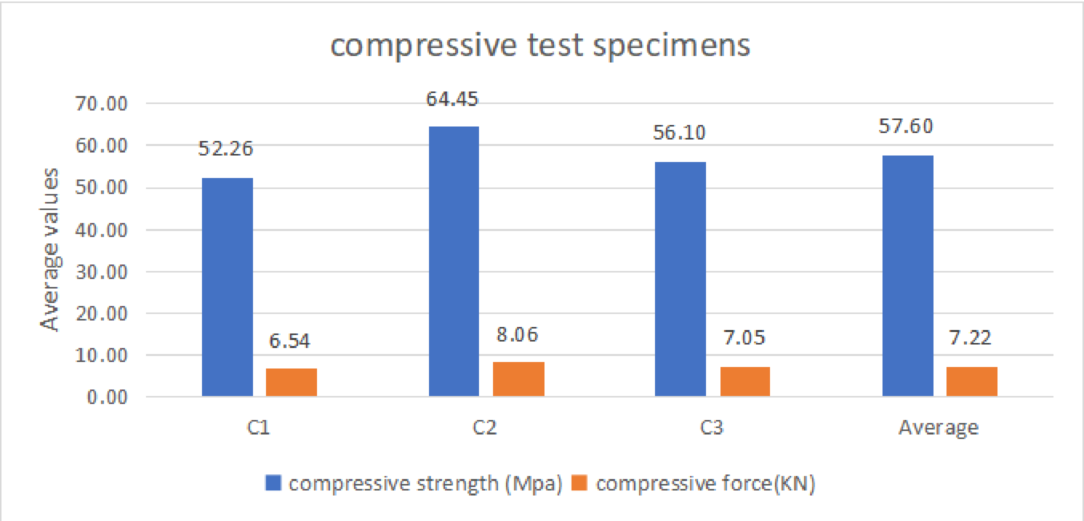


Figure 4.16: Compressive test results of the Bamboo/epoxy composite

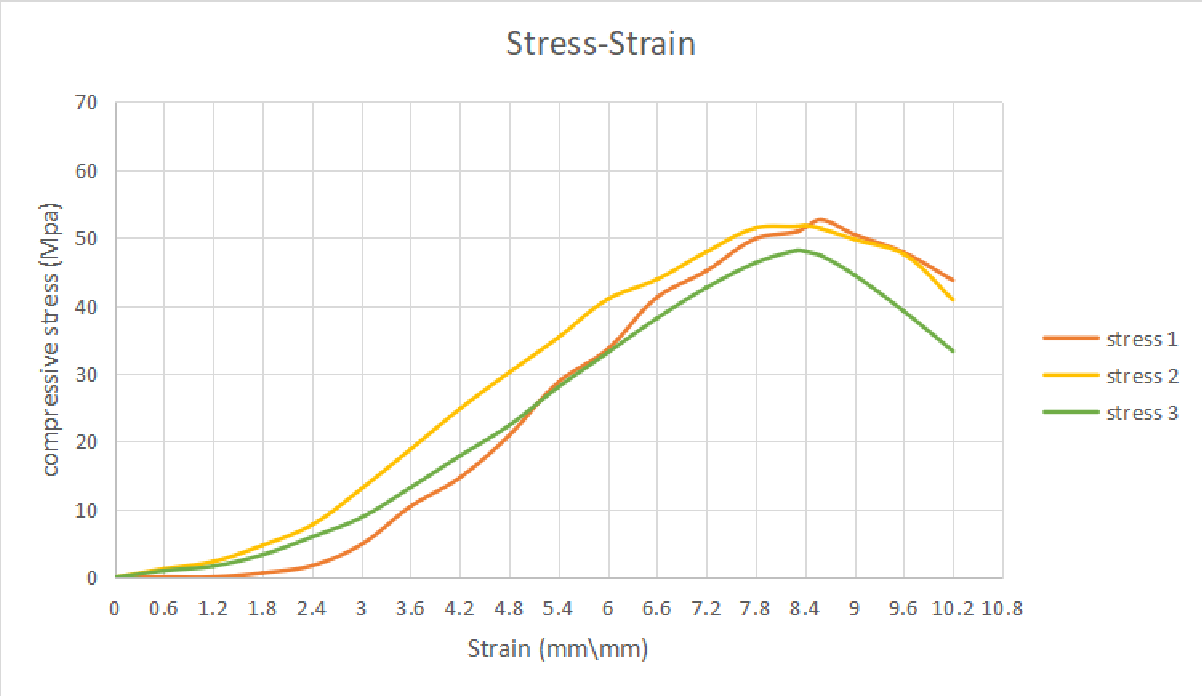


Figure 4.17: Stress-Strain curve of compressive test of woven orientation Bamboo/epoxy composite

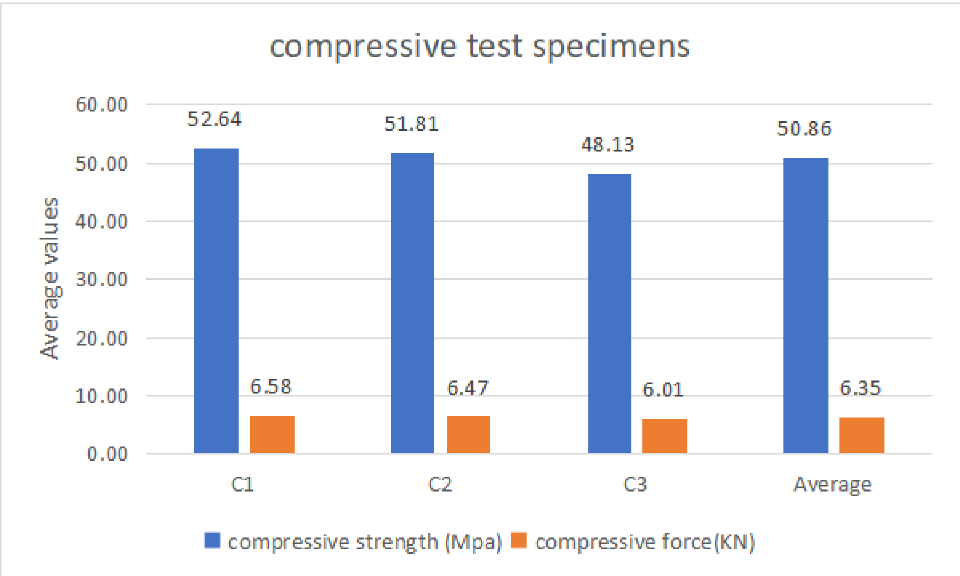


Figure 4.18: Compressive test results of the woven orientation of Bamboo/epoxy composite

4.6.4 Discussion and Comparison of compressive test Results

The experimental compressive test results using two different bamboo fiber orientations - honeycomb and woven - are discussed below.

During the experiments, three different specimens were tested in each setup: honeycomb and woven orientation of the bamboo fiber. In the case of the honeycomb orientation, the following results were observed:

- ✓ The first specimen yielded a compressive stress of 52.26 Mpa under a compressive force of 6.54KN.
- ✓ The second specimen exhibited a compressive stress of 64.45 Mpa at 8.06KN force.
- ✓ Lastly, the third specimen showed a compressive stress of 56.1 Mpa at 7.05KN force.

Thus, it can be seen that compressive stress results varied with the applied compressive force, exhibiting a likely progressive relationship.

On the other hand, the woven orientation of bamboo fiber yielded somewhat different results:

- ➢ The first specimen demonstrated a compressive stress result of 52.64 Mpa at a compressive force of 6.58KN.
- ➢ The second specimen displayed a compressive stress of 51.81 Mpa at a force of 6.47KN.
- ➢ The third specimen's compressive stress was computed at 48.13 Mpa under a 6.01KN force.

