# ADDIS ABABA UNIVERSITY
# INSTITUTE OF TECHNOLOGY
# SCHOOL OF GRADUATE STUDIES

# Design and Analysis of Bamboo and E-Glass Fiber Reinforced Epoxy Hybrid Composite for Wind Turbine Blade Shell

**A Thesis Submitted to the Graduate School of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Masters of Science**

**In**

**Mechanical Engineering (Mechanical Design)**

**By: Abiy Alene**

**Advisor: Dr. Daniel Tilahun**

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**Addis Ababa University**
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**School of Mechanical and Industrial Engineering**

# Design and Analysis of Bamboo and E-Glass Fiber Reinforced Epoxy Hybrid Composite for Wind Turbine Blade Shell

**By**

**Abiy Alene**

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This is to certify that the thesis prepared by **Abiy Alene**, entitled: **Design and Analysis of Bamboo and E-glass fiber Reinforced Epoxy Hybrid Composite for Wind Turbine Blade Shell**, do here by declare this thesis is my original work and that it has not been submitted partially, or in full for a degree in any university/institution, which compiles with the regulations of the university and meets the accepted standards with respect to originality and quality.

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# Abstract

*Design and Analysis of Bamboo and E-glass Fiber Reinforced Epoxy Hybrid Composite for Wind Turbine Blade Shell*

*Abiy Alene*

*Addis Ababa University, 2013*

The main goal of this study is to investigate the performance of bamboo and E-glass fiber reinforced epoxy hybrid composite (BGREC) with different unidirectional (UD) of bamboo to E-glass fiber fraction for wind turbine blade shell application. Manual method of bamboo fiber extraction from Ethiopian highland bamboo *'Yushania Alpina'* species was undertaken.

A 5% sodium hydroxide was used for further lignin, hemicellulose and other fiber remnants removal for the improvement of bond & interfacial shear strength of the bamboo fiber.

Next, BGREC was fabricated with 45% total fiber volume fraction. Of this total fiber volume, the composite is fabricated in different bamboo to E-glass fiber ratio using hand lay-up vacuum assisted technique. Then tensile, in-plane shear, compressive, and flexural tests were carried out. A bamboo to E-glass fiber ratio of 0:100 was found a higher tensile strength; whereas bamboo to E-glass fiber ratio of 50:50 had higher compressive strength. Similarly, a bamboo to E-glass fiber ratio of 50:50 had higher elastic modulus for all the tests carried out. At the end, surface morphology of bamboo fiber; and tensile fractured surfaces morphology, homogeneity & porosity of BGFRECs were observed using SEM. The result showed that the bamboo fibers experienced a substantial changes occurred during alkaline treatment, and good result also attained from interaction among bamboo & E-glass with epoxy. Furthermore, it is found out that the bamboo and E-glass fiber ratio of 50:50 output can have a potential to be used for wind turbine blade shell construction.

***Key words***: Bamboo, E-glass, Epoxy, composite, Alkaline, blade, shell

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## Nomenclature

| | |
|---|---|
| $W_f$ | weight of Fiber (g) |
| $W_m$ | weight of Matrix (g) |
| $Wc$ | weight of composite specimen (g) |
| $\rho_f$ | Density of Fiber (g/cc) |
| $\rho_b$ | Density of bamboo fiber (g/cc) |
| $\rho_m$ | Density of Matrix (g/cc) |
| $V_f$ | Volume of fibers, ($cm^3$) |
| $V_m$ | Volume of matrix, ($cm^3$) |
| $V_C$ | Volume of Composite specimen ($cm^3$) |
| WF | Fiber weight fraction |
| WM | Matrix weight fraction |
| VF | Fibers Volume fraction |
| VM | Matrix Volume fraction |
| $\hbar$ : | Ply thickness (mm) |
| $M_b$ | Mass of bamboo fiber |
| $L_b$ | Length of bamboo fiber |
| $D_b$ | Density of bamboo fiber |
| $\sigma$ | Stress (MPa) |
| $\varepsilon$ | Strain (mm/mm) |
| $\tau_{12}$ | Shear stress (MPa) |
| $\gamma$ | Shear Strain (mm/mm) |
| $G_{12}$ | Shear modulus (MPa) |

## List of Abbreviations and Acronyms

| | |
|---|---|
| ASTM | America Society for Testing and Material |
| UD | Unidirectional |
| Eq. | Equation |
| cc | cubic centimeter |
| SEM | Scanning Electron Microscopy |
| BGREC | Bamboo-Glass fiber reinforced Epoxy hybrid composite |
| VBAHT | Vacuum bagging Assisted Hand Lay-up technique |
| UTM | Universal Testing Machine |
| cfm | cubic feet per minute |
| EEPCO | Ethiopian Electric Power Corporation |
| Davi | Dejen Aviation Industry |
| m | meter |
| mm | millimeter |
| nm | nanometer |
| X | one hundred times |
| kx | one thousand times |
| min | minute |
| AGM | failure mode: **Angled**, failure area: **Gage**, failure location: **Middle** |
| BBB | failure mode: **Buckling**, failure area: **Between loading noses**, failure location: **Bottom** |
| BGM | failure mode: **Brooming**, failure area: **Gage**, failure location: **Middle** |
| CBT | failure mode: **Compression**, failure area: **Between loading noses**, failure location: **Top** |
| DGM | failure mode: **edge Delamination**, failure area: **Gage**, failure location: **Middle** |
| LGM | failure mode: **Lateral**, failure area: **Gage**, failure location: **Middle** |
| MUV | failure mode: **Multi-mode**, failure area: **Unknown**, failure location: **Various** |
| TAM | failure mode: **Tension**, failure area: **At loading nose**, failure location: **Middle** |
| TAT | failure mode: **Transverse shear**, failure area: **At grip/tab**, failure location: **Top** |
| XGM | failure mode: **eXplosive**, failure area: **Gage**, failure location: **Middle** |

# CHAPTER 1: INTRODUCTION

## 1.1. Introduction

Energy is one of unfulfilled human need, in which humans being are explored many things in order to fulfil this desire. Even though there are different sources of energy, wind energy is technically the second most important resource next to hydropower for power generation. Wind energy represents a mainstream energy source of new power generation and an important player in the world's energy market. Beside this, wind power is renewable clean energy with short construction periods, it has significant advantage of quick results [1, 2].

A wind turbine transforms the kinetic energy in the wind to mechanical energy in a shaft and finally into electrical energy in a generator. The maximum available energy is thus obtained if theoretically the wind speed could be reduced to zero: $P=1/2mV_o^2= 1/2\rho AV_o^3$, where p is wind energy, m is the mass flow, $V_o$ is the wind speed, ρ the density of the air and A the area where the wind speed has been reduced. The equation for the maximum available power is very important since it tells us that power increases with the cube of the wind speed and only linearly with density and area. The available wind speed at a given site is therefore often first measured over a period of time before a project is initiated [2].

Due to great potential of wind energy source, i.e. the capacity is 18645MW, 4925MW, and 2005MW with wind speed of 7.5~8m/s, 8~8.8m/s, and more than 8.8m/s respectively at a height of 50m, Ethiopia has developed 51MW wind power with 34 turbine units of each 1500kW capacity (large size turbine blade types) from Adama wind farm projects phase1 [3]. Ashegoda Wind Farm Project site is also on going to generate another 120MW source of wind power. Adama Phase 2 project also is now under construction in order to produce another 100MW electric power. Since 2010, the feasibility study is conducting to construct another wind power farm in addition to Adama and Ashegoda in Debre Birhan project.

The large sized wind turbine blades are made from fibre-reinforced plastics (FRP) owing to the materials' superior strength-to-weight ratio compared to wood and metals [1, 2, 4, and 5]. The major parts of a modern turbine cost (% of total): tower 22%, blades 18%, gearbox 14%, and generator 8% of the total cost. Unfortunately, most materials they used for blade construction are synthetic, which are non-biodegradable in their biological process. This causes synergetic effect on our eco-system. To alleviate this problems, now a day the progress of exploration of materials that are environmental friendly, '*natural plants'*, have been ongoing [6, 7].

## 1.2. Background of the Study

Wind turbine is a complex system consisting of several components where turbine blades form key structural elements for achieving higher power generation [8].

The first wind turbine for electric power generation was built by the company S. Morgan-Smith at Grandpa's Knob in Vermont, USA, in 1941. The turbine was equipped with massive steel blades. One of the blades failed after only a few hundred hours of intermittent operation. Thus, the importance of the proper choice of materials and inherent limitations of metals as a wind blade material was demonstrated just at the beginning of the history of wind energy development. The next, quite successful example of wind turbine for energy generation is so called *Gedser wind turbine*, built by Johannes Juul in 1956-57. The turbine was produced already with composite blades, built from steel spars, with aluminum shells supported by wooden ribs. It was the first success story of wind energy: it has run for 11 years without maintenance [9, 10].

Since 1970s, most of wind turbines are producing with composite materials. Materials such as wood, steel, aluminum, glass-fiber-reinforced plastics (GRPs) and carbon fiber reinforced plastics (CFRPs) have been used [2, 7].

The choice of wind turbine blade materials design usually depends on many parameters such as strength, weight, stiffness, price, fatigue properties, load bearing capacity (tensile strength) and the ability to withstand bending (flexural strength). In addtion The blades must be stiff enough to avoid hitting the towers when deflected by the wind loads. In view of these requirements, only materials with the very high strength, fatigue resistance and stiffness – i.e., composites, are only choice in wind turbine blades design [1, 2, 4].

As of 2013, production wind turbine blades are as large as 120 meters in diameter. Within 2001, an estimated 50 million kilograms of *fiber glass* laminate were used in wind turbine blades [7, 9]. However, problems encountered with the commonly used fiber composite materials like carbon and glass are rise in cost, non-renewable material, the pollution of the environment due to industrial process etc. are common in the globe [6, 7].

One of the directions for solutions is to look for new material applications: recycling and reuse, sustainable production of products, or use of renewable resources.

Attention has to be given to materials such as vegetable fibers including jute, wastes from industry, mining and agricultural products for engineering applications to control environmental degradation and to minimize cost [11].

Natural fibres have become popular reinforcement material for fibre reinforced polymer composite developments. These reinforcement can replace the conventional fibre, such as glass as an alternative material. Other than these natural fibers, bamboo is another interesting material considered as plant fibre and has a great potential to be used in polymer composite industry, especially in wind turbine blade design [6, 8, 12].

According to [6, 11, 12, 13, and 14], bamboo is one of the ecological materials for which it has many distinct characteristics such as:

- It reaches its maximum strength in just few years;
- It is renewable material;
- Have simple production process;
- Have fairly good mechanical properties
- High specific strength, non-abrasive, eco-friendly and bio-degradability characteristics.
- Have low cost and weight etc.

Ethiopia is planning to use wind power plants in addition to the existing hydropower plants to supply the increasing load demand to insure its sustainable development. Components of this wind turbine are imported from the abroad [3]. However, the cost of these components are much high because of the material they made. From its economical points of view, wind turbine blade for this wind power plants can be localize by using local materials that can be fulfill the turbine blades requirement.

According to [1, 2 and 4], materials of wind turbine blades should have properties of:

- Good strength;
- Good load bearing capacity (tensile strength) and ability to withstand bending;
- Good stiffness;
- Environment friendly;
- Low weight and
- Low cost

From the above mentioned wind turbine blades properties aspect, bamboo fiber has been selected in this study for the hybridization with synthetic fiber, i.e. E-glass fiber.

Moreover bamboo fiber has been utilized in this study from the fact that [6, 11, 12, 15 and 16]:

- Ethiopia has Africa’s biggest bamboo resources, i.e. excess of bamboo plant is available.
- The mechanical properties of bamboo fiber is much higher than that of other natural plants.
- From its cost and environmental pollution aspects, bamboo is a better material.
- The weight of fiber obtained from bamboo is much lower than glass fibers and other natural fibers, which is one of important parameters for wind turbine blade design.

Even though this natural plant has the aforementioned characteristics, in the previous years, sufficient studies have not been made on bamboo fibers as reinforcement of super structural materials. The main trouble for the application of bamboo as a reinforcement, still is the lack of sufficient information about its interaction with other synthetic fibers & problem of moisture absorption

This study tried to fill this gap & presents the results of experimental study carried out and a concise summary of the information about the tensile, compressive, flexural, shear and bond strength of bamboo and glass-fiber composite. Finally conclusion had drawn about bamboo’s fiber application for wind turbine blade shell structure.

## 1.3. Problem of the Statement

Ethiopia has a surplus amount of bamboo plant, which has a great potential that can be used as structural material. Beside this fact, the contribution of bamboo plant on agro-economic sector of the country is negligible as compared to other countries.
Moreover, due to an immaturity of awareness about this plant and unavailability of experimental tools, the performance and applications Ethiopian bamboo fibers is not investigated before.

On the other hand, large amount synthetic fibers is used in for wind turbine blade construction. However, these synthetic fibers can cause for environment pollution in both during fiber extraction and during disposal of the used composite materials cases.

Furthermore, the cost of modern wind turbine is higher, and even sometimes another type of energy sources are more preferable from this aspect.

## 1.4. Objective of the Study

The general objective of this study is to design and analyze of UD bamboo and E-glass-fiber reinforced epoxy hybrid composite in order to evaluate its performance for wind turbine blade shell application.

The specific objective of this theses include

- Selection of bamboo with better mechanical characteristics that give better fiber properties
- Extraction of bamboo fibers from Ethiopian highland bamboo.
- Assessing of wind turbine blade design requirements and material properties
- Chemical treatment of bamboo fibres to improve its stiffness & interfacial adhesion
- Determination of fiber and matrix contents of the hybrid composite
- Design of composites plies and laminates
- Preparation of bamboo & E-glass reinforced epoxy hybrid laminates
- Experimental investigation of tensile, shear, compressive and flexural strength.
- Determination of modulus of elasticity for the proposed materials.
- Identification of different failure types
- Morphology analysis of bamboo fiber using SEM.
- Porosity and homogeneity analysis of tensile fractured composite.

## 1.5. Limitation

Among the many, major obstacles while conducting this work were the followings;

- Financial matter
- Materials such as E-glass fiber and resin unavailability in the country.
- Experimental setups unavailability

## 1.6. Organization of the Thesis

This work is organized in five chapters. The first chapter is devoted to brief description of wind energy; the thesis background; problem of the statement; general and specific objectives.

The second chapter presents literature review on composite materials, bamboo plants, bamboo fiber, and the past wind power turbine blades material. The third chapter deals with the experimental program which focused on materials, test piece preparations, experimental methods, conditions and test set up for mechanical tests of bamboo & E-glass-fibers composite. The fourth chapter addresses laboratory test results and discussion.

The last chapter devoted to draw conclusions, recommendations and future works.

# CHAPTER 2: LITERATURE REVIEW

## 2.1. Composite Materials

Currently the need for a material with light weight and high performance is increasing day to day. The improvement of the performance for a material is limited when there is only one composition. Therefore, there have to be a new material with high performance which constitutes two or more conventional materials.

According to [17], Composite materials refers to materials in which two or more distinct materials are combined together but remain uniquely identifiable in the mixture, having strong fibers surrounded by a weaker matrix material. The matrix serves to distribute the fibers and also to transmit the load to the fibers [17, 18].

According to [17, 19] generally composite materials are classified and related to constituents as depicted in *figure 2.1.*

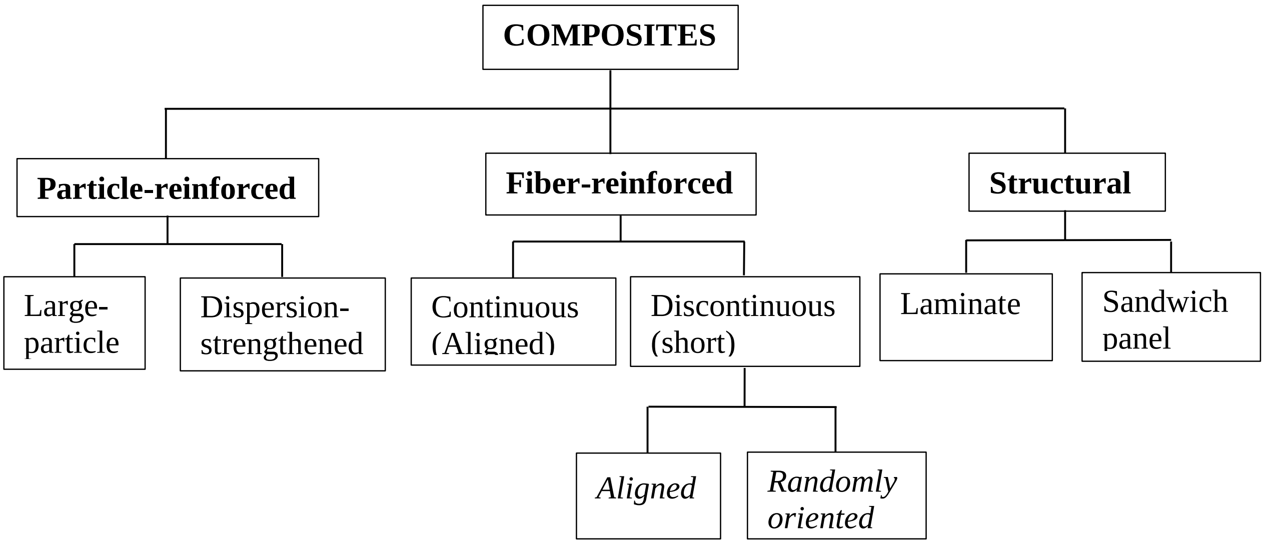


*Figure 2.1: Composite materials classification*

### Laminated Composite

Laminates are sheet constructions which are made by stacking layers (also called plies or laminae and usually unidirectional) in a specified sequence. The layers are often in the form of ‘prepreg’ (fibres pre-impregnated with partly cured resin) which are consolidated in an autoclave. A laminate may have more than 4 layers and the fibre orientation changes from layer to layer in a regular manner through the thickness of the laminate.

This study also focused on composites fabricated from many laminates which are sequentially stacked in a designed angles and orientations.

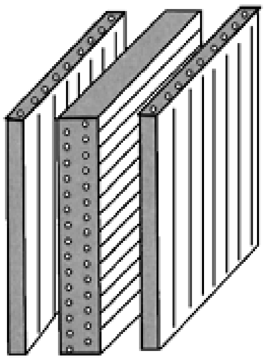


*Figure 2.2: Laminated Composite*

## 2.2. Bamboo Plant

Bamboo is not grass neither wood, while it has two of their characteristics. It belonging to the family of the *Bambusoideae*. It is estimated that 60–90 generae of bamboo exist, encompass approximately 1100–1500 species and there are also about 600 different botanical species of bamboo in the world. Bamboo mainly grows in tropical and sub-tropical regions of Asia, Latin America and Africa [15].

Bamboo, itself is very strong in its longitudinal direction due to strong fiber bundles penetration.

The bamboo culm, in general, is a cylindrical shell, which is divided by transversal diaphragms at the nodes. The thickness and strength of bamboo, however, decreases from the base to the top of the bamboo culm [11].

It is obvious that ecological materials satisfy fundamental requirements like pollution prevention and cost minimization. The use of agricultural by-products, which are environmentally friends, such as rice husk, coconut fibres, sisal and bamboo minimizing energy consumption, conserving non-renewable natural resources, reducing pollution and maintaining a healthy environment [11]. Bamboo is the core of these materials that fulfills these advantages.