Notably, the woven orientation of bamboo fiber specimens displayed somewhat lower compressive stress results compared to the honeycomb orientation.

These test results allow us to compare the compressive capabilities and responses of bamboo fibers under different orientations and compressive forces. This can potentially guide further advanced research into optimizing the use of bamboo fibers and determining the best application conditions and orientations for them. The median values for the compressive test findings developed and contrasted with past research initiatives on the available literature are shown in Table 4.3.

Table 4.3: Compressive Test Result Comparison

Fiber + Matrix	Orientation	Fiber to matrix %	Fabrication method	Type of treatment	Compressive Strength (MPa)
Bamboo+Epoxy (Current work)	Honeycomb	35/65	Hand lay-up	NaOH 5%	57.6
Bamboo+Epoxy (Current work)	Woven	35/65	Hand lay-up	NaOH 5%	50.86
Bamboo and sisal + Epoxy [86]	Bi-woven mat	35/65	Hand lay-up	NaOH 5%	29.92
pineapple + Epoxy [92]	0/90 Bidirectional	40/60	Hand lay-up	NaOH 8%	81.27
Flax-ramie + Epoxy [93]	Random	35/65	Hand lay-up	-	130

4.6.5. Experimental Flexural Test Results

Experimental flexural test results were conducted using bamboo fiber with different orientations - honeycomb and woven. In the experiments performed, three specimens were tested under each orientation and the resulting flexural stresses were measured under varying flexural forces.

In the case of the honeycomb orientation, the first specimen displayed a flexural stress of 66.01 Mpa at a flexural force of 4.32 KN. The second specimen observed a slightly lower flexural stress at 63.17 Mpa, however, this was recorded at a lower flexural force of 3.7 KN. The third specimen exhibited a flexural stress of 64.46 Mpa when it was put under a flexural force of 4.17 KN. From these observations, it can be interpreted that the stress outcomes in the honeycomb orientation of bamboo fiber are reasonably consistent when the specimens are subjected to flexural forces between 3.7 KN and 4.32 KN.

Conversely, in the woven orientation of bamboo fiber, we observed somewhat different outcomes. The first specimen in this orientation registered a stress of 57.19 Mpa at a higher flexural force of 7.15 KN. The second specimen indicated a flexural stress of 60.24 Mpa as a response to a flexural force of 7.53 KN.

The third specimen experienced a flexural stress of 61.91 Mpa under a force of 7.73 KN. It is evident from these test results that the woven orientation of bamboo fiber may require more force to induce stress when compared to the honeycomb orientation.

These test results indicate that the bamboo fiber's orientation can significantly influence the material's performance under flexural forces. Therefore, choosing the appropriate orientation becomes critical based on the application and load conditions.

Table 4.4: Summary of Flexural test results

Test specimen	**Width (mm)**	**Thickness (mm)**	**Span length (mm)**	**Max. applied Force (KN)**	**Max. Flexural Strength (MPa)**
Specimen 1	12.5	5	100	4.32	66.01
Specimen 2	12.5	5	100	3.70	63.17
Specimen 3	12.5	5	100	4.17	64.46
Average values				4.06	64.55

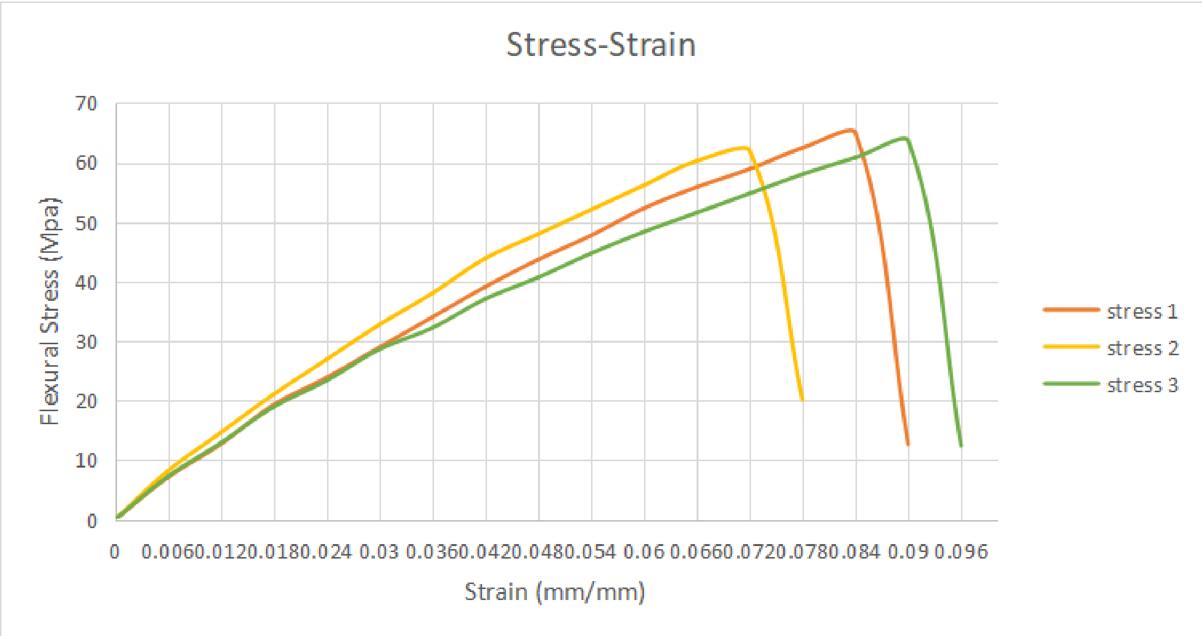


Figure 4.19: Flexural test results of the Bamboo/epoxy composite

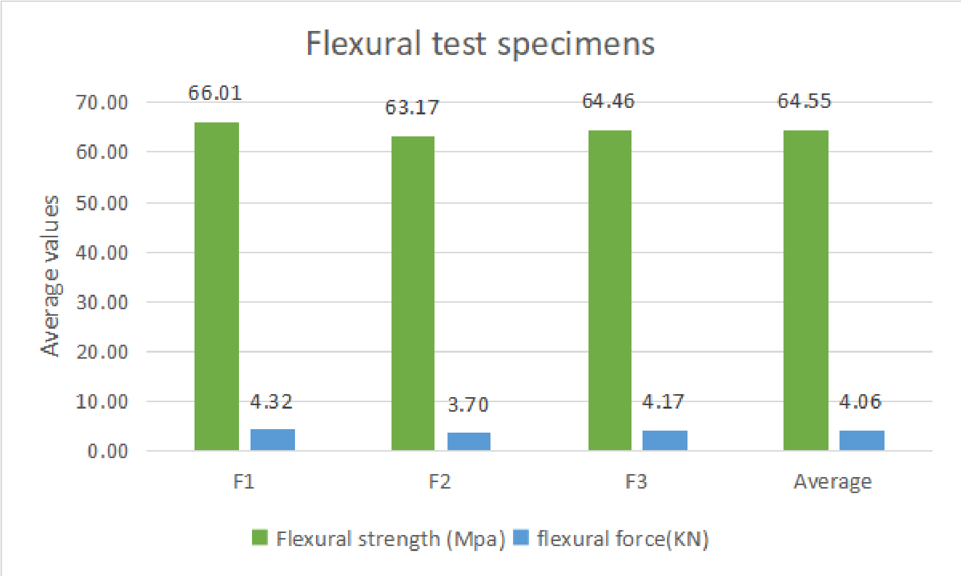


Figure 4.20: Flexural test results of the Bamboo/epoxy composite

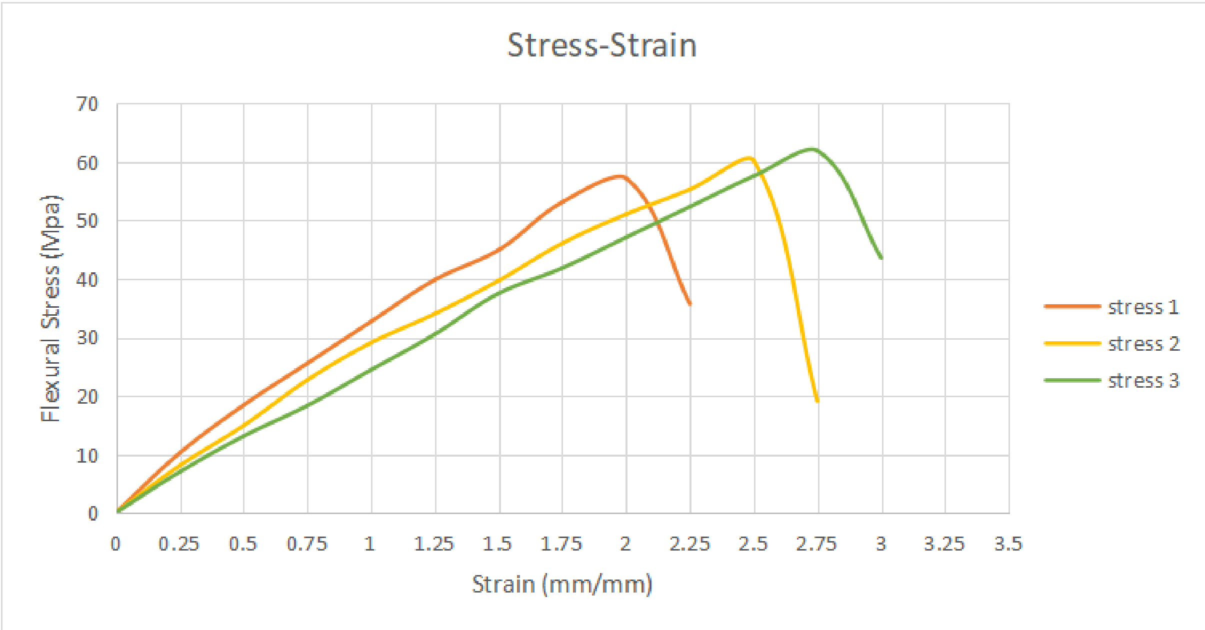


Figure 4.21: Flexural test results of the Bamboo/epoxy composite

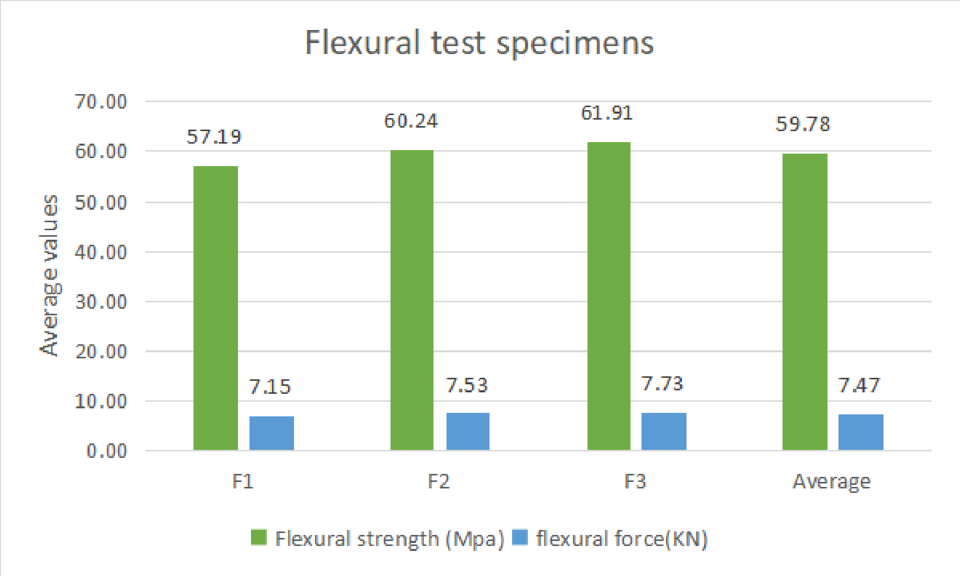


Figure 4.22: Flexural test results of the Bamboo/epoxy composite

4.6.6. Discussion and Comparison of flexural test Results

The flexural strength test of bamboo fiber with different orientations, namely honeycomb and woven, shows some clear differences which we shall analyze and compare here.

The first orientation, that is the honeycomb structure, yielded an average flexural stress of 64.55 Mpa with an applied force of 4.06 KN. The honeycomb arrangement, with its distinctive hexagonal shape, is known for its high strength-to-weight ratio. The results correlate with the knowledge that honeycomb orientation helps distribute the force more proportionally and optimally across the material, thus accounting for the high flexural stress value obtained at a relatively lower level of applied force.

On the contrary, the woven orientation yielded a slightly lower average of flexural stress, clocking in at 59.78 Mpa, even though a substantially higher force of 7.47 KN was applied. Woven structures, while offering good in-plane stiffness and strength, may not work as efficiently as honeycomb structures in bearing out-of-plane loading and might explain the comparatively lower stress-to-force ratio observed in the results.

From these results, it is observed that the honeycomb orientation for bamboo fiber exhibited higher values of flexural stress at a significantly lower applied force as compared to the woven orientation. This indicates the superior efficiency of the honeycomb structure in distributing force and maintaining structural integrity, thereby potentially making it more suitable for applications where high strength and efficiency are required under flexural loading.

It's important to note that as the structure and elements in the woven orientation are more closely packed, it can be more beneficial in situations where resistance to in-plane forces are crucial. On the other hand, the honeycomb orientation is more suitable for instances where the material is subjected to out-of-plane forces.

Therefore, while both orientations have their unique advantages, the honeycomb orientation demonstrated higher flexural stress results, thus indicating superior performance in this particular test. The specimen one in the three-point bending test for flexural strength had a higher value of 4.32 KN bending forces. The flexural strength found 66.01 MPa using the relations. In specimen two, the lowest values are seen. The test specimen average values were computed and compared to earlier investigations. The average value is 64.55 Mpa.

Table 4.5: Flexural Test Result Comparison

Fiber + Matrix (reference)	**Orientation**	**Fiber to matrix %**	**Fabrication method**	**Type of treatment**	**Flexural strength (MPa)**
Bamboo + Epoxy (Current work)	Honeycomb	35/65	Hand lay-up	NaOH 5%	64.55
Bamboo + Epoxy (Current work)	Woven	35/65	Hand lay-up	NaOH 5%	59.78
Bamboo/ sisal + Epoxy [90]	Random	30/70	Hand lay-up	NaOH 10%	54.1
Bamboo/ Sisal +Epoxy [86]	Bi-woven mat	35/35	Hand layup	NaOH 5%	46.81
Pineapple + Epoxy [92]	Random	40/60	Hand lay-up	NaOH 5%	62.3

4.6.7. Charpy Impact Test Results

The specimens were notched to generate a stress concentration area that precisely indicates the point of failure for the Charpy impact test in accordance with ASTM D256. The amount of impact energy received by each specimen under identical testing settings was displayed by the computer-controlled Charpy impact testing machine.

The Charpy Impact Test was conducted on two sets of bamboo fiber specimens, employing distinct fiber orientations: honeycomb and woven. The experiment was aimed at assessing the impact energy and toughness of the materials under test.

The first set featured three specimens arranged in a honeycomb orientation. The impact energy and toughness(J/cm^2) for these specimens were determined as follows:

- Specimen 1 recorded 4.79 J of impact energy and 13.31 J/cm2 of toughness.
- Specimen 2 registered slightly lower figures, with an impact energy of 4.66 J and toughness rate of 12.64 J/cm^2.
- Specimen 3 was in close range with the second, having measured an impact energy of 4.61 J and a toughness rating of 12.81 J/cm^2.