Different researchers conduct tests on the mechanical properties for different species of bamboo fibers as a function of age, moisture content, density, etc. The optimum strength value occurs between 2.5 to 4 years [16].

Many researchers describe that bamboo fiber has a tensile strength greater than 500MPa and reaches up to 850MPa. The ratio of tensile strength to specific weight of bamboo is six times greater than that of steel [6, 16, and 20].

### 2.2.1. Diversity of Bamboo Plants and Utilization in Ethiopia

Different bamboo species are available in Ethiopia. Ethiopia has Africa's biggest bamboo resources and this plant can be harvested in sustainable cycles on 30%-40% of the mature culms every two years [15].

The total resource base of Ethiopia is confined to two indigenous bamboo species out of more than 1500 species of bamboo in the world and 43 species in Africa. The highland bamboo (Yushania Alpina), 8cm diameter and 17m height covers 15% and the monotypic genus lowland bamboo (Oxythenantera Abyssinica), with solid culms at maturing age, 5cm diameter and 7m high covers 85% [15].

The Ethiopian natural bamboo forest covers about 1 million hectares, which is about 7% of the world total and 67% of the African bamboo forest area.

In Ethiopia, in the past and even in present, the economic potential of bamboo has not been explored and the role of bamboo resources in national economies is negligible.

However, now a day, bamboo has been used in traditional way in the country side a little bit for the scaffolding, construction of houses, fuel feed houses, fuel, feed fodder, beehives, hats, mats, baskets, handicrafts, small furniture and other countless products [21].

The location of the bamboo rich sources in Ethiopia are as shown in *figure 2.3* [15].

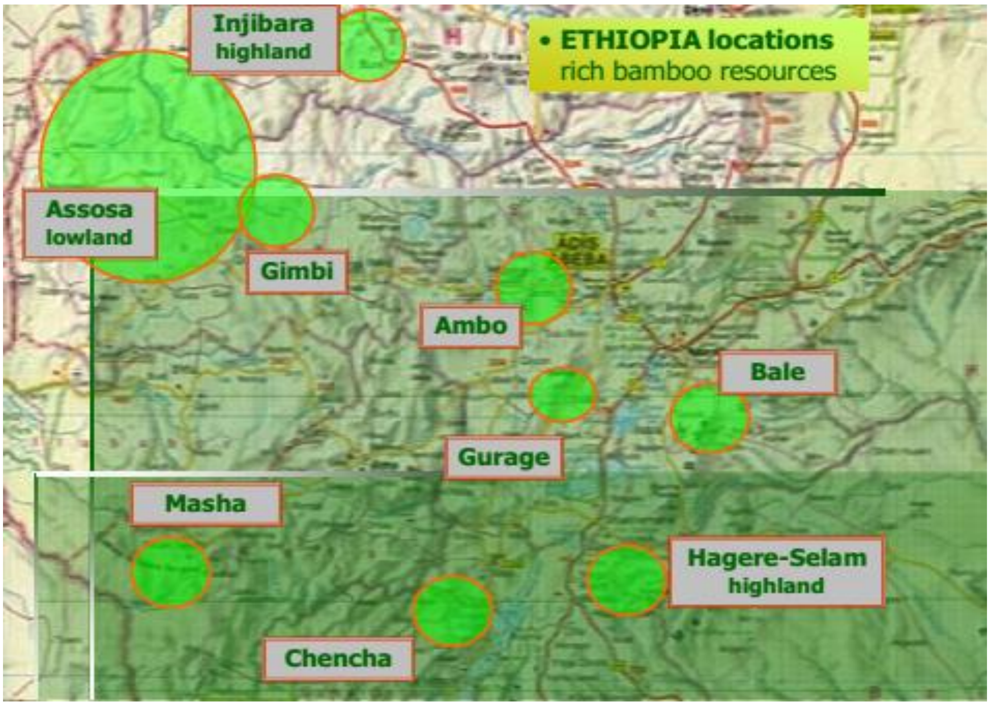


*Figure 2.3: Diversity of Bamboo in Ethiopia (From ECBP-Documentation, Workshop Presentation)*

From the *figure 2.3* above Assosa, Injibara, Gimbi, Ambo, Gurage, Bale, Masha, Chencha and Hagere-Selam are rich in bamboo sources. The largest source of bamboo plant present in Assosa is lowland type which has solid culm at maturating age. Due to its solid culm at maturating age it is not preferable to use bamboo splits for fiber extraction process. This is because as culm diameter increase the internal softness part thickness will increase. Consequently the amount of fiber obtained and even the strength of the fiber will be decreased. Therefore, due to its abundance, highly dense fibers present along the culm and naturally its thin wall thickness, bamboo species from the highlands of Injibara was selected for this investigation.

### 2.2.2. Bamboo Fiber

Bamboo has many culms. There is a variety between different culms on stiffness, strength and fracture toughness. The culm of a bamboo plant is a ligno-cellulosic natural functionally graded composite material. Fibers are densely located around the outer cortex and similarly on the top of the culm. As a result when we examine bamboo timber; from inner to the outer and from the bottom culm to the top, the mechanical strength of the bamboo is augment.

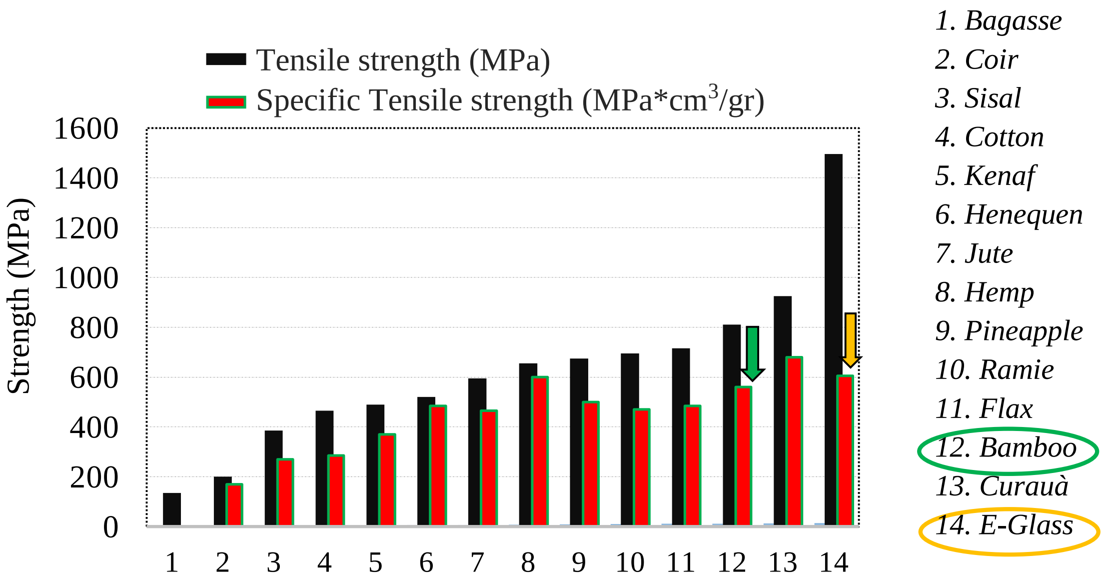


*Figure 2.4: Comparison of Natural fibres strength and specific strength.*

The chemical constituents of bamboo are primary cellulose, hemi-cellulose and lignin. The bamboo has 60% cellulose and a considerably high percentage of lignin (about 32%) [20]. The bamboo fiber is often brittle compared with other natural fibers, because the fibers are covered with lignin. Therefore, a devised process should be adopted to extract the bamboo fibers for reinforcement of composite materials. However once proper method of fiber extraction is selected, the result obtained is comparable even with glass fiber [16].

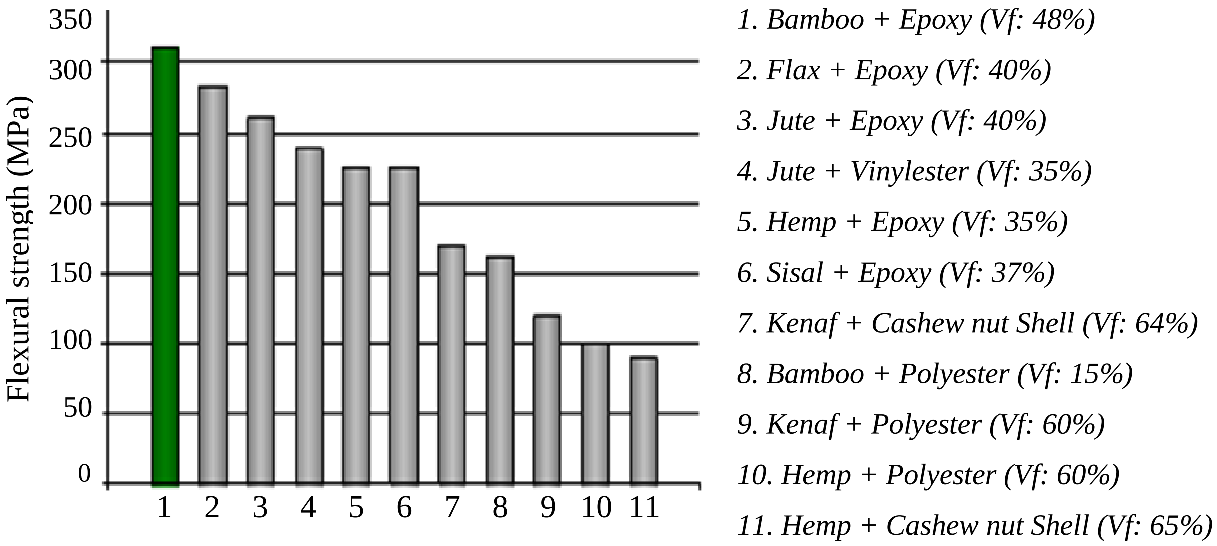


*Figure 2.5: Comparison of UD Natural fibres/ Thermoset matrix Flexural strength*

*Figure 2.4* and *2.5* illustrated the comparison of mechanical properties of natural fiber composites & fiber glass composites [16]. These result indicate that the mechanical properties of bamboo fiber is super higher than that of other natural fibers and also nearer to glass fiber characteristics. This situation creates an ambition to focus and further study of this fiber reinforcement for wind power turbine shell, which is focused in this work.

**Extraction Process of Bamboo fiber**

Bamboo fibers can be extract in different ways. Some of them are explained below.

**Chemical Processing**: It is basically hydrolysis alkalization. The crushed bamboo is "cooked" with the help of Sodium hydroxide (NaOH) into a form of regenerated cellulose fiber. Hydrolysis alkalization is then done through carbon disulfide combined with multi-phase bleaching. Although chemical processing is not environmental friendly but it is preferred by many manufacturers as it is a less time consuming process [22].

**Mechanical Processing:** In this method, the crushed bamboo is treated with biological enzymes. This breaks the bamboo into a mushy mass and individual fibers are then combed out. Although expensive, this process is eco-friendly [22].

**Steam-explosion processing:** Raw bamboo was first cut into bamboo culms with 70-80cm in length by saw machine, and put into an autoclave with over-heated steam at 1750C and 0.7-0.8 MPa for 60 minutes. Then, the steam was suddenly released for 5 minutes and the cycles of sudden-steam release were continuously repeated for 9 times to assure the complete facture of cell walls. Finally, they were washed in hot water with addition of soap at 90-950C for 15 minutes to remove ash and dried in the oven for 24 hours at $105^{0}$C [22].

### 2.2.3. Previous Works Related to Glass & Bamboo Fiber Hybrid Composites

A research project at “Roskilde University, Denmark” studied the properties of bamboo material and made a life cycle analysis (LCA) to compare the performance between bamboo turbine blades and glass fibre turbine blades with sustainable perspective [12]. The result concluded that bamboo material fulfilled the requirement of constructing a turbine blade and has a high performance associated with sustainable development. The life cycle analysis is carried out from social-environmental and social-economical aspect. However as the report indicate, the mechanical properties of the bamboo is much lower from glass fiber which is taken from another research. This study focused on bamboo cost and bamboo recyclability. But, in wind turbine blades material selection, strength and service life are the key elements in which this study misses & the problem of weakness of bamboo fiber on energy efficiency is mentioned here but not addressed.

**R.T. Durai Prabhakaran** investigated a critical review of various materials for future for wind turbine blade design. In this study various fibre reinforcements, thermoset composites, thermoplastic composites, natural fibre composites, and hybrid composites were included.
He also explained disadvantages and disadvantages of various materials and its limitations that can give good insight for material selection for both large and small turbine blades. Finally, he concluded the end-of-life of the wind turbine blades, thermoplastics blades can be recycled, which is a major advantage compared to its thermoset counterpart but it needs few more advances before implementing as blade materials. Whereas the natural fibre composites cannot be an immediate solution for large blades, but for smaller blades these materials can become a good choice. He present the merit and demerit of different materials in an explanatory way. Furthermore he concluded that, another interesting material in future blades design could be hybrid composites.

**Sushanta K.S, et al, (2008)** studied polypropylene–bamboo/glass fiber hybrid composites mechanical analysis and fabrication as well as its dynamic behavior. Moreover hybrid composites of polypropylene reinforced with bamboo and glass fibers (BGRP) were fabricated using an intermeshing counter rotating twin screw extruder followed by injection molding. Maleic anhydride grafted polypropylene (MAPP) has been used as a coupling agent to improve the interfacial interaction between the fibers and matrix. The mechanical properties of the hybrid composites were studied from tensile, flexural, and impact tests.

Nearly, 69, 86, and 83% increase in tensile flexural and impact strength respectively has been observed as compared with virgin polypropylene. Bamboo fiber (4–6 mm length, diameter 85–120mm, density 0.863 g/cm$^3$) and glass fiber (6 mm, density 2.56 g/cm$^3$) were used as reinforcement. However this study didn't conduct an alkali treatment for this bamboo fiber. Similarly he used bamboo fiber in chopped form, which is not actually manifest its characteristics.

**Rao H.R, et al, (2010)** studied hybrid of bamboo/glass fiber-reinforced epoxy composite's flexural and compressive properties; and effect of alkali treatment of the bamboo fibers on these properties was included in the study. Bamboo fibers with a thickness of 0.3 mm (Dendrocalamus strictus), purchased prom the market were soaked in 1% NaOH. The glass-chopped strand mat was used in making the hybrid composite.

They used vacuum oven which was maintained at 100$^0$C for 3hrs to complete the curing of the composite. Finally they conclude that these hybrid composites with alkali-treated bamboo fibers were found to exhibit good flexural and compressive properties.

However they didn't use any standards (ASTM, ISO, DIN, etc.) during this fabrication (sometimes there is a critical case in conditioning) and testing processes. They used their own dimensions for the compressive testing, thus the validity of these results is under question according to International standards. In addition the physical properties of bamboo and chopped mat fibers used is not stated. The bamboo fiber they used is in random orientation.

**V.V. Prasad et al, (2011)** studied chemical resistance and tensile properties of bamboo and glass fibers reinforced epoxy hybrid composites. In their study, they were included:

The chemical resistance of Bamboo/Glass reinforced epoxy hybrid composites to acetic acid, Nitric acid, hydrochloric acid, sodium hydroxide, ammonium hydroxide, sodium carbonate, benzene, toluene, Carbon tetrachloride and water. The Tensile properties of these composites. The effect of alkali treatment of the bamboo fibers on these properties was studied.

While conducting this research, they used 1% NaOH soaked bamboo fiber and chopped mat glass fiber for different bamboo to glass fiber ratio. Then, they obtained that the maximum tensile strength difference among these different bamboo to glass fiber ratio is insignificance.

Finally they conclude that the hybrid composites with alkali treated bamboo fibers were found to possess higher tensile properties with good chemical resistance. However in this study since the following points are not included during the study, the result obtained is not satisfactory with the current trend of bamboo fibers characteristic.

The bamboo fiber physical properties such as age, moisture content and species of the bamboo is not addressed. Furthermore, a 1% alkaline treatment is insufficient to remove any fatty material and hemi cellulose. Not addressing these points in the study, the obtained result is lower and the above mentioned points may be responsible for this behavior. Moreover they didn’t consider the bamboo fibers orientation during specimen fabrication.

## 2.3. Wind Turbine Blade Materials in the Past

Modern wind power turbine has several components such as tower, blade, hub and nacelle. The blade, as part of the prime mechanical wind turbine rotor, is a key element within the wind turbine system and as such research aimed at improving blade performance is of great importance.

The anatomy of the modern wind power turbine is illustrated in *figure 2.6* below.

Rapid development in material technology has given influential impact on some variation structure of the wind power turbine. The variation mainly depends on positive reaction for lowering the prices of wind turbine construction and operational cost [1, 2, 4, and 5].

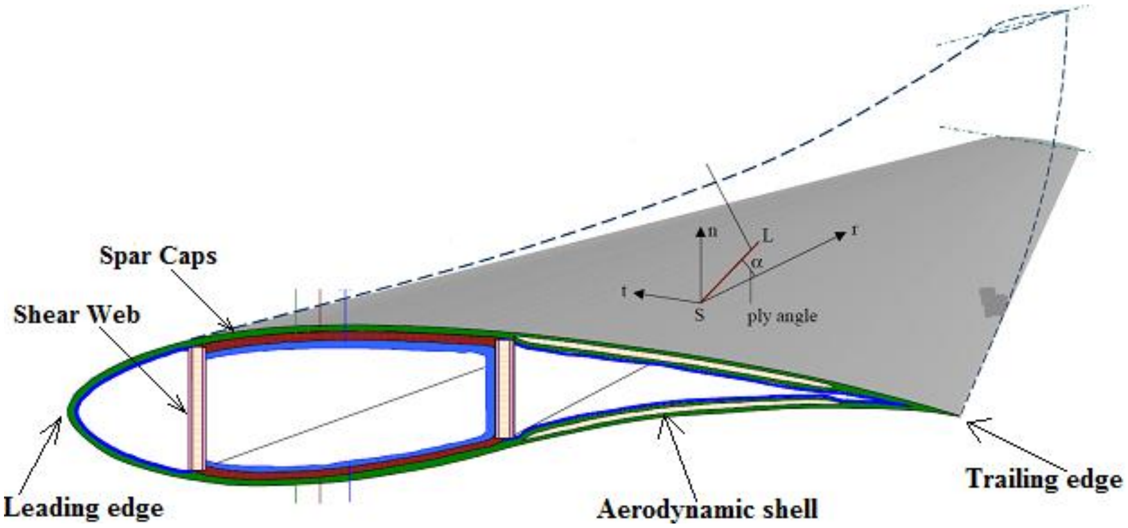


*Figure 2.6: Anatomical framework of wind power turbine blade*

As one of the most important parts of wind power turbines, the blade is required to have a reasonable structural form, advanced materials and a scientific production technology to endure the bending moments and tension caused by different loads such as wind force, blade weight and centrifugal force [1, 2, 4, 8, 9, 10]. Therefore, the design and manufacturing process have a decisive influence on the structural performance of the blade.

Because of the light-weight, high-strength, good corrosion resistance, high bearing capacity and designable characteristics, composite materials are broadly used in wind turbine industry.

Unsupported part of blade shell is able to resist buckling load, so, here, sandwich composites are used. The sandwich structure ensure much higher stiffness than monolithic composites. The blade skin is made of mat or fabric fibers expect to resist bending loads. Whereas integral webs and spars are made of biaxial layups at +/-$45^0$, which enable to resist shell buckling or shear stresses due to flapwise bending [2, 4, 5, 7, and 10].