These results demonstrate a relative consistency in impact energy and toughness within the range, underscoring the stability of the honeycomb orientation in bamboo fibers.

A second test was then conducted using a woven bamboo fiber orientation. Here are the details for this set:

- ✓ Specimen 1 showed significantly lower impact energy and toughness values, specifically 1.03 J and 2.23 J/cm^2 respectively.
- ✓ Specimen 2 was marked by an improvement, achieving 2.07 J of impact energy and a toughness measure of 4.48 J/cm^2.
- ✓ Specimen 3 exhibited a further significant increase in both counts, with an impact energy value of 2.47 J and a toughness measurement of 5.34 J/cm^2.

When comparing the data from the two sets, it's clear that the bamboo fibers arranged in the honeycomb orientation provide a markedly higher impact energy and toughness than the woven orientation equivalents. This suggests that the honeycomb pattern contributes to creating a more resilient final product compared to the woven version.

The experimental data offer meaningful insights into bamboo fiber's potential performance, which can be leveraged in a variety of material design applications.

Table 4.6: Charpy Impact Test Results

Test Specimens	**Dimensions (mm)**	**Impact Energy (J)**	**Toughness (J/cm^2)**
Specimen 1	64x12.7x5	4.79	13.31
Specimen 2	64x12.7x5	4.66	12.64
Specimen 3	64x12.7x5	4.61	12.81
Average values		4.69	13.02

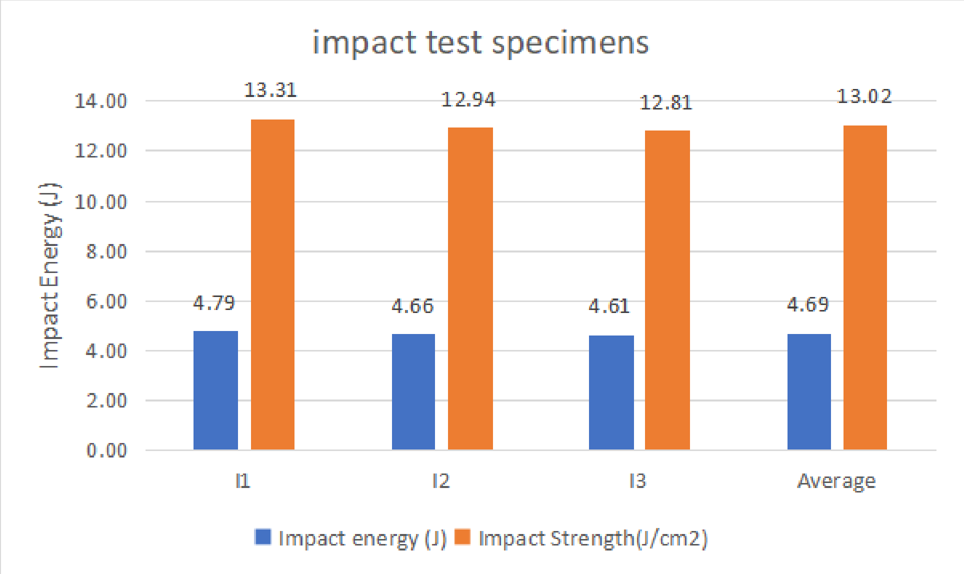


Figure 4.23: Impact (Charpy) test of the Bamboo/epoxy composite

Table 4.7 Impact results of the specimens

Test Specimen	Dimensions (mm)	Impact Energy (J)	Toughness (J/cm^2)
Specimen 1	64x12.7x5	1.03	2.23
Specimen 2	64x12.7x5	2.07	4.48
Specimen 3	64x12.7x5	2.47	5.34
Average values		1.86	4.02

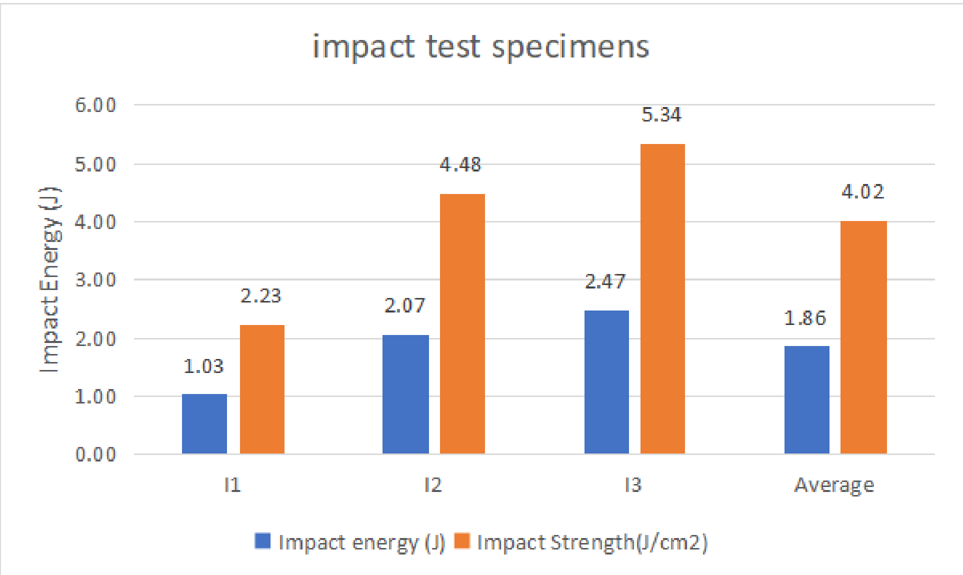


Figure 4.24: Impact (Charpy) test of woven orientation of Bamboo/epoxy composite

4.6.8. Discussion and Comparison of impact test Results

The Charpy Impact Test results of bamboo fiber specimens with different orientations – honeycomb and woven – lay industry emphasis on the importance of fiber composition on its toughness and impact energy. The tests reveal noteworthy differences in impact energy and toughness between the two orientations.

Under the honeycomb orientation of bamboo fiber, there is an average Charpy Impact Test Result of 4.69J impact energy, with toughness measuring at an average of 13.02 J/cm^2. This suggests that the honeycomb formation integrates a considerable amount of energy and is significantly tough under pressure. The characteristics of the honeycomb structure, which offers a better distribution of forces and optimizes the strength-to-weight ratio, seems to contribute to its superior results in terms of both impact energy and toughness.

On the contrary, bamboo fiber specimens with woven orientation demonstrated considerably lower Charpy Impact Test Results. With an average impact energy of 1.86J and a toughness measure average of 4.02 J/cm^2, the woven orientation evidently showed less capacity to absorb energy and withstand pressure compared to its honeycomb counterpart.

The substantial discrepancy between these two orientations of bamboo fibers underscores the influence of fiber organization in determining their mechanical properties. Specifically, the honeycomb orientation markedly outperforms the woven orientation in terms of toughness and absorbing impact energy. Thus, for applications where higher impact energy absorption and toughness are required, honeycomb orientation of bamboo fiber could be an advantageous option.

It should be noted, however, that while these results provide key insights, they should be viewed in light of two aspects: first, the inherent variations in bamboo fiber, a natural material, and second, the scope for further optimization of the woven fiber’s structure and composition to enhance its mechanical properties.

Table 4.8: Charpy Impact Test Result Comparison

Fiber+Matrix (reference)	Orientation	Fiber to matrix %	Fabrication method	Type of treatment	Impact Energy (J)	Impact strength (J/cm^2)
Bamboo + Epoxy (current work)	Honeycomb	35/65	Hand lay-up	NaOH 5%	4.69	13.02
Bamboo + Epoxy (current work)	Honeycomb	35/65	Hand lay-up	NaOH 5%	1.86	4.02
Bamboo/Sisal+ Epoxy [90]	Random	30/70	Hand lay-up	NaOH 10%	4.8	14.8
Bamboo/Sisal + Epoxy [86]	Bi-woven mat	35/65	Hand lay-up	NaOH 5%	4.18	4.4
Kenaf + Epoxy [94]	woven	40/60	Hand lay-up	NaOH 5%	4.05	16.7

4.6.9. Water Absorption Test Results

The experiment was carried out to determine water absorption levels in bamboo fiber, subjected to two different orientation configurations: honeycomb and woven.