**Fiber reinforcement composites for wind turbine:**

The reinforcements readily available in the markets for composite product developments are glass fibres (E-and S-glass), carbon fibres (IM- and HS-carbon), aramid fibres, steel fibres, natural fibres (jute fibre, hemp fibres, bamboo fibres, etc.), hybrid fibres (glass/carbon), and thermoplastic polymer fibres (polyamide fibres, PET fibres, PP fibres, etc.). Current turbine blades are made by glass and carbon fiber reinforcements [4, 5, and 8].

**Natural fiber composites for wind turbine:**

Natural fibres have become popular reinforcement material for fibre reinforced polymer composite developments. The reinforcement can replace the conventional fibre, such as glass, aramid and carbon as an alternative material [8].

The main advantageous of natural fibres (flax, hemp, and jute fibres) include low cost, fairly good mechanical properties, high specific strength, on-abrasive, & eco-friendly. In spite of impressive specific mechanical properties, the main challenges associated with these reinforcements include severe moisture absorption, fire resistance, mechanical properties and durability, variability, and manufacturing/processing of natural fiber reinforced plastic composites [6, 8, and 12].

Bamboo is another interesting material considered as plant fibre and has a great potential to be used in polymer composite industry. Bamboo has 60% cellulose with high content of lignin and its microfibrillar angle is 2–10 deg, which is relatively small [6, 12]. This peculiar property has made bamboo fibre as fibre for reinforcement in variety of polymeric matrices.

# CHAPTER 3: MATERIALS, METHODS AND CONDITIONS

## 3.1. Materials

In this work materials such as bamboo fibers; E-glass fibers and Epoxy resin with its hardener are utilized directly for hybrid composite preparation. E-glass fibers and epoxy resin with its hardener are obtained from Dejen Aviation (Davi), Bishoftu, Ethiopia; whereas bamboo fiber is extracted from bamboo culms coming from Injibara, North West part of the country, which is procured from Addis Ababa in a green form.

### 3.1.1. Bamboo Fiber

Bamboo plant is either naturally grown or farmed in a farm yard in countryside of Ethiopia. The Ethiopian natural bamboo forest covers about 1 million hectares, which is about 7% of the world total and 67% of the African bamboo forest area [21]. From this fact, availability of this plant for fiber extraction process is not a problem. Such situation causes for the relying on this plant alone for different studies in the past. This in turn causes for the unavailability of sufficient research carried out in the past on the potential and presence of different natural plants in Ethiopia beyond bamboo plant.

The bamboo, which is used in this study is taken from the Injibara, which grown in farm yard. Bamboo is taken from this area because of:

- Available of suppliers, and much amount of bamboo timber present in Addis Ababa;
- Presence of an information about plants such as age ; and
- Its good mechanical properties.

The bamboo type is from the highland bamboo (*Yushania Alpina)* species. The single bamboo timber has an average length, diameter and wall thickness of 20m, 180mm and 50mm, respectively. The average unit price is 60 Ethiopian birr for a single bamboo timber.

The fiber length and fiber wall thickness is increase with increase of age of bamboo [21]. According to [25] research finding, the strength of bamboo increases with an increment of age. The optimum strength value occurs between 2.5 and 4 years. Then it became to decreases at a later age. However, as age increases the extraction of bamboo fiber from the culm is more difficult. From these aspects, for this study a green bamboo with a three years old which is the highest age of bamboo timber available on suppliers is taken for fiber extraction.

The fiber obtained from this plant has whitish in color after dried, in average 200mm to 400mm length and 300 up to 400 µm in diameter.

**Extraction process of bamboo fibers**

Bamboo fibers can be extract from the bamboo culm through different ways such as by mechanical means using different machines such as advanced roller & mechanical dryer; by chemicals means, applying different chemicals and or by steam explosion technique, using steam gases.

However, in this work bamboo fiber was extracted using manual extraction technique due to the following reasons.

- No need of advanced equipment, such as roller, mechanical dryer, boiler, autoclave, etc.
- High aspect ratio of fiber (length-to-diameter ratio),
- Low energy consumption and
- Easy control of fiber property

In general the extraction process of the bamboo fibers is concisely summarized as below.

Nodes, most inner parts and very thin layer of exoderm of the highland bamboo have been removed and remaining parts have cleaved in longitudinal direction to thin slabs by using circular band saw.

The strips are bundled and are kept in water for five days in order to soften them. After removing, they are beaten gently at slow constant impact load using rubber hammer in order to loosen and separate the fiber. The resulting fiber bundle is combed using wire comb. The process of beating and combing is repeated until individual fibers are separated.

Finally these fibers were soaked using NaOH chemical for 24 hours at $60^0$C in the induction furnace in order to remove excess fats from individual fiber.

*Figure 3.1* depicted a manual extraction process of bamboo fibers. In part (a) of this figure, the cleaved bamboo strips are socked under the water in the bath. Part (b) shows that wetted bamboo strips hammering with rubber hammer whereas part (c) shows the above stages in different phases, phase 1 cleaved bamboo after soaking, phase 2 bamboo strips hammered for few times and phase 3 bamboo strips hammered for many times.

Part (d) of this figure illustrated that the final outcome of the extracted bamboo fiber. Here even if the fiber is extracted from the stem of the culm, still excess fatty like material known as lignin and celluloses are not removed which shown visually. So, to remove this remnant alkaline treatment has been undertaken.

### 3.1.2. Sodium Hydroxide (NaOH)

Sodium hydroxide, also known as lye or caustic soda, has the molecular formula NaOH and is a highly caustic metallic base and alkali salt. Pure sodium hydroxide is a whitish solid, which is available in pellets, flakes, granules, and as a 50% saturated solution [26].

Sodium hydroxide is soluble in water, ethanol and methanol. This alkali is deliquescent and readily absorbs moisture and carbon dioxide in air.

Although molten sodium hydroxide possesses properties similar to those of the other forms, its high temperature comparatively limits its applications.

Sodium hydroxide is used in many industries, mostly as a strong chemical base in the manufacture of pulp and paper, textiles, drinking water, soaps and detergents [26].

Sodium hydroxide which used in this work was in pellets form, purchased from local suppliers with a brand name and code of **RANKEM, S0290** respectively.

*Figure 3.1: Manual extraction process of bamboo fiber*

*a) Bamboo strips immersed in water;*
*b) Beating of bamboo strips with hammer;*
*c) Wet bamboo fiber bunch after combing process in different phases*
*d) Final phase of manually extracted bamboo fiber.*

### 3.1.3. Glass Fiber

Fiber glass materials usually have laminate structure with different fibers orientations in the reinforcing glass layers. Various glass fibers orientations result in anisotropy of the material properties in the plane parallel to the laminates.

E-glass fibers are, by far, the most common types found in composites. These types have good combinations of chemical resistance, mechanical and insulating properties.
Furthermore, E-glass offers the more attractive economics.
E-glass has the following advantages as compared to other types of glass fibers

- E-glass fiber is cheap in price
- E-glass fiber has good electrical insulator characteristic
- E-glass fiber has higher mechanical strength than other glass fiber types.
- E-glass is low susceptibility to moisture (resists attacks from water)

Due to the above promising characteristic, E-glass fiber has been taken as bamboo fiber reinforcement for this study.

E-glass fibers are usually exist in three principal types including, continue glass fiber, chopped glass fiber and unidirectional glass fiber. The types of E-glass fiber which is used in this study is unidirectional (UD) E-glass type. UD fiber type has a good mechanical properties as compared to other fiber types and most of the time it uses in the fabrication of wind turbine blade structures.
The typical mechanical properties of UD E-glass is provided in *appendix B.*

*Figure 3.2* below shows E-glass fibers which is used for this work.

*Figure 3.2: Unidirectional E-glass fiber*

### 3.1.4. Epoxy Resin and its Hardener

Among main group of the matrix materials, thermoset resins is the major one which includes polyesters, phenolic, melamine, silicones, polyurethanes and epoxies.

The resin used for this study is Epoxy Resin with brand name of SYSTEM #2000 EPOXY RESIN, which is manufactured by Fiber Glast Development Corporation Company
It has superior flexural strength, tensile strength, bond strength, adhesive characteristics and fatigue resistance than other types of resins.

In general, epoxy resins have the following advantage over the other resin types

- Better adhesive properties (the ability to bond to the reinforcement or core)
- Superior mechanical properties (particularly strength and stiffness)
- Improved resistance to fatigue and micro cracking
- Reduced degradation from water ingress (diminution of properties due to water penetration)
- Increased resistance to osmosis (surface degradation due to water permeability) Quantity of resin required

**Hardener (catalyst)**

Epoxy resin is cured by adding a catalyst, which causes a chemical reaction without changing its own composition. The catalyst initiates the chemical reaction of the epoxy resin and monomer ingredient from liquid to a solid state.
The curing agent applied in this work for the liquid epoxy resin is hardener with brand name of SYSTEM #2060 HARDNER Manufactured by Fiber Glast Development Corporation Company. Here, in #2060, the number 60 indicates that the mixture of epoxy and hardener will change from liquid to solid state after 60 minutes if it used as an impregnation.
The ratio of epoxy resin to hardener used for this study was based on their masses. In general ratio is calculated based on manufacturer guide lines and that was 27% hardener for 100% epoxy. According to manufacturer guide lines, better mechanical properties of composites after curing process are attained if & only if the above mentioned ratio is correctly applied irrespective of any environmentally determined conditions.
Finally, these proper amount of epoxy & hardener is mixed and stirred for few minutes using deep stick material.

The typical mechanical properties of epoxy and hardener which used in this work is depicted in *appendix B.*

## 3.2. Test Pieces

### 3.2.1. Preparation of Test Pieces

Before the reinforcement of bamboo fiber with glass fiber, bamboo fibers were chemically treated in order to enhance its property. Next to that fiber volume fraction and matrix volume fraction of this composite material is determined. Before the composite laminate is fabricated, ply stacking sequences of laminated hybrid composite structure is designed.

Finally bamboo & E-glass reinforced epoxy hybrid composite is fabricated. Composite materials can be prepared by different methods. However due to many reasons such as part size and shape, cost, familiarity with the technique and availability of tools, in this work composite is fabricated using hand layup vacuum assisted techniques.

#### 3.2.1.1. Alkaline treatment and mat preparation of bamboo fiber

Bamboo fibers exhibit a high level of moisture absorption and poor wettability, as a result the bamboo composite shows poor in adhesion at the fibre–matrix interface, leading to deboning of the fibre under a certain loading. This prevents the applied load from being transferred effectively from matrix to the fibre [14]. Hence, interfacial adhesion and surface modification of such fibres is improved by employing alkali solution [19, 22]. This process is undertaken by removing of the amorphous regions of raw cellulose fiber, hemicellulose, lignin, and pectin using alkali solution. In general, removal of these fatty like components from bamboo fiber leads the fibers to:

- Improve an adhesive properties for fibre–matrix interface;
- Improve fiber’s shear strength;
- Improve fiber’s rigidity and stiffness;
- Improve moisture absorption problems;
- Reduce fiber’s weight; etc.

However, as concentration of NaOH increased the result obtained worsened the mechanical properties of the fibres [14, 16, 22, 26, and 27]. For this reason, after several trials, medium concentration of NaOH (i.e. 5%) is used for this work. In general, this study consumed 500 grams of NaOH pellets. *Eq.3.1* shows the chemical reaction between bamboo fiber and aqueous sodium hydroxide solution.

$$\text{Bamboo fiber-OH} + \text{NaOH} \rightarrow \text{FIBER-O}^{-}\text{Na}^{+} + H_2O \qquad (3.1)$$

The treatment and mat preparation process is concisely summarized as follow.

First, prepare bamboo fiber bundles. Then prepare 5% concentration of NaOH solution.

Next soaked the fibers in NaOH solution for 24 hours at temperature of $60^0$C.

Then, the fiber washed many times with distilled water in order to neutralize it. Then after this fiber is re-combed many times using wire brushes until 170-300μm diameters of individual fibers attained. Finally these fibers dried in sunlight for fifteen days. After the fiber dried, the mat prepared in $0^0$, $90^0$ and $\pm 45^0$ orientation as a unidirectional layers. In order to keep the fiber's position while sewing individual fibers, different materials such as plastic scotch, sewing machine, angle and dimension measuring instruments, etc., are used.

*Figure 3.3* shows that in part (a) chemically socked bamboo released from the $60^0$C induction furnace. Here, the solution of NaOH chemical & fiber has kept under the vacuum, since NaOH can react with air, as a result that can absorb moisture. This cause to increase the water content in the solution. Part (b, c) displays that bamboo fiber after soaking and washing process; and part (d) shows that mat prepared from chemical treated bamboo fiber in $0^0$, $\pm 45^0$ and $90^0$.

*Figure 3.3: Alkaline treatment & mat preparation of bamboo*

*a. Bamboo fiber soaked by NaOH*
*b. Bamboo fiber after soaked with sodium hydroxide*
*c. Alkaline treated and dried bamboo fiber*
*d. Unidirectional (UD) bamboo mat with different angles*

### 3.2.1.2. Fiber and matrix volume content of the composite

In design, fabrication and analysis of composite materials, the first and critical task is the determination of ingredient percentages such as fiber and matrix (resin) fraction presence in laminate. These components are microstructural elements of the composite laminate in which composites strength and properties are determined and limited by these values. In generals, result obtained from the equations presented below are mandatory for:

- Composite laminate preparation
- In order to use ASTM standard. To determine size of laminates that meets the ASTM requirements prior to laminate fabrication, these values are necessary.
- Finite element analysis purpose. Even though it didn't in this study, but, if anyone who want do this task in future it is possible to take these values as a primary data for analysis.
- The improvement of fabricated laminate for the future by varying these values.
- These values can be used as a design manual in collaboration of composite laminate's different experimental results which are fabricated by these content [18], etc.

#### i. Fiber and matrix weight fraction (WF, WM)

$$\text{Fiber weight fraction} = \frac{\text{Weight of fiber}}{\text{Total Weight}}$$

$$WF = \frac{W_f}{W_f + W_m} \tag{3.2}$$

$$\text{Matrix weight fraction} = \frac{\text{Weight of matrix}}{\text{Total Weight}}$$

$$WM = \frac{W_m}{W_f + W_m} \tag{3.3}$$

$$W_f + W_m = W_c \tag{3.4}$$

$$WF + WM = 1 \tag{3.5}$$

#### ii. Fiber and matrix volume fraction (VF, VM)

Volume of fibers, matrix and composite is given by

$$V_f = \frac{W_f}{\rho_f}\ ; \quad V_m = \frac{W_m}{\rho_m}$$

$$V_c = V_f + V_m \tag{3.6}$$

$$\text{Fiber volume fraction} = \frac{\text{volume of fiber}}{\text{Total volume}}$$

$$\text{VF} = \frac{V_f}{V_f + V_m} = \frac{V_f}{V_c} \qquad (3.7)$$

$$\text{Matrix volume fraction} = \frac{\text{volume of matrix}}{\text{Total volume}}$$

$$\text{VM} = \frac{V_m}{V_f + V_m} = \frac{V_m}{V_c} \qquad (3.8)$$

VF +VM=1

Let $\rho_f$ and $\rho_m$ are density of fiber and matrix respectively. Then we have

$$\text{VF} = \frac{W_f \times \rho_m}{W_f \times \rho_m + W_m \times \rho_f} \qquad (3.9)$$

Similarly;

$$\text{VM} = \frac{W_m \times \rho_f}{W_f \times \rho_m + W_m \times \rho_f} \qquad (3.10)$$

**iii. Mass density of ply (ρ)**

$$\rho = \frac{\text{Total weight}}{\text{Total volume}} = \frac{\text{weight of fiber}}{\text{Total volume}} + \frac{\text{weight of matrix}}{\text{Total volume}}$$

$$= \frac{\text{volume of fiber}}{\text{Total volume}} \rho_f + \frac{\text{volume of matrix}}{\text{Total volume}} \rho_m$$

$$\rho = \rho_f \times \text{VF} + \rho_m \times \text{VM} \qquad (3.11)$$

**iv. Ply thickness, $\hbar$**

The thickness of plies is simply the number of grams of mass of fibers ($W_f$) per unit area

$$\text{Total volume} = \hbar \times 1(\text{m}^2) \qquad \Leftrightarrow \hbar = \frac{\text{Total volume}}{1(\text{m}^2)}$$

$$\hbar = \frac{W_f}{\text{VF} \times \rho_f} \qquad (3.12)$$

In terms of mass of fraction of fibers, thickness expressed as

$$\hbar = W_f \left[\frac{1}{\rho_f} + \frac{1}{\rho_m}\left(\frac{1 - \text{WF}}{\text{WF}}\right)\right] \qquad (3.13)$$

Where:

$W_f$: weight of Fiber (g)

$W_m$: weight of Matrix (g)

Wc: weight of composite specimen (g)

$\rho_f$: Density of Fiber (g/cc)

$\rho_m$: Density of Matrix (g/cc)

$\hbar$ : Ply thickness (mm)

WF= Fiber weight fraction

WM= matrix weight fraction

$V_f$: Volume of fibers, (cm3)

$V_m$: Volume of matrix, (cm3)

Vc: Volume of Composite specimen (cm3)

VF: Fibers Volume fraction

VM: Matrix Volume fraction

Here, fiber is the sum of bamboo fibers and glass fibers.

In this study, preliminary data from manufacturers' manual about E-glass fiber and epoxy are taken. By using the above aforementioned equations, these values were evaluated and presented in *table 3.1*.

*Table 3.1: Fiber and matrix volume contents*

| **Primary Data** | | **Calculated Results** | |
|---|---|---|---|
| ***Parameters*** | ***Value*** | ***Parameters*** | ***Value*** |
| Bamboo fiber weight | 139.7 grams | Bamboo fiber volume | 118.3 cc |
| Glass fiber weight | 1209 grams | Glass fiber volume | 470.43 cc |
| Total fiber weight | 1348.7 grams | Total fiber volume | 588.73 cc |
| Bamboo fiber density | 1.181 g/cc | Matrix volume | 722.0 cc |
| Glass fiber density | 2.57 g/cc | Total fibre volume ratio | 45.0% |
| Composite weight | 2150.1 grams | Matrix volume ratio | 55.0% |
| Matrix weight | 801.4 grams | Total fiber weight ratio | 62.7% |
| Matrix density | 1.110 g/cc | Matrix weight ratio | 37.3% |
| | | Bamboo Ply thickness | 0.392mm |
| | | E-glass ply thickness | 0.414mm |

### 3.2.1.3. Composite plies and laminates design

The characteristics of composite materials resulting from the combination of reinforcement and matrix in general depend on

- The proportions of reinforcements and matrix
- The form of the reinforcement
- The fabrication process

The proportion of reinforcement and matrix which has done in this work has been elaborated in the previous sub title.

Similarly, the fabrication process undertaken in this work has been discussed in the next subtopics. The form of reinforcement and some preliminary conditions for this bamboo and E-glass fiber reinforced epoxy hybrid composite fabrication process has been presented here.

Plies in composite materials are sub structures of the composite laminate and most of the time they are considered in ‘prepreg’ (fibres pre-impregnated with partly cured resin) form.

So, composite laminates are formed by stacking different plies with different angles and orientations by forming different laminated layers.