For the honeycomb orientation, three specimens were tested. The first specimen demonstrated a wet weight of 6.85 grams, and, after drying, it weighed 6.73 grams. The difference in mass provides evidence of water absorption by the bamboo fiber. The second specimen had a wet weight of 6.38 grams which reduced to 6.23 grams upon drying, further reiterating the ability of the bamboo fiber to absorb water. Lastly, the third specimen evidenced a decrease in weight from 6.4 grams (wet) to 6.23 grams (dry).

In terms of the woven orientation configuration, the results varied somewhat from their honeycomb counterparts. The first specimen here displayed a wet weight of 4.11 grams, which lessened to 4.01 grams after drying. The recorded weights for the second specimen were 4.31 grams (wet) and 4.26 grams (dry). The third specimen, though initially weighing 4.14 grams when wet, reduced to 4.11 grams post-drying.

In summary, the water absorption test results clearly show a differential pattern based on the orientation of the bamboo fiber. The weights recorded during the experiment provide vital insight into the water absorption potential of bamboo fibers under applied conditions, making noteworthy observations on the impact of different fiber orientations on water absorptive capacities. The honeycomb orientation turns out to be more absorbent than the woven one, as apparent from the experimental data.

The formula for measuring the water absorption is

$$\frac{Ww-Wd}{Wd} * 100 \qquad (19)$$

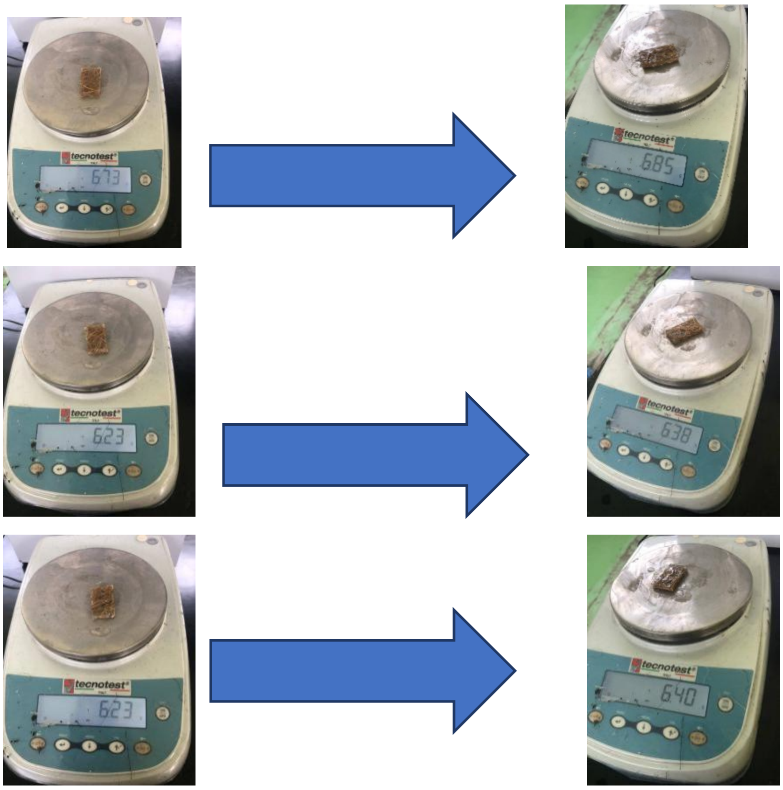


Figure 4.25 water absorption results of honeycomb orientated bamboo/epoxy composite

Table 4.9. Water absorption results of honeycomb orientation bamboo fiber

Test specimen	**Dry weight (grams)**	**Wet weight (grams)**	**Water absorption (%)**
Specimen A	6.73	6.85	1.79
Specimen B	6.23	6.38	2.41
Specimen C	6.23	6.4	2.73
Average	6.4	6.54	2.31

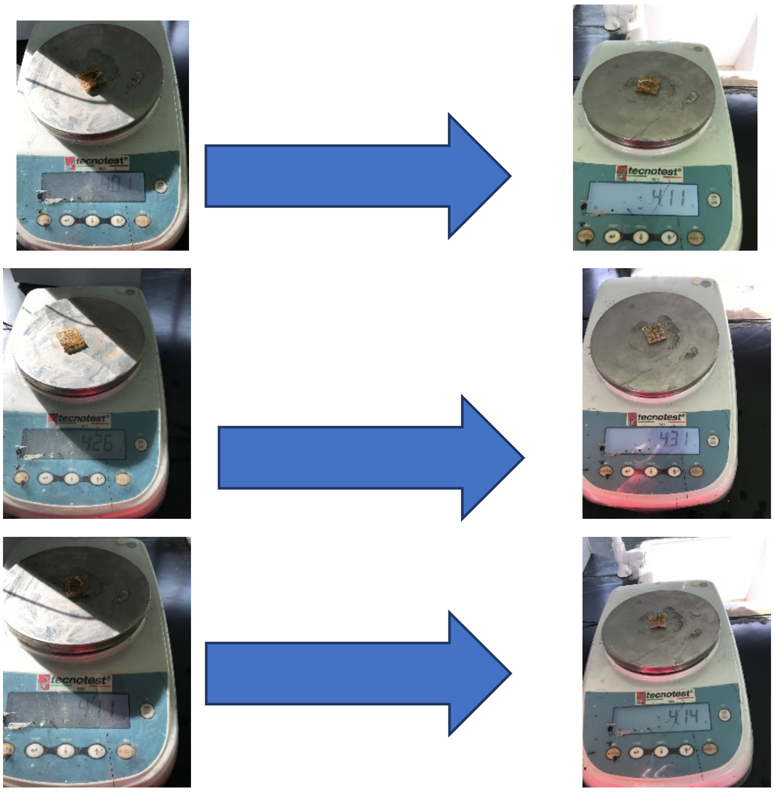


Figure 4.26 water absorption results of honeycomb orientated bamboo/epoxy composite

Table 4.10. Water absorption results of woven orientation bamboo fiber

Test specimen	**Dry weight (grams)**	**Wet weight (grams)**	**Water absorption (%)**
Specimen A	4.01	4.11	2.49
Specimen B	4.26	4.31	1.17
Specimen C	4.11	4.14	0.73
Average	6.4	6.54	1.46

The dry weight and wet weight of samples generated in accordance with ASTM standards was recorded and computed with the objective to determine the water absorption rate of each specimen and evaluate the overall water repellent capacity of the honey comb-oriented bamboo/epoxy composite.

In the honeycomb orientation, specimen 1 showed a water absorption of 0.12 grams (1.79% of its dry weight), specimen 2 showed an absorption of 0.15 grams (2.41% of its dry weight) and specimen 3 showed a water absorption of 0.17 grams (2.73% of its dry weight).

On the other hand, using the woven orientation of bamboo fiber, specimen 1 showed an absorption of 0.10 grams (2.49% of its dry weight), specimen 2 showed a water absorption of 0.05 grams (1.17% of its dry weight), and specimen 3 absorbed 0.03 grams (0.73% of its dry weight).

Comparatively, the honeycomb-oriented specimens absorbed more water than their woven counterparts, indicating that the orientation of bamboo fiber significantly influences its water absorption capacity. It is discernible from the percentage calculations that honeycomb oriented fibers have higher water retention capabilities, which can be utilized in applications requiring greater absorption. However, in scenarios that require less water absorption, woven orientation of bamboo fibers might be preferable due to their lower water retention capacity.