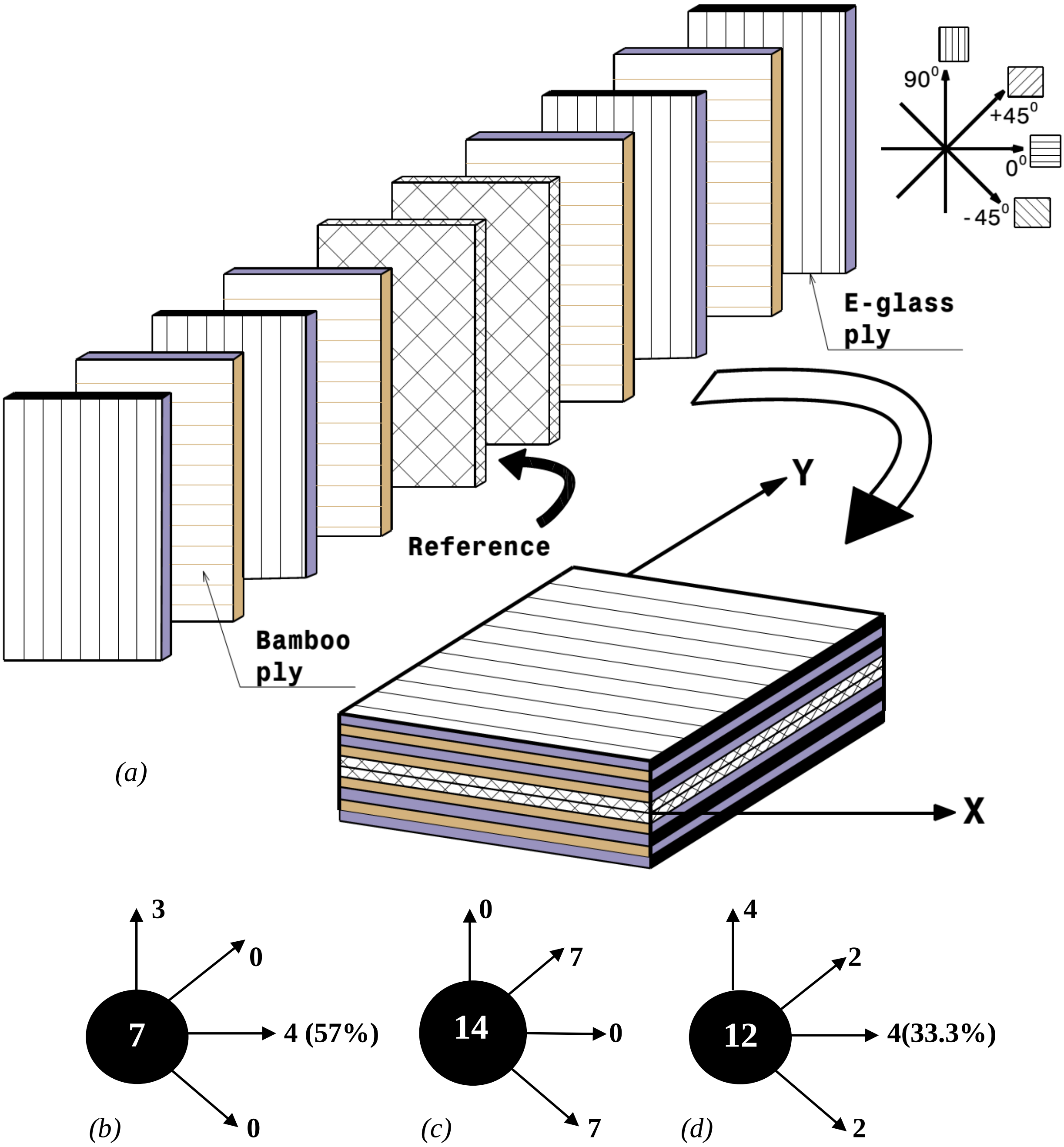


*Figure 3.4: Stacking sequences of laminated hybrid Composite structure*

Based on the reinforcement, matrix and curing process, the components architecture of the bamboo & E-glass reinforced epoxy hybrid composite has been defined in *figure 3.4 (a) - (d)*.

Epoxy has low strength. It doesn't support any load. So, the main purpose of epoxy is to transfer loads to the fiber. As a result, the orientation/ angle of the fiber in the composite determines the strength of the composite.

From this points of view, this BGFREC has been fabricated with proper components architecture of the composite lamina.

Middle plane also used in order to separate the composite in to two half thickness of laminate symmetrically as well as in order to keep the balance of the stack. This assists the composite not easily to delaminate during the loading. Generally, 7 laminae are used for tensile & shear specimens' preparation. Of them one lamina is used as middle plane. Similarly, 10 laminae are used for compressive & bending test specimens as shown in *figure 3.4 (a)*.

Furthermore, amount of layers used with its respected angle have shown in *figure 3.4,* part *(b)* for tensile, part *(c)* for shear and part *(d)* for compressive and flexural according to composite materials laminate configuration standards.

#### 3.2.1.4. Composite fabrication process

#### Vacuum bagging Assisted Hand Lay-up technique (VBAHT)

The hand lay-up is one of the oldest composite fabrication techniques and belongs to the open mold category. The operator places the reinforcement and the resin mix manually on a one-sided mold and thereafter the resin-reinforcement mixture is compressed with a hand roller. Another new technique is vacuum bagging which is a clamping method that uses atmospheric pressure to hold the adhesive or resin-coated components of a lamination in place until the adhesive cures.

Hand lay-up technique has been greatly improved by vacuum bagging (VBAHT), with a small increase in capital investment. The impregnating procedure is the same, but before cure, the component is sealed on the mold under a vacuum bag. Then air is drawn and the component is compressed by the atmospheric pressure against the mold surface by the vacuum bag. This pressurization drives the excess resin and most of the entrapped air out of the component. The key goal of VBAHT is to produce a homogeneous laminated composite. The homogeneity of laminate is achieved through removal of excess resin and squeezing from of the impregnated fiber-epoxy mixture in to a compacted thickness of laminate at high pressure. So, if the procedure is properly carried on and if vacuum bagging materials are properly used as shown in *figure 3.6*, universally, there is no any doubt about the homogeneity of fabricated laminate.

Light but weak polymer matrix is impregnated with light but stiff and strong fibers in order to give consolidated composites that has light, stiff & strong properties, as the flow chart of this process is depicted in *figure 3.5*.

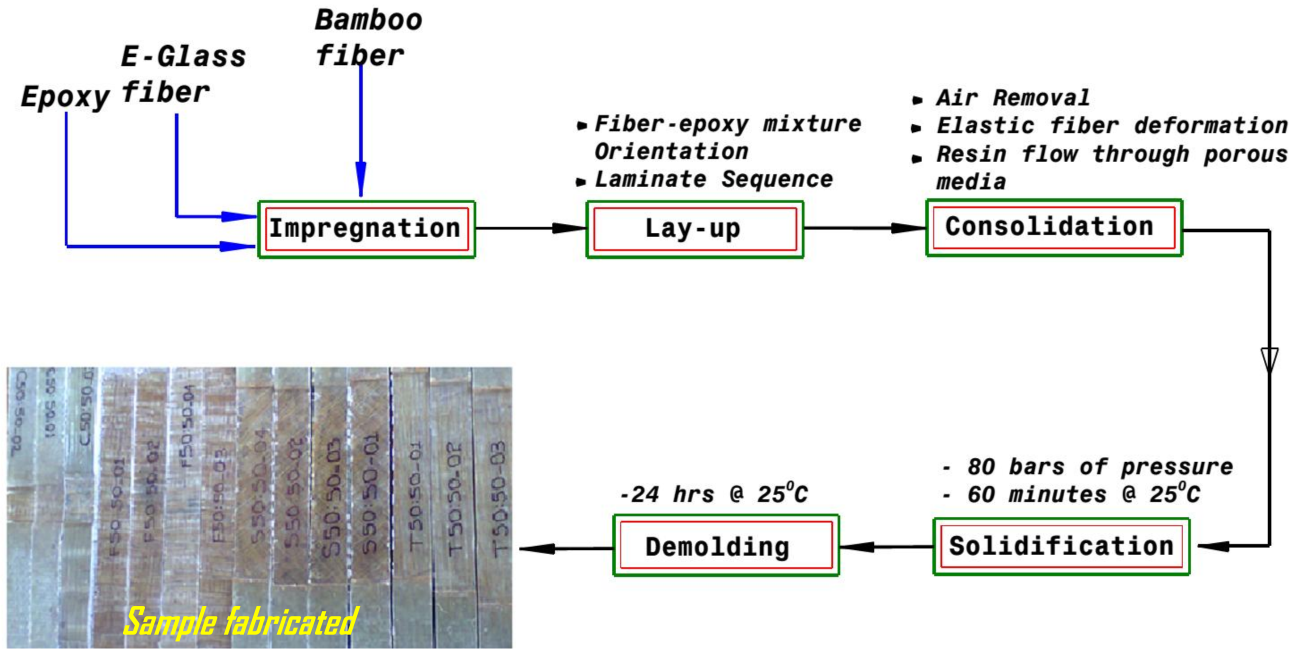


*Figure 3.5: Flowchart of fabrication process of laminated composite using VBAHT*

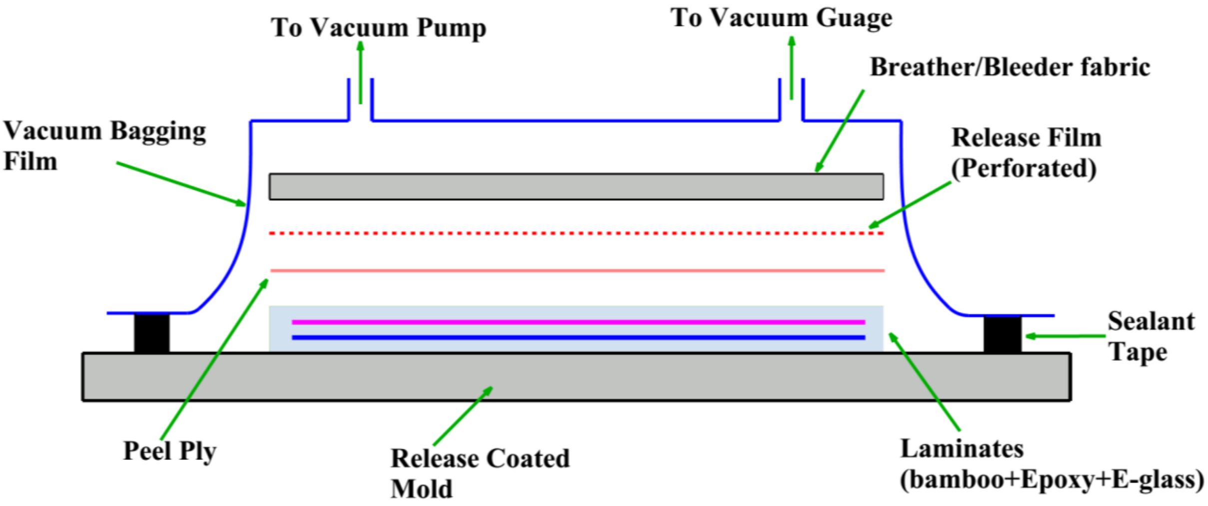


*Figure 3.6: Hand Lay-up Assisted by Vacuum bagging technique*

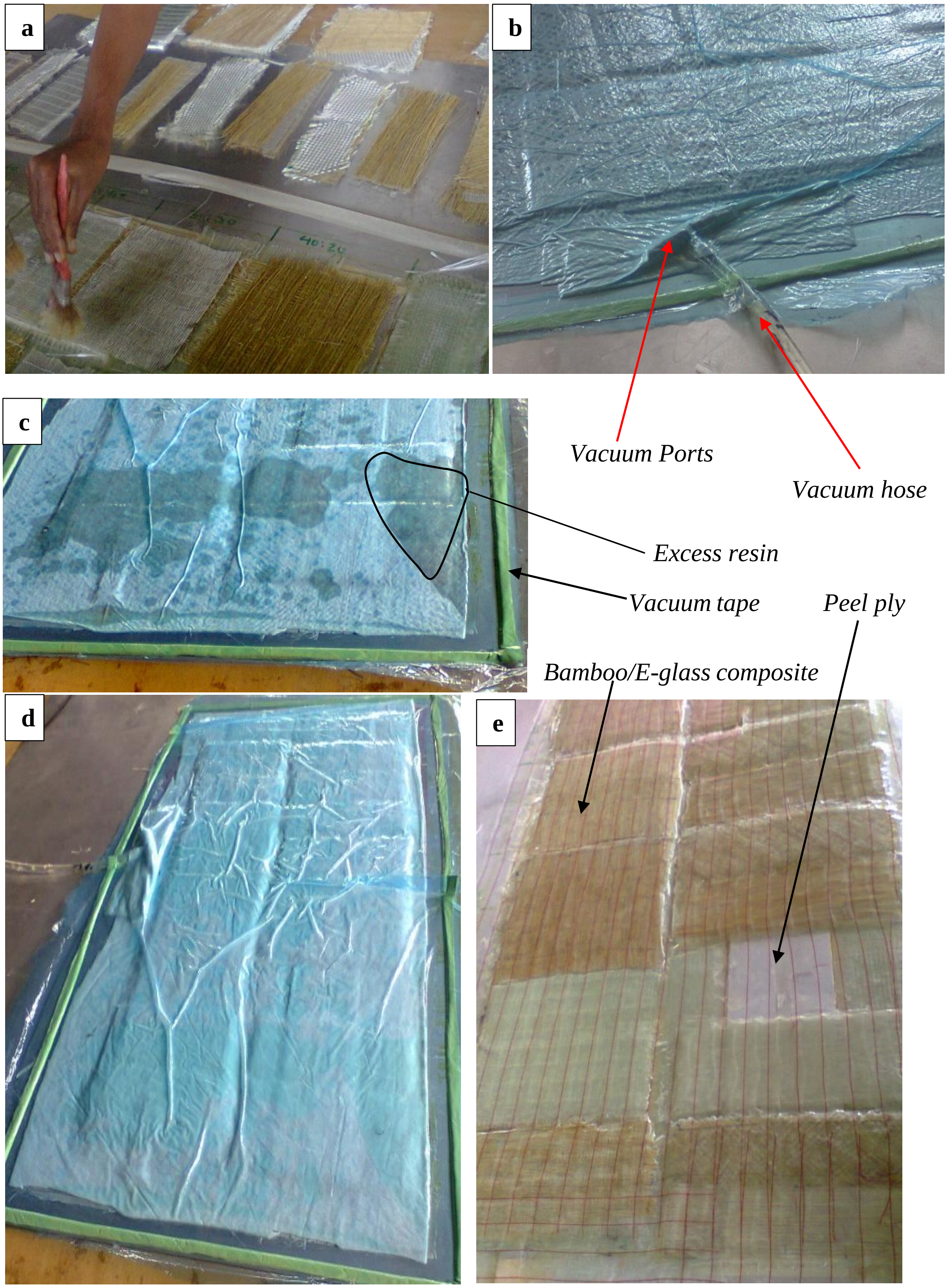


*Figure 3.7: Composite fabrication by vacuum bagging system*

a) *During impregnatinon & hand lay-up process*
b) *Impregnation process is ongoing and immediately of vacuum bagging process*
c) *Collecting of excess resin for removal*
d) *Intermediate stage of vacuum bagging process*
e) *Final stage of vacuum bagging process*

*Figure 3.7* illustrated a composite fabrication process. The hand lay-up process is undertaken manually using brushes as depicted in *figure 3.7 (a)*. In part *(b)* of this figure, the air is removing by using T shaped ports from the mold in order to create vacuum inside the mold. This is used to eliminate any voids or pores from laminates after curing process. In general the mold is sealed by vacuum tape before the vacuuming process is undertaken. Part *(c)* illustrated excess amount of epoxy is collected somewhere and transported elsewhere where deficiency of epoxy is occurred. This process is assisted by vacuum pump. If there is excess epoxy in the entire mold, the pump sucks these epoxy via release film holes into the breather. All these processes are proceeded in order to obtain a homogeneous type of laminate. Part *(e)* shows that cured laminate. Here, the upper striped part is peel ply, which is intentionally used for making upper surface of laminates being rough.

In general, in order to fabricate the aforementioned composite laminate using VBAHT, the following materials listed below are directly incorporated in this process according to the proper order of vacuum bagging materials that is illustrated in *figure 3.6*.

#### 3.2.1.5. Material of hand layup vacuum bagging assisted method

**i. Rotary vacuum pump**

The pump used for this work is taken from Dejen Aviation, Unmanned Air Vehicle department, which has the following spake:

Model No: 2TW-4C
Capacity: 8cfm
Vacuum: 6.7×$10^2$Pa
Power: 220-240v/50Hz

*Figure 3.8: Rotary vacuum pump*

**ii. Peel Ply (Release Fabric)**

Peel ply is the first rough fabric to be placed inside the Vacuum bag. Peel ply is a woven fabric mainly of nylon. It sticks with the composite laminate but it can be pulled without problems. Its main purpose is to make rough composite surface after curing process. It also used to separate the breather and the laminate or the vacuum bag and the laminate. Excess epoxy can wick through the release fabric and be peeled off the laminate after the laminate cures.

**iii. Perforated nylon**

A perforated plastic film may be used in conjunction with the release fabric. This film helps hold the resin in the laminate when high vacuum pressure is used with slow curing resin systems or thin laminates. Perforated films are available in a variety of holes size and patterns depending on the clamping pressure, and the resin's open time and viscosity.

### iv. Pressure fabric (breather)

A breather (or bleeder) cloth allows air from all parts of the envelope to be drawn to a port or manifold by providing a slight air space between the bag and the laminate.

### v. Vacuum nylon (vacuum bag)

The vacuum bag, in most cases, forms half of the airtight envelope around the edge of the mold. The vacuum bag is always larger than the mold and allow for the depth of the mold. The vacuum nylon is clear and transparent plastic material which enables to allow easy inspection of the laminate as curing process begins.

### vi. Mastic sealant (Vacuum tape)

Vacuum tape is used to provide a continuous airtight seal between the bag and the mold around the perimeter of the mold. The Vacuum tape may also be used to seal the point where the manifold enters the bag and to repair leaks in the bag or plumbing.