4.6.10. Discussion and Comparison of water absorption test Results

For the water absorption test, the samples were first weighed according to their dry weight before being immersed in water for 24 hours. A precise balance was used to weigh the dry specimens, and the difference in weight was used as a gauge to measure the extent to which the composite withstood water. Compared to the other specimens, specimen A exhibited more water resistance, whereas specimen C had the lowest level of water resistance. The bamboo/epoxy polymer composite with honeycomb orientation for prosthetic socket displayed an average water absorption of 2.31 percent. Evaluating the average outcomes in light of earlier research on relevant reinforcement and matrix type.

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Table 4.11. Water absorption comparison

Fiber and matrix	**Fiber Orientation**	**Fabrication method**	**Time absorption**	**Temperature**	**Water absorption %**	**Reference**
Bamboo + epoxy	Honeycomb	Hand layup	24hrs	Room temp	2.31	Current work
Bamboo + epoxy	Woven	Hand layup	24hrs	Room temp	1.46	Current work
Bamboo + epoxy	Bi-direction mat (0/90)	Hand layup	135 days	Room temp	8.4	[36]
Bamboo + epoxy	Woven	Hand layup	24hrs	Room temp	3.2	[95]
Sisal/ Coir and Epoxy	Random	Hand layup	24hr	Room temp	3	[96]

CHAPTER FIVE

Conclusion and Recommendations

5.1 Conclusion

This research study has examined and evaluated the properties of bamboo epoxy composite with reinforcement in a bio-imitated honeycomb design. There were done tests for compression, flexural, impact, tensile strength and water absorption. After carefully examining the honeycomb design, it discovered six sides of the same size that are stacked at an angle of 72 degrees from one another when the prepared layers of bamboo fiber hand layup knit single ply are stacked. Using the hexagon of a honeycomb design as the foundation, layers of composite material with a mix of 35% bamboo fiber and 65% epoxy resin are stacked in a sequence of 72 degrees, or [0, 72, 144, 216, 288]. The following succinct conclusions can be drawn from this experimental work:
Based on the experimental and numerical analysis results obtained for the composite material consisting of a bamboo fiber honeycomb orientation and epoxy matrix with a stacking sequence of 0/72/144/216/288, the following conclusions can be drawn:

Tensile Strength: The experimental tensile test yielded a value of 53.4 MPa, while the numerical analysis predicted a slightly higher value of 57.96 MPa. This indicates that the composite material has good tensile strength, which is essential for withstanding forces that may act to pull the material apart. The numerical analysis results align reasonably well with the experimental findings, suggesting that the chosen stacking sequence and material combination have been accurately modeled.

Compressive Strength: The experimental compressive strength was measured at 57.6 MPa, whereas the finite element (FE) analysis predicted a higher value of 61.75 MPa. These results demonstrate that the composite material exhibits adequate resistance to compressive forces, which are important for applications where the material needs to withstand crushing or buckling loads. The FE analysis provides a slightly higher compressive strength prediction, indicating the potential for improved performance compared to the experimental results.

Flexural Strength: The experimental flexural strength was determined to be 64.55 MPa, while the FE analysis predicted a higher value of 70.19 MPa. This indicates that the composite material possesses good resistance to bending forces, which is crucial for applications that involve bending or flexing of the material.

The FE analysis suggests a slightly higher flexural strength, indicating a potential for improved performance compared to the experimental findings.

Overall, the results obtained from both the experimental and numerical analyses indicate that the composite material made from a bamboo fiber honeycomb orientation and epoxy matrix, with the specific stacking sequence of 0/72/144/216/288, exhibits promising mechanical properties for prosthetic socket applications. The material demonstrates good tensile, compressive, and flexural strength, which are vital characteristics for providing structural integrity and durability in such applications.

Further research and development can focus on optimizing the composite material's properties, exploring additional mechanical tests, and investigating its long-term durability and biocompatibility for prosthetic socket applications. Additionally, the potential for cost-effective manufacturing techniques, sustainability considerations, and the overall feasibility of implementing such a composite material in a real-world prosthetic socket design should be explored in future studies.

In this experiment, the mechanical properties of an epoxy and bamboo fiber composite with a honeycomb configuration is examined. While working on this project, learned a lot about natural fibers, and this project report includes the results of the mechanical tests that did on the materials. The results of the tests indicate that the composite made of bamboo fibers structured like a honeycomb and epoxy resin has good mechanical capabilities.

5.2 Recommendations

This thesis appears to be a promising contribution to the field of prosthetics.

The use of composite materials in prosthetic sockets has gained attention due to their favorable mechanical properties and lightweight nature. This thesis takes an unusual tack by delving into the production and characterization of a composite material produced from bamboo fiber and epoxy. The mechanical characteristics of the composite material are further improved by using a honeycomb arrangement. Prosthetic socket design is a complex process that requires careful consideration of several factors such as comfort, fit, durability, and cost-effectiveness. The material used in the socket plays a significant role in determining these factors. This thesis aims to create a composite material with superior mechanical properties that can meet the requirements of prosthetic sockets.

Overall, this thesis has the potential to advance the development of prosthetic socket materials while contributing to the ongoing research in the area of composite materials. I recommend this thesis for further investigation and dissemination to the relevant stakeholders in the field of prosthetics.

5.3 Future Works

- The prospective research areas for honeycomb pattern fiber reinforced composite materials are listed below.
- Examine how the thickness of the ply affects the bamboo epoxy composite's strength in honeycomb orientations.
- Study the effects of thermal development and its compatibility with amputees' biological legs as well as the fatigue failure characteristics of bamboo epoxy composite in honeycomb orientations used in ankle socket applications.
- Research the fracture toughness and failure modes of honeycomb-oriented reinforced epoxy composite.
- Fiber length is one of the factors that may influence how a composite is produced, and its impact on the material's mechanical, chemical, and erosive qualities can be researched.
- The hand layup approach has been adopted in the current study to fabricate composites, as far as fabrication technique is concerned. It is advised to employ injection molding to create composite test samples since it is more accurate and helps to minimize human error.
- Although the influence of temperature on water absorption might be examined as future research, the resistance on water absorption of composites have been studied in the current work.
- Studying the impact of chemicals on the composites' mechanical characteristics is another worthwhile endeavor. Other chemical characteristics including bamboo epoxy composites' ability to absorb moisture and their swelling and wearing characteristics can also be researched.