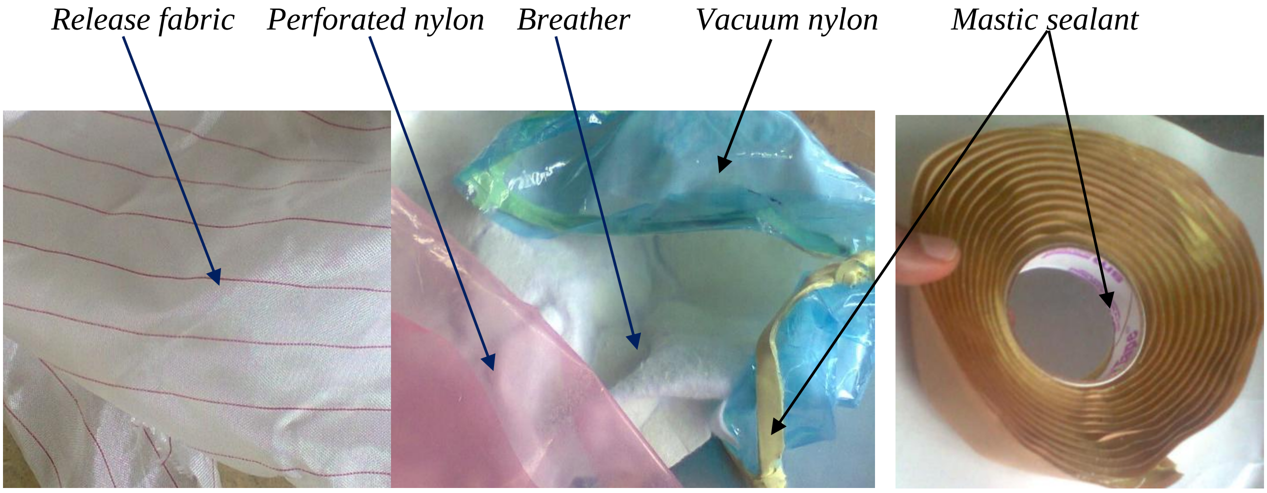


*Figure 3.9: Materials for vacuum bagging system*

### vii. Vacuum bagging mold

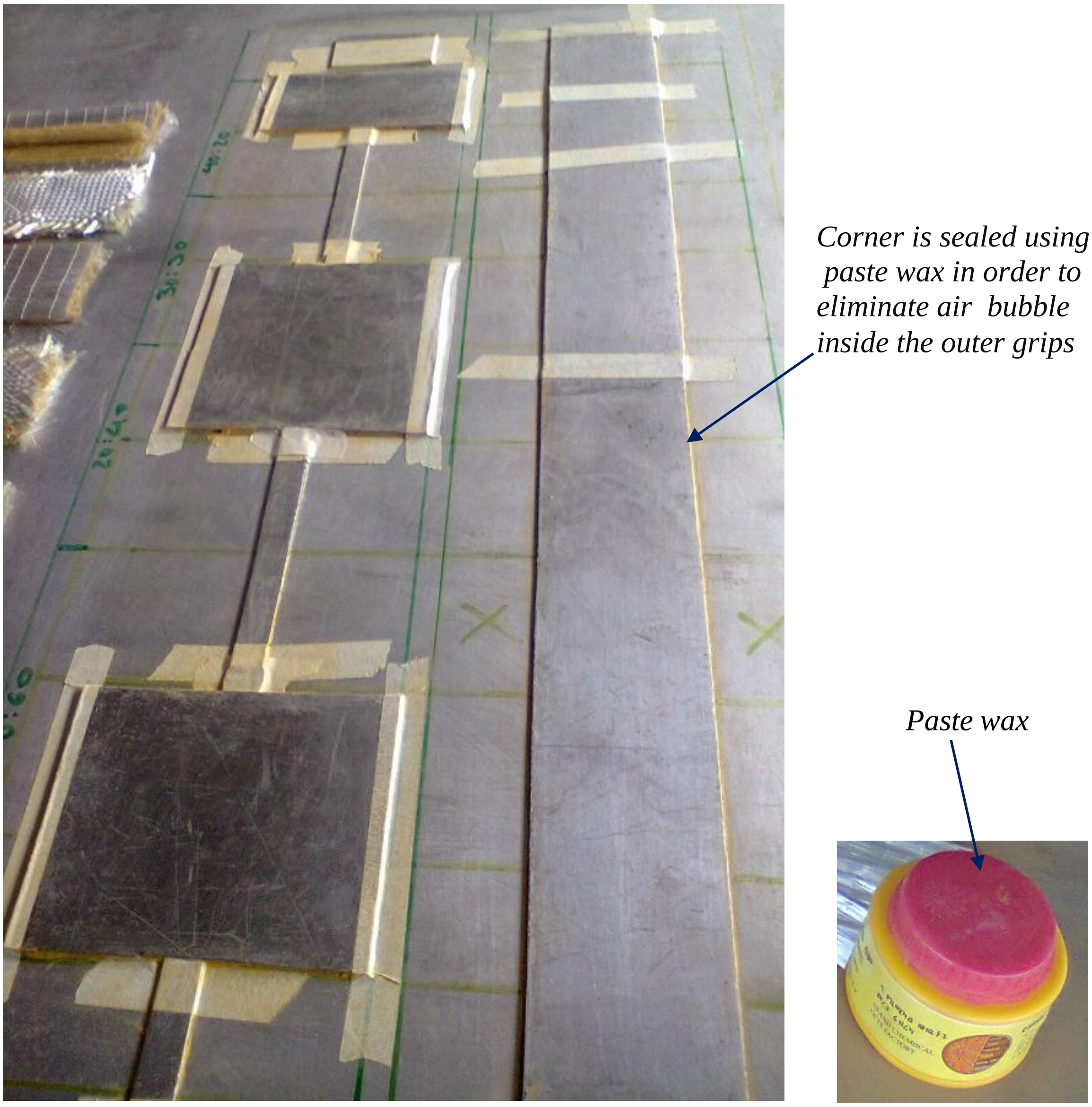
The mold structure must be too strong in order to support the mold itself in its proper shape during the impregnating process as well as in order to carry the composite laminates after the impregnating process.

Vacuum bagging molds should take advantage of the fact that atmospheric pressure is equal everywhere on the outside of the envelope. The mold surface must be airtight and smooth enough to prevent bonding to the laminate.

By taking the above conditions in to consideration, a 1.5 mm thickness of aluminum sheet is used as a mold in this work since the final product of the composite is in a plate form. This mold is depicted in the *figure 3.10*.

### viii. Mold Release

Mold release is essential for preventing the epoxy from sticking to the mold when laminates are apart. Even though, there are several types of mold release used depending on the mold material and desired characteristics of the finished part, the most common type and used for this work is paste wax, which shown as in *figure 3.10*. This is usually put on in up to 5 layers for new molds and at least one layer before each new part is molded. Fine detail and gloss level are obtained with the use of paste wax, but it can be difficult to buff anything with a textured surface. Usually this release agent is quick, cheap and widely available.



*Corner is sealed using paste wax in order to eliminate air bubble inside the outer grips*

*Paste wax*

*Figure 3.10: Aluminum sheet Vacuum mold and mold release*

### 3.2.2. Dimension of Test Pieces

American Society of Testing Materials (ASTM) was used to prepare and conduct a test of this bamboo and E-glass-fiber hybrid composite.

All the test pieces for tensile, in-plane shear & compressive testing dimensions were based on ASTM standards and their values are illustrated in *figure 3.11* [28, 29, 30 and 32].

Similarly, the three point bending test pieces dimension were based on 32:1 span to thickness ratio according to [31, 32]. And accordingly, its value became Span length=128mm, width= 20mm, thick=4mm & its overall length is greater than 20% of support span length i.e. 170mm.

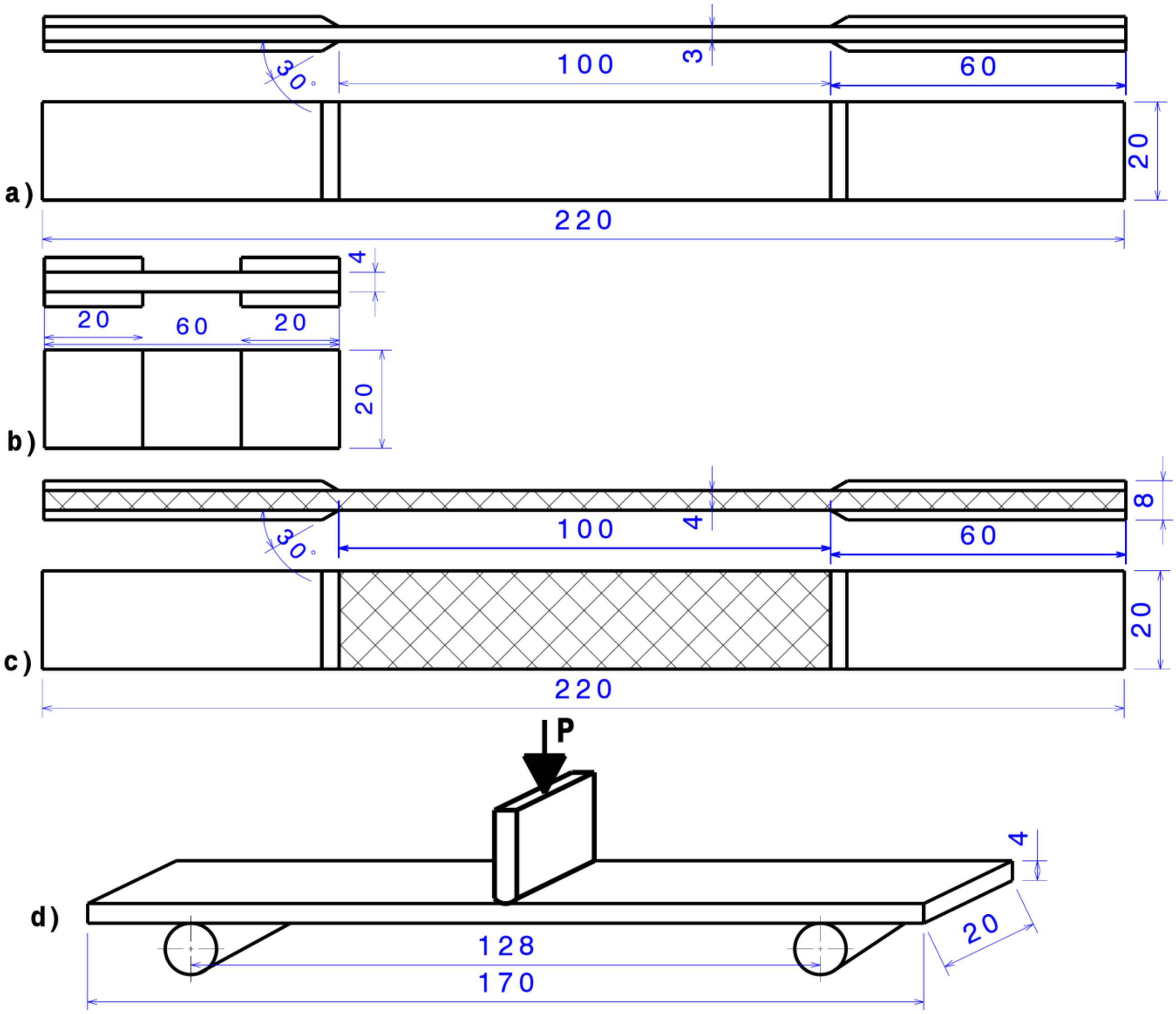


*Figure 3.11: Test Specimens*

- *a) Specimen for Tensile Test*
- *b) Specimen for Compressive Test*
- *c) Specimen for In plain Shearing Test*
- *d) Specimen for Three point Bending test*

## 3.3. Experimental Method

Before specimens are fabricated, manually extracted bamboo fiber was socked with caustic soda and kept for 24 hours at $60^0$C in induction furnace. Chemically socked fiber has properly covered and sealed by several materials in order prevent a direct contact between the chemical and furnace. Usually this chemical is highly reactive with metals and may damage the furnace components during the reaction if there was a direct contact.

The experimental specimens are fabricated from bamboo & E-glass reinforced epoxy hybrid composite as illustrated in previous topic, based on 45% fiber volume fraction.
Regarding to the fiber ratio, six different ratio of bamboo fibers to E-glass fibers has undertaken for this study. These ratios are 100:0; 0:100; 15:85; 30:70; 50:50 and 70:30.
The content of epoxy has been determined after the composite fabrication.
For each of the test three specimens are taken in order to show the repeatability of the results through which minimizing the experimental errors.
After the composite laminates are prepared, next, test pieces are cut properly using circular band saw from the laminates. In order to minimize stress concentration of test piece around the grip, a $30^0$ fillet around the tab edge is engraved for tensile and in-plane shear test specimens.

The next task was experimental investigation of prepared test pieces on universal testing machine by varying a load from the dynamometer load cell. After each test, displacements at different load response is generated in a data acquisition system as an output.
The tensile test was conducted along the longitudinal direction of the BGREC on universal testing machine according to [28, 32].
The compressive test was conducted along the longitudinal direction of the BGREC on universal testing machine according to [30, 32].
The three point bending test was also conducted at the middle span of the specimen of the BGREC on universal testing machine according to [31, 32].

Similarly, the In-Plane Shear Response by off-axis tensile tests of a ±45° was conducted on universal testing machine according to [28, 29, and 32]. Even though there are different shear testing methods, $\pm45^0$ Tension Shear is Easy to perform. And also it prevails a combined stress state (not pure shear).
When a $\pm45^0$ laminate is loaded in unidirectional tension, a biaxial state of stress is induced within each of the $+45^0$ and $-45^0$ lamina. In laminated composites, a 123 Cartesian Coordinate System describing the principle material coordinate system for a laminated material, where the

1-axis is aligned with the ply principal axis, as illustrated in *figure 3.12*, in which a coordinate system in ±$45^0$ off axis tensile load [29].

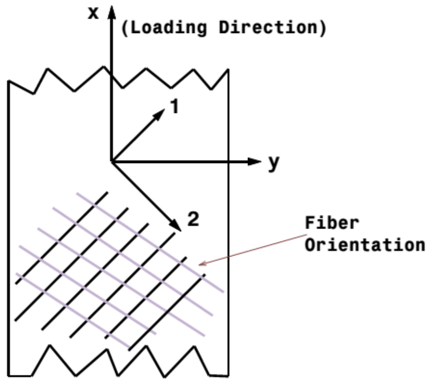


*Figure 3.12: Material Coordinate System*
*x and y represent the specimen or reference axes, while 1 and 2 represent the material or local axes*

Finally scanning electron microscope observation is undertaken in order to investigate the microstructure of the bamboo fibers. The interfacial adhesion between fiber–matrix was also investigated by examining the tensile fracture surface of BGREC test pieces.

The fabricated specimens' surface prepared for SEM were cleaned and smoothed, and finally cut into the appropriate shape by a slow-speed cutter.

Prior to SEM observation, all specimens were coated with a thin layer of gold in COXEM sputter ion-coater, at voltage of 800ev with a 20 mA plasma current at coating rate of 2.2 nm/min that produced 15nm plating thickness, in order to avoid electrical surface charging and poor image resolution.

## 3.4. Experimental Conditions

### 3.4.1. Testing Conditions

The experiment was conducted at constant strain rate values in quasi-static condition for tensile, in-plane shear, compressive and flexural testing under constant room temperature.

Tensile, in-plane shear and compression tests of the fabricated composite were conducted using electro hydraulic UTM in AAiT mechanical testing lab condition (room temperature & humidity) at a cross head speed of 0.75mm/min.

Similarly, the three point bending test also conducted on electro hydro universal testing machine using a cross head speed of 1.5mm/min.

During the test, load is continuously applied for all the specimens from dynamometer load cell until the specimen fails.

### 3.4.2. Density of Bamboo Fibers

The individual extracted bamboo fiber diameter were measured with a Digimatic digital caliper and its value was 170-310 μm with total length of 0.2-0.4m. Similarly this chemically treated and dried fiber has been weighted using electronics balance and its average value was recorded that 0.067milligrams.

Then, density of the fiber was calculated using the following linear density formula

$$\rho_b = \frac{M_b}{L_b \times (\pi \times D_b{}^2 / 4)} \qquad (3.14)$$

Where $M_b$, $L_b$ and $D_b$ is mass, length and diameter of bamboo fiber respectively.

According to above basic mass and volume formula, bamboo fiber density has determined and its value is 1181kg/m$^3$ or 1.181 gm. /cc. Then after all the analysis has undertaken in this study is based on this value. This lower value tell us that the fiber obtained is much lower in weight. The response for this lower value is due to alkaline treatment (fatty like materials removal) as well as the nature of bamboo fiber is light weight. *Table3.2* shows bamboo fiber is much lighter. The E-glass fiber is over two times weigh than the bamboo fiber.

*Table 3.2: Density comparisons of different fibers*

| **Fiber types** | **Density (g/cc)** |
|---|---|
| E-glass | 2.57 |
| Cotton | 1.51 |
| Sisal | 1.33 |
| Jute | 1.46 |
| Bamboo | 1.18 |

## 3.5. Experimental Setup

### 3.5.1. Scanning Electron Microscopy (SEM)

Microstructures of bamboo fiber were examined by scanning electron microscopy (SEM) using EM-30, CXS-3TAH-113031 COXEM equipment.

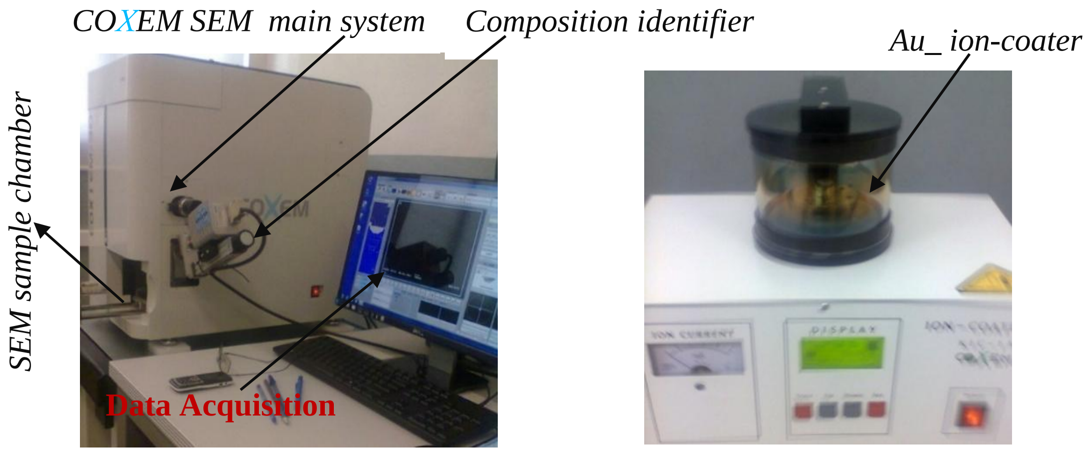


*Figure 3.13: Scanning Electron microscopy*

### 3.5.2. Experimental Setup

**Band Saw**

The circular Band Saw is used for cutting purposes.

The machine has a cutting speed of 500-1000m/min, with blade length 2560mm and maximum work piece height of 230mm.

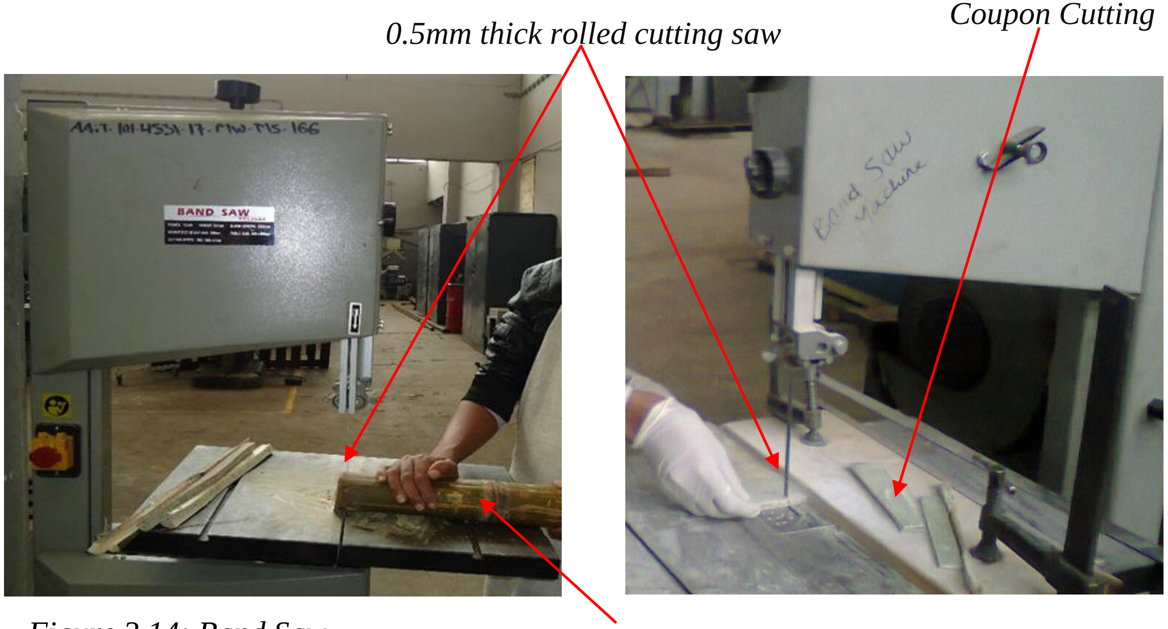


*Figure 3.14: Band Saw*

**Induction Furnace**

Chemically soaked bamboo fiber was kept for 24 hours at $60^0$C in Elite Thermal System *Model No: BIF12/125-2416 and Serial No: 1208/01/01* induction furnace.

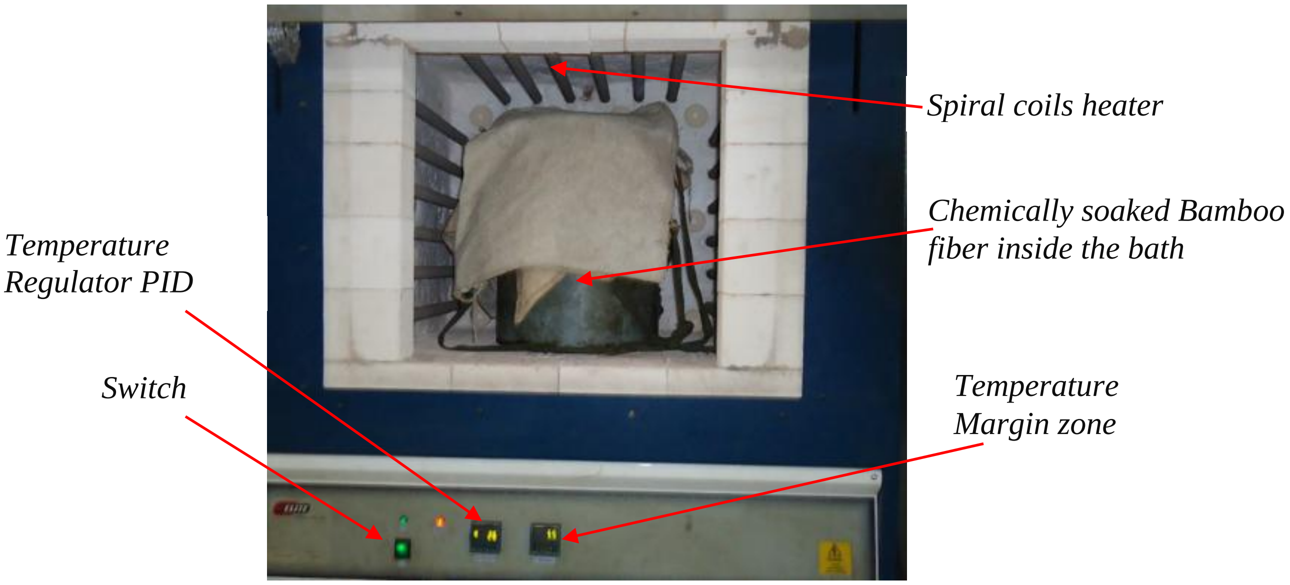


*Figure 3.15: Induction Furnace*

**Universal Testing Machine**

All the mechanical tests were investigated using Computer Controlled Electro-Hydraulic Servo Universal Testing Machine model: WAW-600; which has a capacity of up to 600kN, with 0.01 - 500 mm /min test speed. Test world data acquisition software is used to acquire data from the machine during testing.

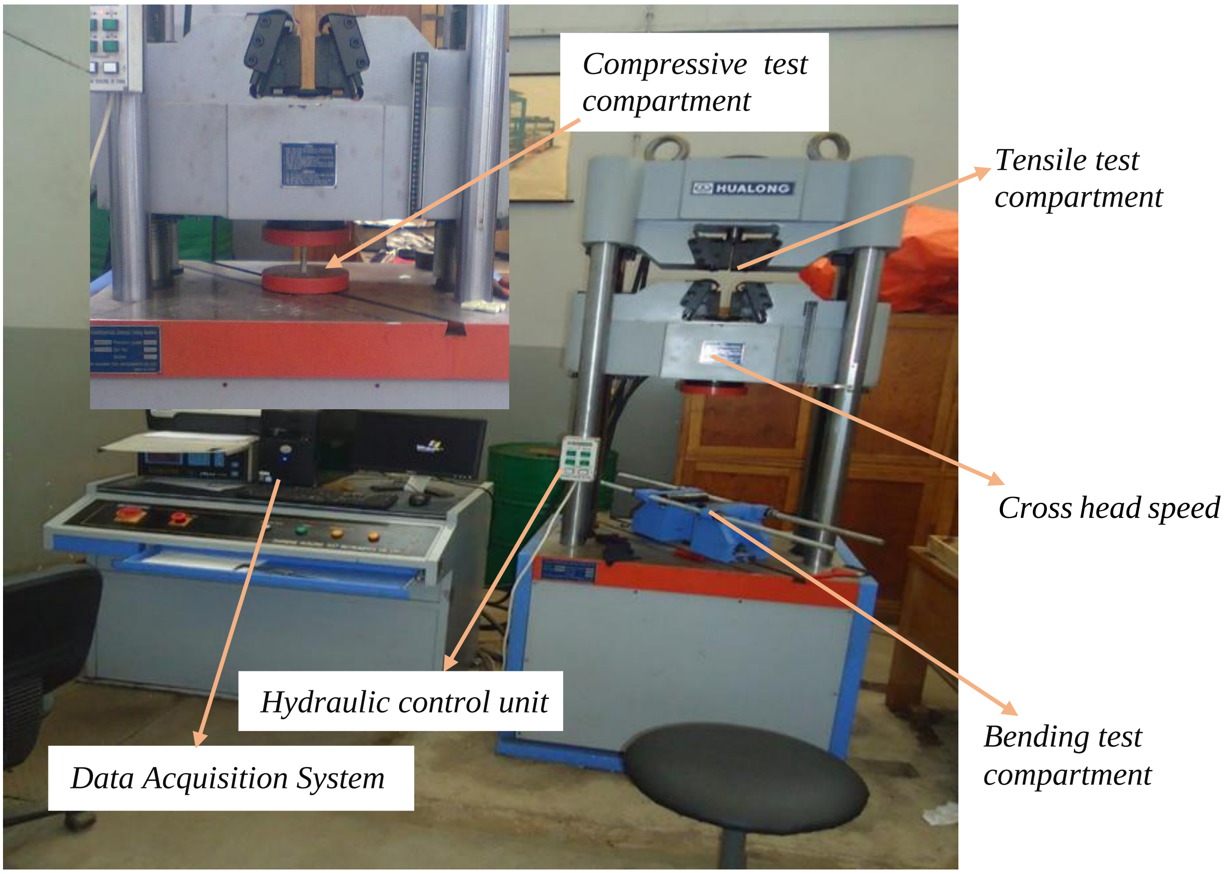


*Figure 3.16: Computer-Electrohydraulic Universal Testing Machine*

Beside these equipment and apparatus, different tools such as digital calipers, electronic balance, etc. are also used during fiber extraction, composite preparation and sample testing process.

# CHAPTER 4: EXPERIMENTAL RESULT AND DISCUSSION

## 4.1. Experimental Results

### 4.1.1. Tensile Test

BGREC was fabricated with 45% fiber volume fraction and 55% matrix volume fraction in a [0/90/0/90]$_s$ laminae orientation. Regarding to bamboo and E-glass fibers, six different ratios based on volume has undertaken. A total of three specimens were used for repeatability.

The variation of recorded test result among the three specimens in each of the six bamboo to E-glass fiber ratio is not significant. Typical stress–strain curves of BGREC under tensile loading for different bamboo and E-glass fiber ratio is presented in *figures 4.1*.

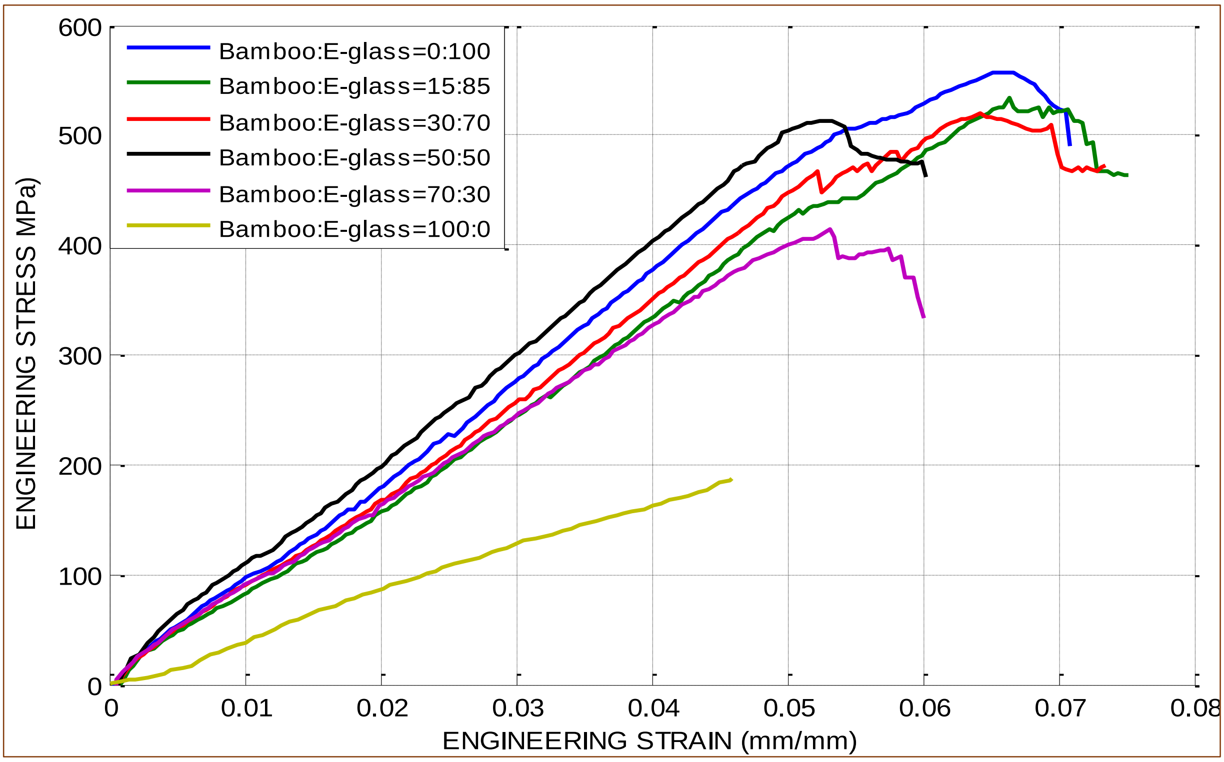


*Figure 4.1: Engineering Stress vs. Engineering Strain*

Engineering stress/strain are laboratory stress/strain that obtain by taking load & elongation of a given specimen as primary output from the experiment that defined the curve of stress-strain.

### 4.1.2. In-Plane Shearing Test

To determine the in-plane shear properties of the laminates, off-axis tensile tests were carried out in a UTM. The specimens prepared from the laminate with an off-axis angle of $45^0$ such that the fiber orientation is $\pm45^0$ ($-45^0$ & $45^0$).

The typical stress–strain curves for BGREC under in-plane shearing load with various percentage of bamboo & E-glass fiber ratio is presented in *figures 4.2*.

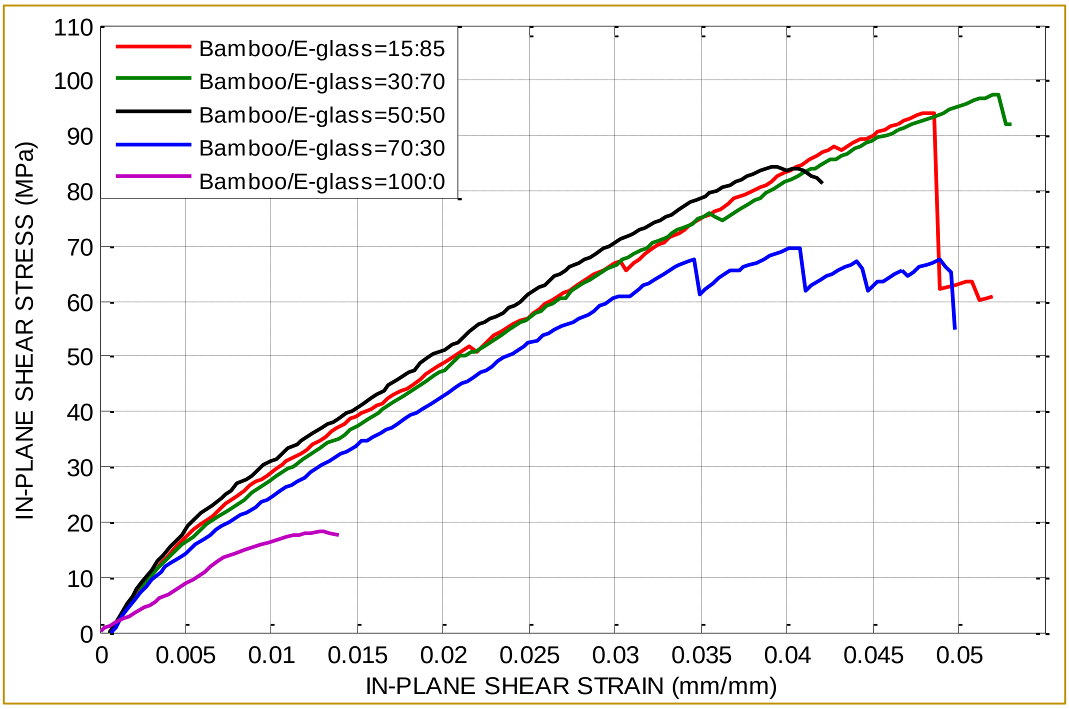


*Figure 4.2: shear stress vs. In-plane shear strain*

### 4.1.3. Compressive Test

Compressive test were prepared as [902/02/-45/45]$_s$ orientation. Five types of bamboo to E-glass ratio (15:85, 30:70, 50:50, 70:30 and 0:100) in a 45% total fiber volume fraction were used. For each of the ratio, three specimens were prepared for repeatability. And each of the three specimens result showed a small difference among their result output. And its average stress–strain curves is presented in *figure 4.3*

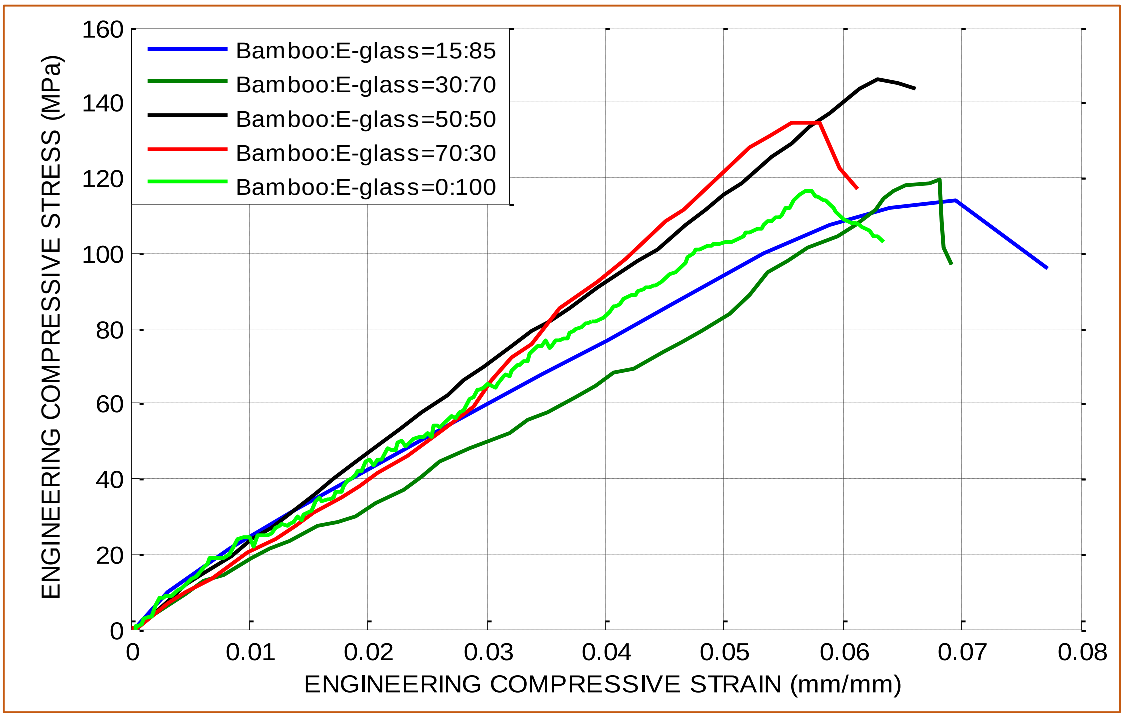


*Figure 4.3: Compressive Stress vs. Compressive Strain*

### 4.1.4. Flexural Test

The three point bending test specimens were prepared as $[90_2/0_2/-45/45]_s$ laminae orientation according to ASTM standard. The dimensions were 128mm support span, 20mm width, 4mm thickness and 170mm overall length as shown in *figure 4.4*.

Five types of bamboo to E-glass fiber ratio (15:85, 30:70, 50:50, 70:30 and 0:100) in a 45% total fiber volume fraction were used. For each of the ratio, three to four specimens were prepared for repeatability. And each of the three specimens result showed that there is no big difference among their result output.