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Appendices

Appendix-A

Compression test specimen C001 results

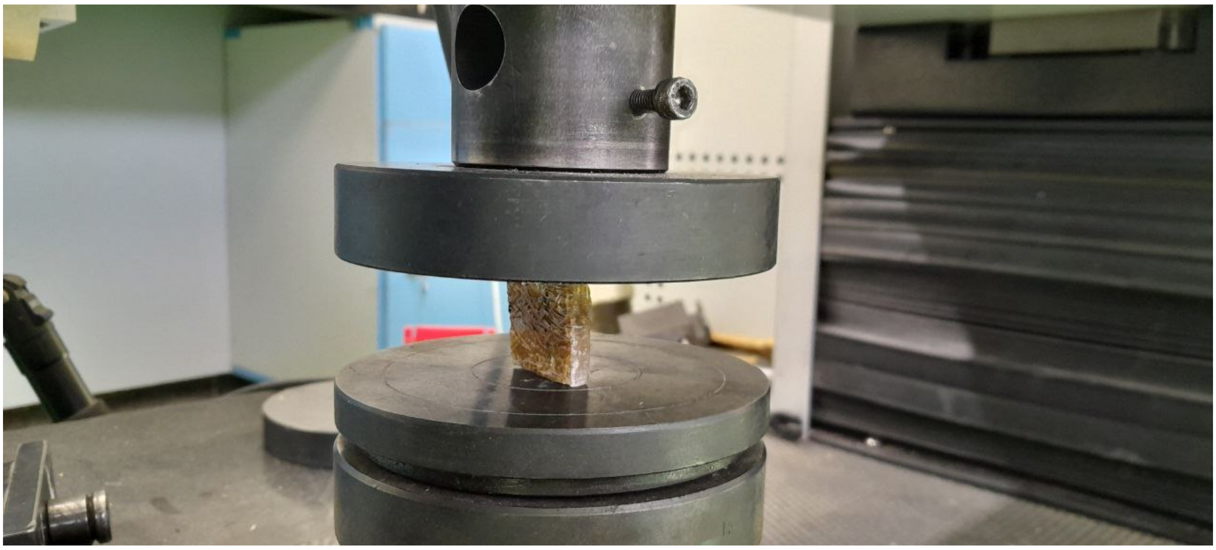
Time	Load	Elong	Disp	Stress	Strain	Width
59.4	6.261	1.9474	-1.981	50.089	3.895	0.000
59.5	6.266	1.9507	-1.984	50.128	3.901	0.000
59.6	6.271	1.9541	-1.988	50.166	3.908	0.000
59.7	6.274	1.9574	-1.991	50.192	3.915	0.000
59.799	6.279	1.9607	-1.994	50.231	3.921	0.000
59.9	6.282	1.9641	-1.998	50.257	3.928	0.000
60	6.284	1.9674	-2.001	50.27	3.935	0.000
60.1	6.289	1.9707	-2.004	50.309	3.941	0.000
60.2	6.29	1.9741	-2.008	50.322	3.948	0.000
60.299	6.295	1.9774	-2.011	50.361	3.955	0.000
60.4	6.302	1.9807	-2.014	50.413	3.961	0.000
60.5	6.307	1.9841	-2.018	50.452	3.968	0.000
60.6	6.316	1.9874	-2.021	50.53	3.975	0.000
60.7	6.323	1.9908	-2.024	50.582	3.982	0.000
60.799	6.329	1.9941	-2.028	50.634	3.988	0.000
60.9	6.339	1.9974	-2.031	50.712	3.995	0.000
61	6.349	2.0008	-2.034	50.79	4.002	0.000
61.1	6.355	2.0041	-2.038	50.842	4.008	0.000
61.2	6.367	2.0074	-2.041	50.933	4.015	0.000
61.299	6.376	2.0107	-2.044	51.011	4.021	0.000
61.4	6.388	2.0141	-2.048	51.101	4.028	0.000
61.5	6.396	2.0174	-2.051	51.166	4.035	0.000
61.6	6.406	2.0207	-2.054	51.244	4.041	0.000
61.7	6.414	2.0241	-2.058	51.309	4.048	0.000
61.799	6.422	2.0274	-2.061	51.374	4.055	0.000
61.9	6.433	2.0307	-2.064	51.465	4.061	0.000
62	6.44	2.0341	-2.068	51.517	4.068	0.000
62.1	6.449	2.0374	-2.071	51.595	4.075	0.000

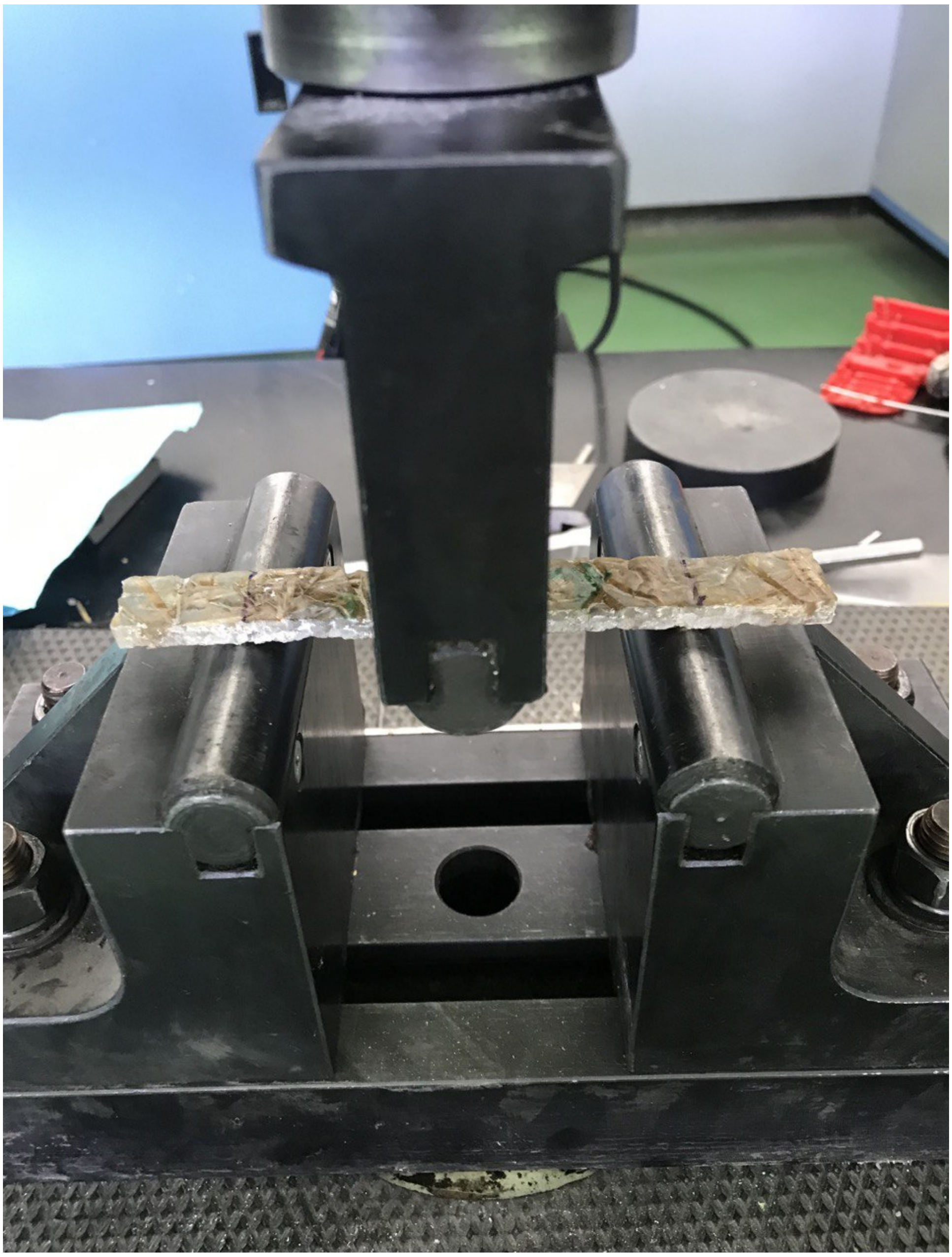
62.2	6.457	2.0407	-2.074	51.66	4.081	0.000
62.299	6.467	2.044	-2.078	51.738	4.088	0.000
62.4	6.477	2.0474	-2.081	51.816	4.095	0.000
62.5	6.485	2.0507	-2.084	51.881	4.101	0.000
62.6	6.492	2.0541	-2.088	51.933	4.108	0.000
62.7	6.5	2.0574	-2.091	51.998	4.115	0.000
62.799	6.508	2.0607	-2.094	52.062	4.121	0.000
62.9	6.511	2.0641	-2.098	52.088	4.128	0.000
63	6.518	2.0674	-2.101	52.14	4.135	0.000
63.1	6.526	2.0707	-2.104	52.205	4.141	0.000
63.2	6.532	2.0741	-2.108	52.257	4.148	0.000
63.299	6.537	2.0774	-2.111	52.296	4.155	0.000
63.4	6.54	2.0808	-2.114	52.322	4.162	0.000
63.5	6.542	2.0841	-2.118	52.335	4.168	0.000
63.6	6.545	2.0874	-2.121	52.361	4.175	0.000
63.7	6.545	2.0908	-2.124	52.361	4.182	0.000
63.799	6.544	2.0941	-2.128	52.348	4.188	0.000
63.9	6.539	2.0974	-2.131	52.309	4.195	0.000
64	6.532	2.1007	-2.134	52.257	4.201	0.000
64.1	6.524	2.1041	-2.138	52.192	4.208	0.000
64.2	6.519	2.1074	-2.141	52.153	4.215	0.000
64.299	6.514	2.1107	-2.144	52.114	4.221	0.000
64.4	6.513	2.1141	-2.148	52.101	4.228	0.000
64.5	6.508	2.1174	-2.151	52.062	4.235	0.000
64.6	6.5	2.1207	-2.154	51.998	4.241	0.000
64.7	6.495	2.1241	-2.158	51.959	4.248	0.000
64.799	6.492	2.1274	-2.161	51.933	4.255	0.000
64.9	6.487	2.1307	-2.164	51.894	4.261	0.000
65	6.487	2.1341	-2.168	51.894	4.268	0.000
65.1	6.483	2.1374	-2.171	51.868	4.275	0.000
65.2	6.485	2.1407	-2.174	51.881	4.281	0.000
65.299	6.487	2.144	-2.178	51.894	4.288	0.000
65.4	6.487	2.1474	-2.181	51.894	4.295	0.000
65.5	6.482	2.1507	-2.184	51.855	4.301	0.000
65.6	6.48	2.1541	-2.188	51.842	4.308	0.000