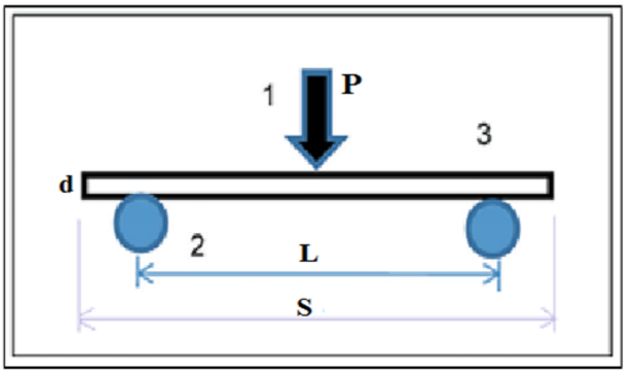


*Figure 4.4: Three-point bending*
*1: load probe, 2: support, 3: specimen, d: depth of specimen,*
*L: support distance (span) and S: overall length of specimen*

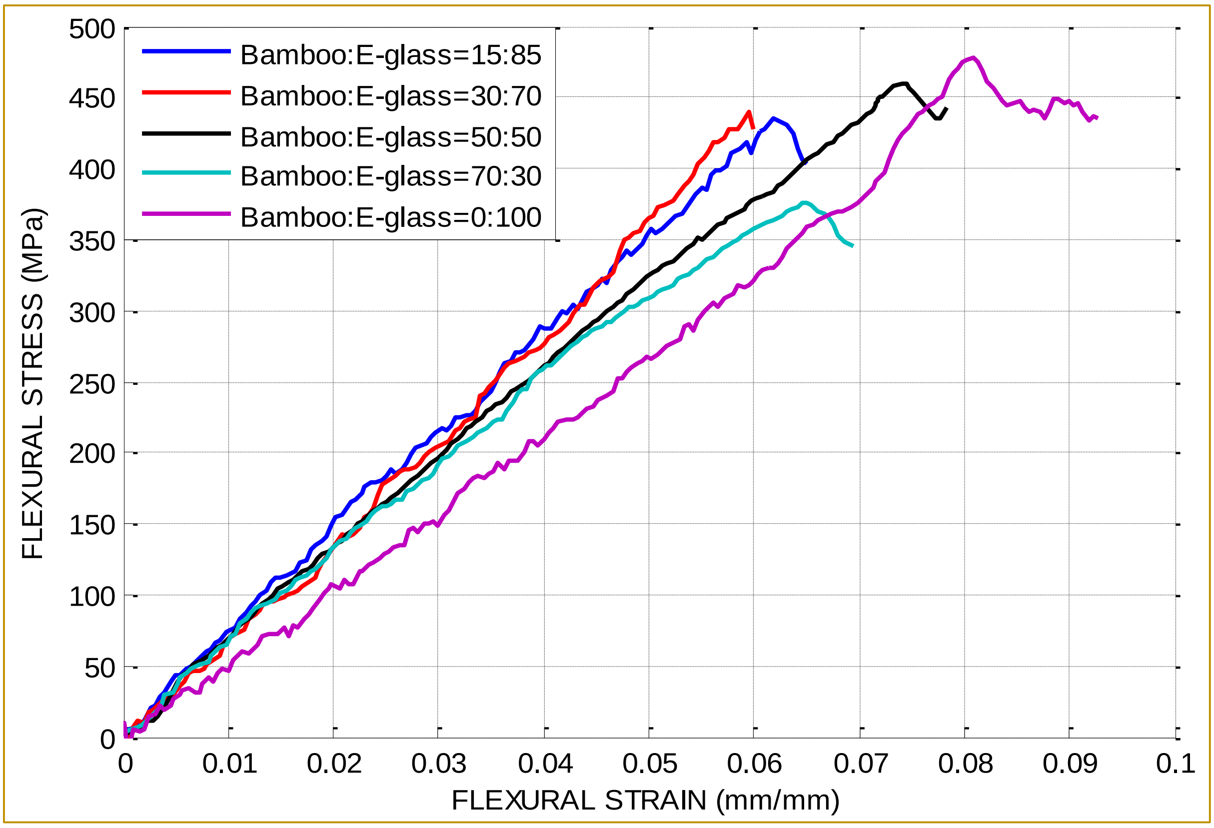


*Figure 4.5: Flexural Stress vs. Flexural Strain*

### 4.1.5 Failure Modes

The intact and damaged specimens of tensile, in-plane shear, compressive and flexural tests are depicted in *figure 4.6* and *4.7* respectively.

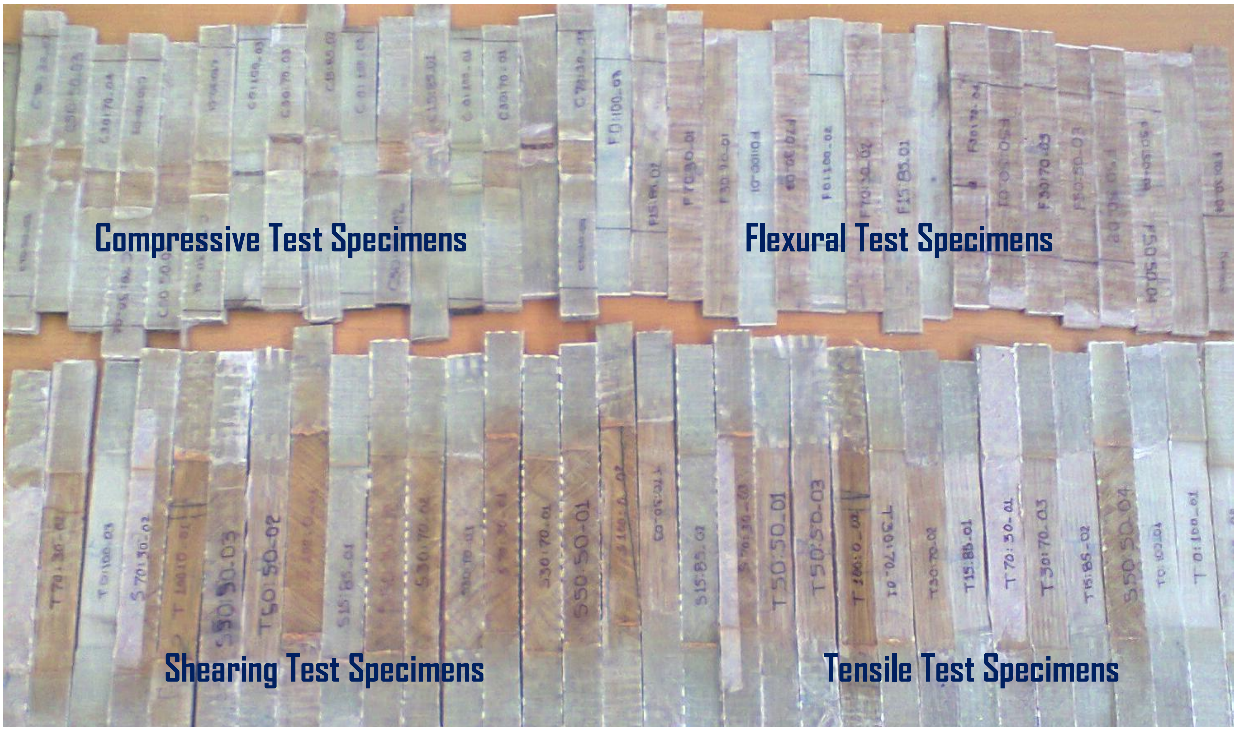


*Figure 4.6: Tensile Specimens before Testing*

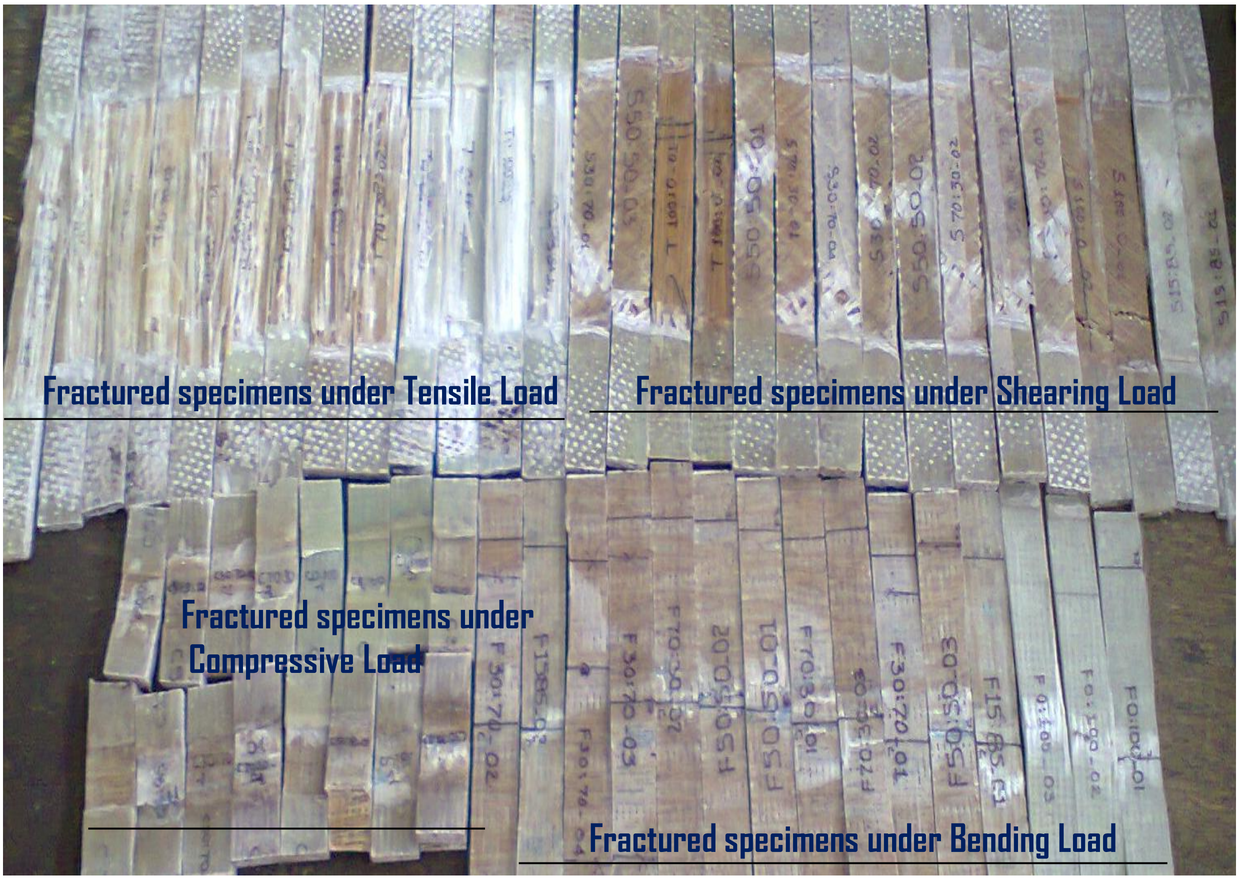


*Figure 4.7: Test Specimens after Testing*

## 4.2. Discussion

### 4.2.1. Tensile Test

Typical stress–strain curves for BGREC under tensile loading was presented in *figures 4.1*. In this figure, tensile stress increased linearly with increase in strain until point of ultimate load under tensile loading. Above this point, the stress–strain curve showed sharp, staggered decreases in load and fracture. Laminate under a tensile loading, a kink is observed in few specimens in the stress–strain graph, indicating the BGREC load and the curve continues with increasing load, but with a smaller slope, signifying a reduced stiffness in the direction of the load. Tensile fracture of unidirectional is mainly longitudinal cracking of fibers. In some specimens, partial damage occurred when the tensile stress reached 75-85% of ultimate stress. The stress–strain curves under tensile loading are regular up to ultimate point where strength of 0:100 is greater than the others because of absence of bamboo fibers.

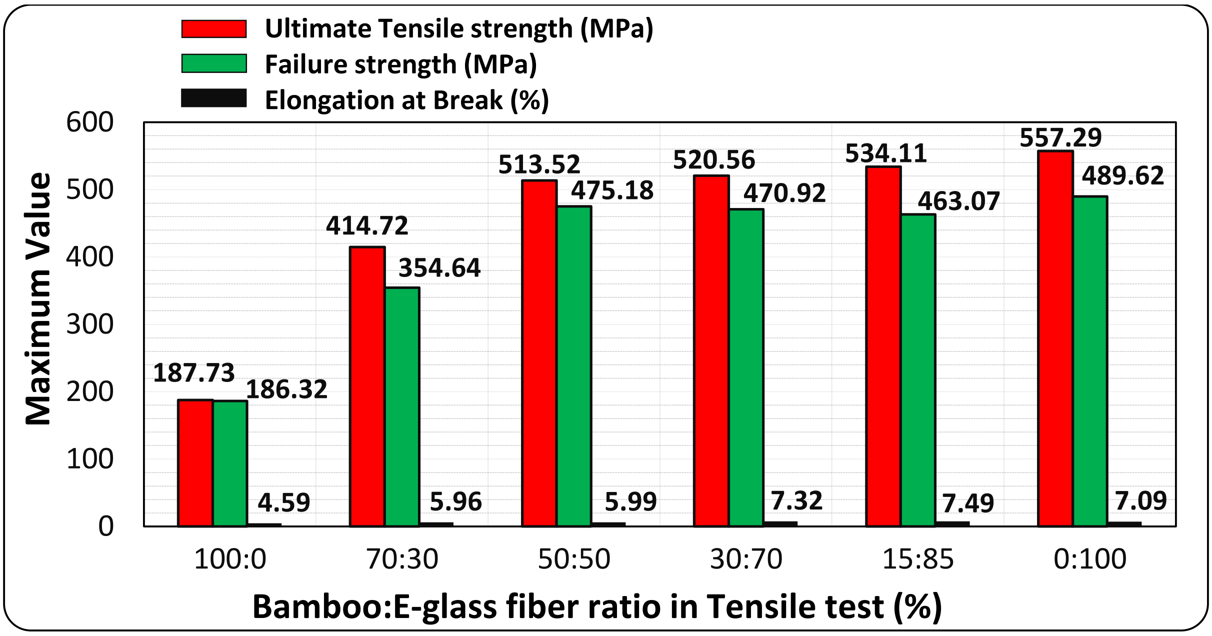


*Figure 4.8: Comparison of different bamboo & E-glass ratio tensile peak value*

Even though the tensile strength of bamboo alone composite (100:0) is much lower than others, its hybrid with the super strengthened E-glass fiber gave a better characteristics even nearer to E-glass fiber alone composite (0:100). This clearly depicted in *figure 4.1 and 4.8.*

The ultimate strength, failure strength and elongation at break is clearly illustrated in *figure 4.8*. The minimum ultimate strength is 187.73 MPa for bamboo alone composite and the maximum value is 557.29 MPa for E-glass alone composite. In general, we concluded that as increase of bamboo fiber percentages, the tensile strength is slightly decreased and tensile modulus is increased in 70:30 and 50:50 bamboo to E-glass fiber ratio.

### 4.2.2. In-Plane Shearing Test

The Maximum in-plane Shear Stress can be determined using *Eq. 4.1*

$$\tau_{12} = \frac{P}{2 \times b \times h} \tag{4.1}$$

Where $\tau_{12}$ = maximum in-plane shear stress, MPa;

P= maximum force at or below 5 % engineering shear strain, N

b= width of specimen, mm and

h= thickness of specimen, mm

The in-plane shear modulus of this unidirectional laminate is determined from the initial slope of the shear stress–strain curve over a strain range of 0.1–0.5% using *Eq.4.2*, and its value is figured in *figure 4.12*.

$$G_{12} = \frac{\sigma_{xx}}{2(\varepsilon_{xx} - \varepsilon_{yy})} = \frac{\tau''_{12} - \tau'_{12}}{\gamma''_{12} - \gamma'_{12}} \tag{4.2}$$

The typical stress–strain curves for BGREC under in-plane shearing load and ultimate stress with percentage of bamboo & E-glass fiber ratio was presented in *figures 4.2*. This graph showed that shear stress increased linearly with increase in strain until point of ultimate load under shearing load. Above this point, the stress–strain curve showed a slow decrement in load and failure happened at ultimate failure point.

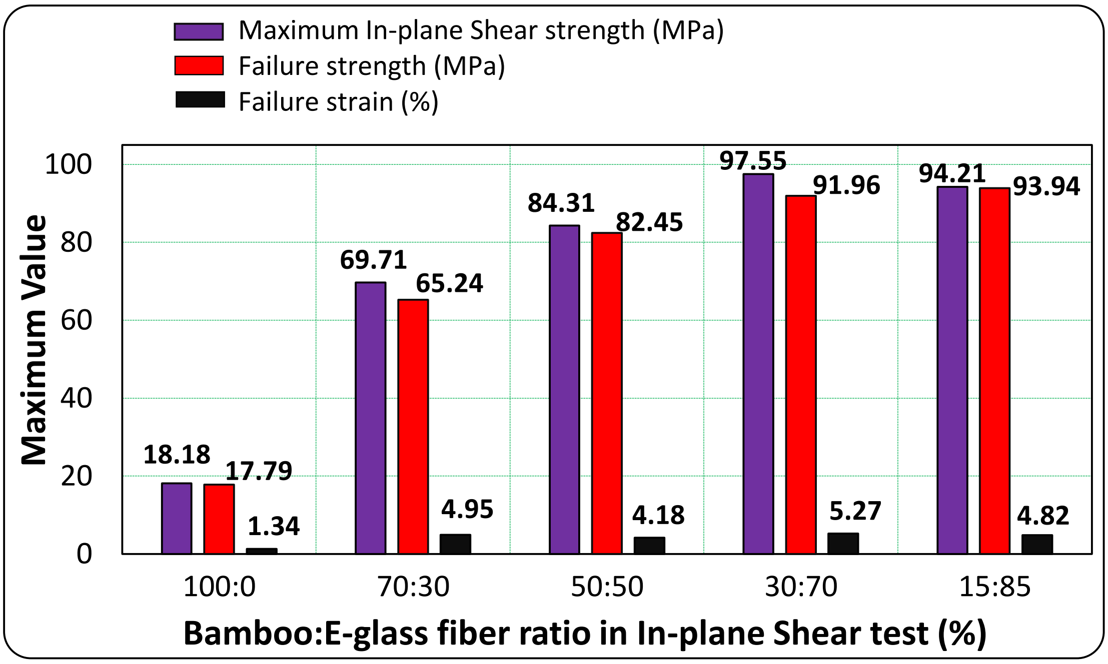


*Figure 4.9: Comparison of different bamboo/E-glass ratio Shear peak value*

The maximum in-plane shear strength, failure strength & failure strain is illustrated in *fig. 4.9.*

The minimum shear strength is 18.18 MPa for bamboo alone composite and the maximum value is 97.55 MPa for 30:70 ratio.

Still an increment of bamboo fibers in the BGREC causes a slow decrement in in-plane shear strength.

However, according to [19, 33, 34, 35], the application of composite materials in mechanical engineering is limited by poor transverse and shear properties as well as their impact behavior of unidirectional composites. Form this truth, the result obtained in this study is much better.

### 4.2.3. Compressive Test

*Figure 4.3* indicated that compressive stress increased with an increment of strain until point of ultimate stress under compressive loading. Above this point, the stress–strain curve showed non-linear segments. This graph shown that the increment value is non-linear, in which the responsible for this response is jerky/stick-slip behavior, which is discussed in next sub-topic. During fracture, compressive stress of BGRECs rapidly decreased with buckling of specimens. According to the Tsai–Hill criteria [18, 34], the compressive properties of composites continuously decrease as the angle of orientation of the fibers increases from $0^0$. In this study, fibers direction in all laminae are same i.e. unidirectional, but ply angles are different in all type of BGRECs samples. In general, due to an increment in numbers of layers and orientation of middle layers fibers from $0^0$, the compressive strength obtained is much lower than the tensile strength which are all fibers of laminate are in unidirectional way.