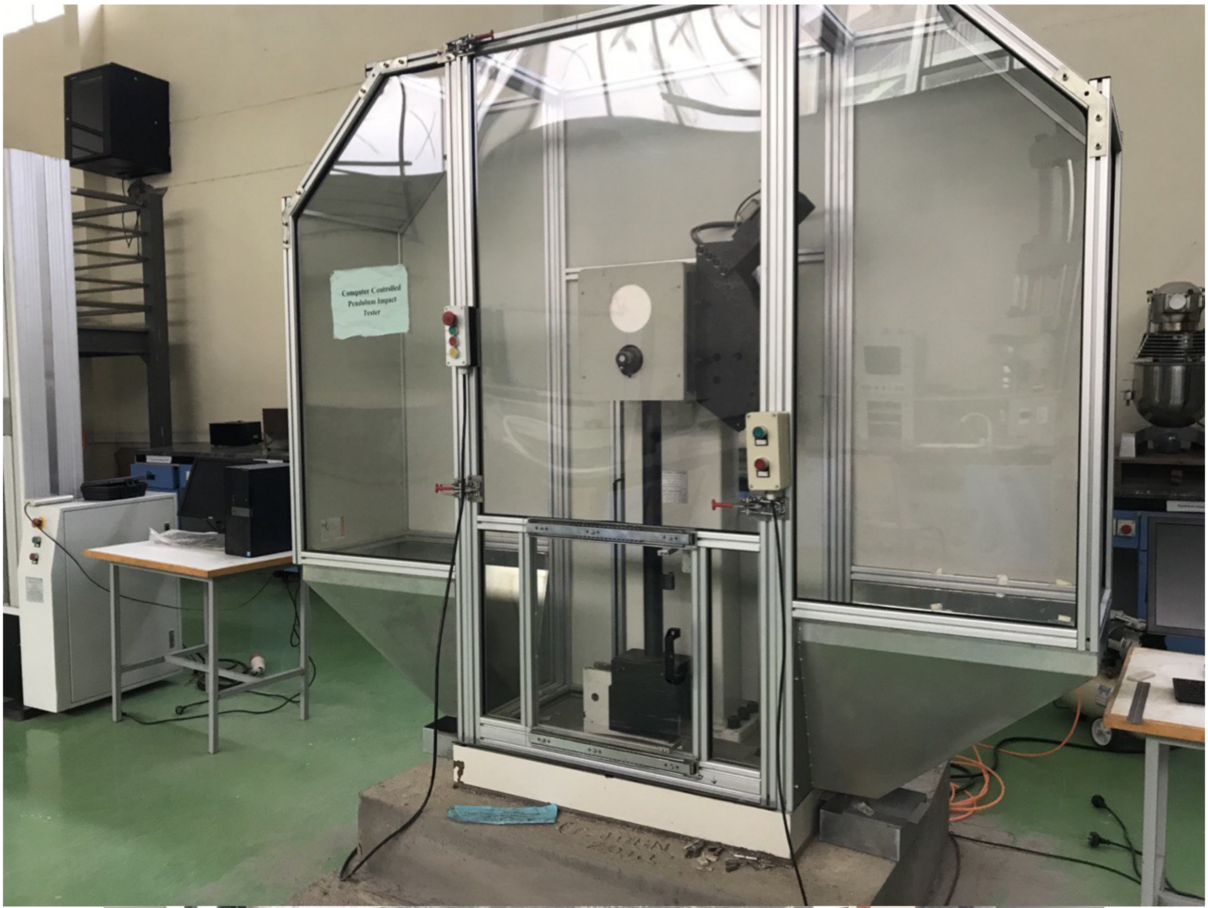
65.7	6.475	2.1574	-2.191	51.803	4.315	0.000
65.799	6.472	2.1607	-2.194	51.777	4.321	0.000
65.9	6.467	2.1641	-2.198	51.738	4.328	0.000
66	6.454	2.1674	-2.201	51.634	4.335	0.000
66.1	6.446	2.1708	-2.204	51.569	4.342	0.000
66.2	6.44	2.1741	-2.208	51.517	4.348	0.000
66.299	6.422	2.1774	-2.211	51.374	4.355	0.000
66.4	6.406	2.1808	-2.214	51.244	4.362	0.000
66.5	6.394	2.1841	-2.218	51.153	4.368	0.000
66.6	6.384	2.1874	-2.221	51.076	4.375	0.000
66.7	6.373	2.1907	-2.224	50.985	4.381	0.000
66.799	6.358	2.194	-2.228	50.868	4.388	0.000
66.9	6.344	2.1974	-2.231	50.751	4.395	0.000
67	6.337	2.2007	-2.234	50.699	4.401	0.000
67.1	6.334	2.1979	-2.238	50.673	4.396	0.000
67.2	6.329	2.2019	-2.241	50.634	4.404	0.000
67.299	6.329	2.2058	-2.244	50.634	4.412	0.000
67.4	6.329	2.2096	-2.248	50.634	4.419	0.000
67.5	6.328	2.2133	-2.251	50.621	4.427	0.000
67.6	6.324	2.2169	-2.254	50.595	4.434	0.000
67.7	6.324	2.2204	-2.258	50.595	4.441	0.000
67.799	6.326	2.2238	-2.261	50.608	4.448	0.000
67.9	6.326	2.2273	-2.264	50.608	4.455	0.000
68	6.323	2.2307	-2.268	50.582	4.461	0.000
68.1	6.316	2.2341	-2.271	50.53	4.468	0.000
68.2	6.313	2.2374	-2.274	50.504	4.475	0.000
68.299	6.316	2.2407	-2.278	50.53	4.481	0.000
68.4	6.316	2.2441	-2.281	50.53	4.488	0.000
68.5	6.321	2.2474	-2.284	50.569	4.495	0.000
68.6	6.316	2.2508	-2.288	50.53	4.502	0.000
68.7	6.313	2.2541	-2.291	50.504	4.508	0.000
68.799	6.307	2.2574	-2.294	50.452	4.515	0.000

Appendix-B

Specimens during testing






Computer Controlled
Pendulum Impact
Tester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Voltage
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Model
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Power
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Serial No.
031068
Hz
50HZ
Date
2016.12

Impact test