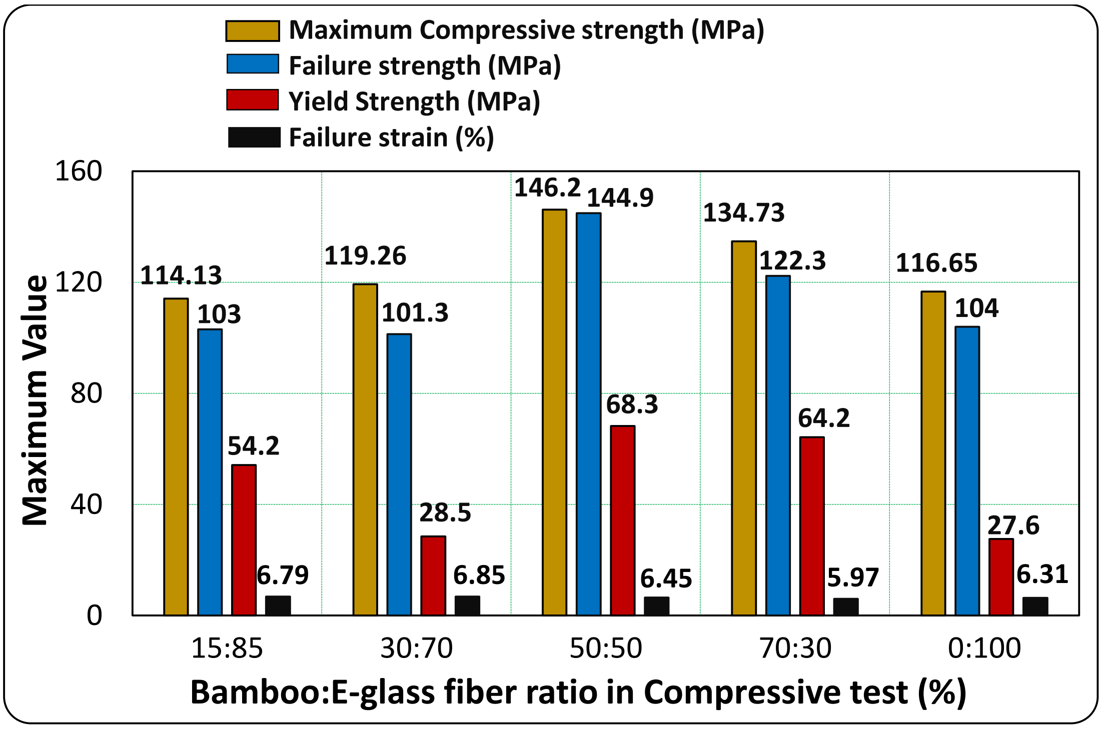


*Figure 4.10: Comparison of different bamboo & E-glass ratio compressive peak value*

*Figure 4.10* illustrated the peak values of compressive strength, failure strength, failure strain and (0.2%) yield strength. Ratio of 50:50 recorded a higher compressive strength, 146.22 MPa; and a minimum value is obtained from the 15:85 ratio, which is 114.13MPa. Usually these wood product materials are better in compression resistance; and as a result the outcome for 50:50 is of this fact. However, like that of another test outcomes, the result obtained from compressive test is not satisfactory. This is because of the UTM's compartments available in AAiT is not complete and accuracy of the machine for this test is not pretty good. This became a consequence for lowering of the compressive strength result obtained.

### 4.2.4. Flexural Test

Under three point bending in *figure 4.4* when the load P is applied at mid span of a rectangular specimen of span L between two rollers, the highest flexural strength is determined by:

$$\sigma_{bf} = \frac{3 \times L \times P}{2(b \times d^2)} \tag{4.3}$$

The deflection of the specimen by considering specimens as a beam ($D_c$) from the center as illustrated in *figure 4.4* can be expressed as:

$$D_c = \frac{r \times L^2}{6d} \tag{4.4}$$

The maximum flexural strain $\varepsilon_f$ also calculated from:

$$\varepsilon_f = \frac{6 \times D_c \times d}{L^2} \tag{4.5}$$

The bending elastic modulus ($E_B$) is determined from the slope of load- deflection curve in a linear region and mathematically it expressed as:

$$E_B = \frac{m \times L^3}{4(b \times d^3)} \tag{4.6}$$

Where:

$\sigma_{bf}$ = calculated fracture stress (flexural strength), MPa

P = load at a given point on the load- deflection curve, N

$D_c$= is the maximum deflection at the center of the specimen (camber distance), mm

m= is the slope of the tangent to the straight-line portion of the load-deflection beam.

L= support span of specimen, mm

b = width of the specimen tested, mm

d = depth of the specimen, mm

r = strain, mm/mm

*Figure 4.5* indicated that flexural stress increased a little bit linearly with increase in strain until point of maximum flexure stress under bending load. Above this point, the stress–strain curve showed non-linear segments. As observed from this graph, the elastic range of the curve is not perfect linear, which is expected in composite materials actually. However, in this case its non-linearity is overwhelmed. Even though there is no an authentic reasons for this non-linear response, some reasons such as alignment of UTM, homogeneity of materials & slipping of specimens during bending load induced for stick-slip phenomena.

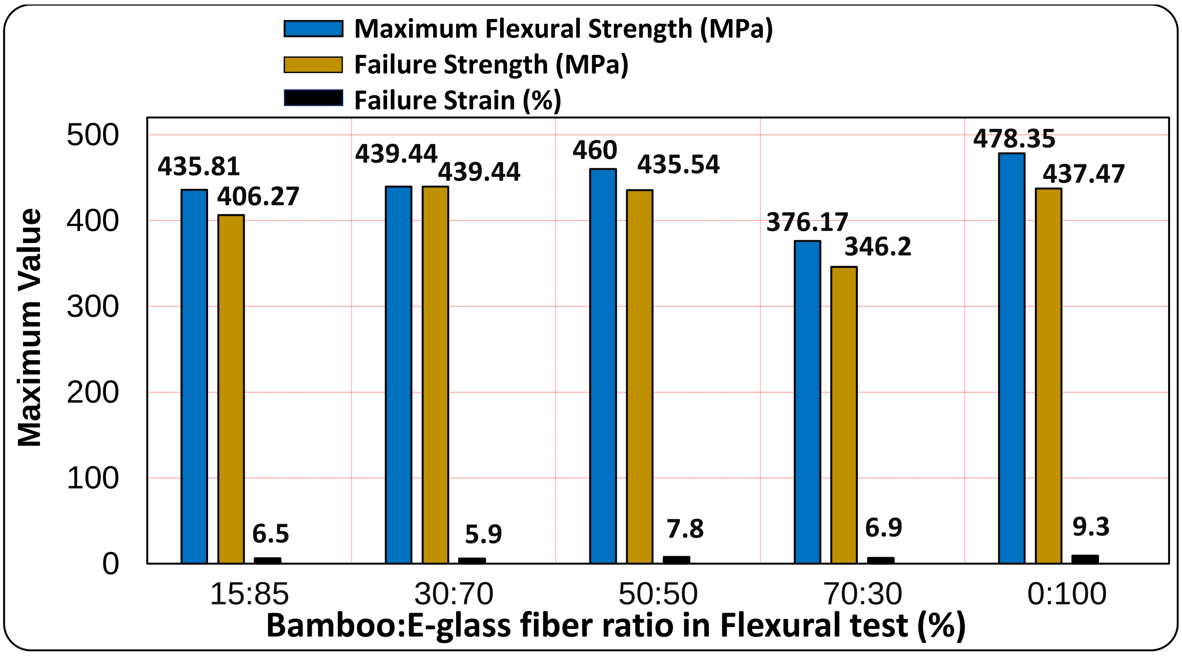


*Figure 4.11: Comparison of different bamboo/E-glass ratio Flexural peak value*

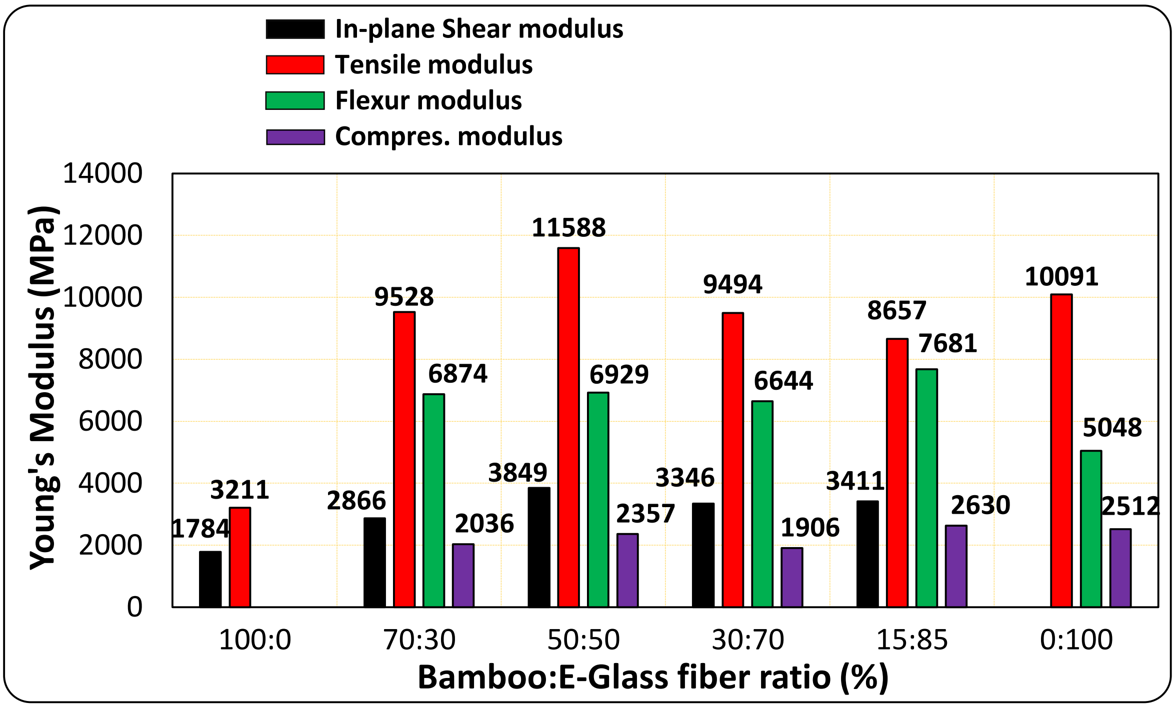


*Figure 4.12: Comparison of Young's Modulus for different fiber ratio*

The peak value of flexure rupture, failure strength and failure strain of each BGREC ratio in bending load is clearly illustrated in *figure 4.11*.

Here, bending fractures concentrated near the middle of the test specimen where load was applied. The minimum flexural strength is 376.17 MPa for 70:30 composite and the maximum value is 478.35 MPa for 0:100 composite. However, here the bamboo & E-glass ratio of 50:05 result also has higher value than 15:85 and 30:70 ratios.

Bamboo, E-glass & epoxy bond revealed a strong fluctuations of stress-strain curve (slip-stick effect) recorded during uniaxial compression and bending tests. This slip-stick effects causes difficulties in interpretation of testing results obtained due to non-linearity of the curve. The load oscillations happened due to the stick-slip between the granules of bamboo and glass fibers. These granules form chains of particles within the epoxy to support the applied load. When the chain becomes unstable, some granules will slide out causing the load to drop. This drop causes a sudden drop in the stresses during compression & bending. This stick-slip phenomenon usually occurs in an anisotropic materials when the particles begin to slide and roll over each other.

From the relative displacements of the matrix and fiber elements at the interface, relative slipping of the cracked interface is usually expected due to the ‘stick-slip' nature of frictional stress transfer. Stick-slip fracture follows a crack propagation and crack arrest behavior which indicates unstable crack growth [36]. This jerky (stick–slip) behavior is related to the known physical mechanism of dislocation movements, namely, the pinning (stick/slow) and depinning (slip/fast) of dislocations. Stick–slip is characterized by the system spending characteristically unequal times in the stick and slip states [37, 38].

The mechanical behavior of granular materials is highly dependent on the arrangement of particles, particle groups, and associated pore spaces. Changes in the internal structure due to large deformation may cause changes in the mechanical behavior. These change may include: particle sliding, rolling, and interaction; shear band formation; and fabric anisotropy. During those changes, stick-slip behavior may take place between the granular particles [36].

According to [39], the stick-slip seems to disappear at large strain rates and that stick-slip is sensitive to rapid variation of deviator stress forcing it to disappear. Moreover slick-slip disappears in relatively large specimens with fast loading rates. Therefore strain variations are largely affected by the stick-slip behavior of the bonds. So, we can conclude that the lower value of the strain rate used for compression and flexural test responses for this jerky effect.

The cross head speed for compressive and flexural testing were 0.75mm/min & 1.5mm/min respectively. Strain rate is given bay (Cross head speed) / (Gage Length).

Modulus of elasticity for tensile, shear, compressive and flexural tests also determined, as illustrated in *figure 4.12*. The minimum and maximum values of tensile modulus for these composites are found to be 3211 and 11588 MPa respectively.
As we observe from the graph, a good tensile modulus is recorded in a 50:50 ratio of bamboo to E-glass fiber ratio.
Shear modulus of elasticity also determined, and 3568 MPa for 100:0 and 5418 MPa for 50:50 ratios were a minimum and maximum values.
As well the compressive moduli of these composites vary between 1906 and 2630 MPa.
Similarly, the flexural modulus also vary between 5047.7 and 7681.26 MPa.

The elastic moduli achieved from the tensile, compression and bend test are generally close to each other within the same material in the case of isotropic materials [32, 40]. But these values are not closer as shown in *figure 4.12* due to anisotropic characteristics. There are several factors that might affect the elastic moduli, which are:

- Elastic and plastic deformation at the rollers at the supports or the loading points might not be sufficiently small in comparison to the beam deflection.
- If a short specimen is bend tested, deformation due to shear stress may take place, which are not ideal for the calculation according to the beam theory.
- Materials might have different elastic moduli under tension, compressive and bending.

Therefore, the elastic moduli in tension, compression and bending should be identified to an avoid confusions for the interpretation of the mechanical behavior of the anisotropic materials.

This observation clearly indicates that the BGREC with 50:50 bamboo to E-glass ratio has relatively higher moduli in almost all the tests carried out. As a result, this ratio has a better load-bearing capacity.
As presented in background of this study, the critical properties for wind turbine shell are strength, rigidity, cost and environmental friendly are the mains. From all the experiment results obtained, by compromising the strength, the good rigidity, environmental friendly and the cost minimization (the expensive E-glass by hybrid with a cheaper bamboo fiber), a bamboo to E-glass ratio of 50:50 is better to fulfill these requirements. Moreover, major challenges for large size wind turbine blade is large deflection because of the material it used. From this aspect, result obtained from 50:50 has good stiffness that can withstand this problem.

So, this is better ratio that can be fulfill most of the requirements for large size wind turbine blade shell.

The in detailed graph of this 50:50 bamboo to E-glass ratio is presented in *appendix A*. In these graphs, cross sectional area of the specimens used, maximum Strength, failure Strength and elongation at break and failure strain in percentage also included for each case.

The determination of elastic modulus (E), was carried out by taking 0.2% offset strength from the given stress-strain curves. And this offset line's slope, or ratio of stress range and corresponding strain range gave a modulus of elasticity for that particular material.

Elongation at break, also known as fracture strain, is the ratio between changed length and initial length after breakage of the test specimen. It expresses the capability of a material to resist changes of shape without crack formation. The elongation at break is determined from the tensile testing and its value is expressed as percent.

### 4.2.5. Failure Modes

All specimens under tensile loading except 100:0 ratio, have similar failure modes; that is explosive failure types at the middle of gage area. In the case of 100:0 ratio, types of failure identified are lateral failure types in the middle of gage area. It also observed that some specimens start to fail at grips and some at multimode types.

For all layers of laminate, first matrix (adhesive between fibers) failure occurs followed by fibers failure through then fracture propagates spontaneously. Further it is observed that among seven layers, any one layer first break then propagates & explode to the other layers.

Compressive failure was attributed by micro buckling surrounded by delamination. The delaminated portions spread to the intact areas of the laminate by a combination of delamination buckling and growth, the buckling further enhancing the growth of damaged area. The culmination of this last event is the complete loss of stiffness of specimens.

In the case of in-plane shearing test, most of the specimens failed by lateral failure type, in the middle of gage area; and only a few specimen's failure by edge delamination.

In the case of flexural test, bending failure on the tension surface of specimens was due to matrix and fiber breakage while on the compressive surface was due to buckling of specimens. Failure modes of fractured specimens of BGRECs on different loading conditions have been identified using ASTM failure identification codes standards and are presented in *table 4.1*.

*Figure 4.13: Tensile and Compressive failure types*

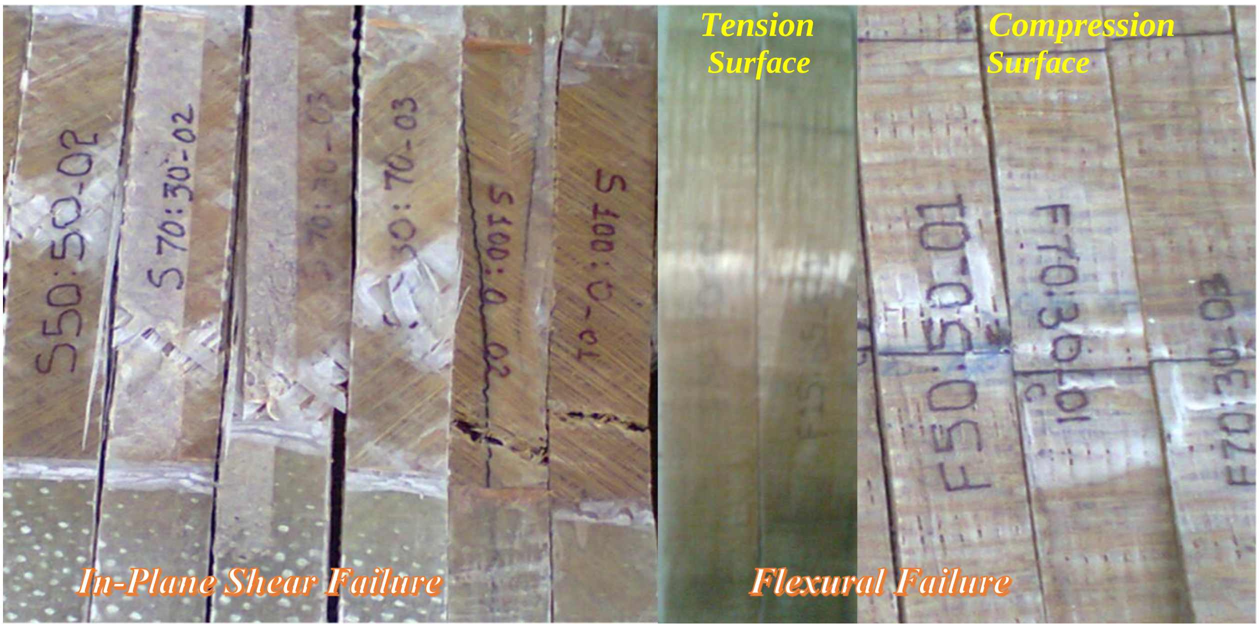


*Figure 4.14: In-plane Shear and Flexural failure types*

*Table 4.1: Mode of failures under different loading conditions*

| **Loading condition** | **ASTM standards** | **Mode of failures identified in terms of codes** |
|---|---|---|
| Tensile | D3039 | XGM, LGM |
| Shear | D3518/D3039 | AGM, DGM, LGM |
| Compressive | D3410 | AGM, BGM, TAT |
| Flexural | D790 | BBB, CBT, MUV, TAM |

*<u>NB:</u> the term of code of failure definition is elaborated in list of abbreviations & acronyms.*

### 4.2.6. Scanning Electron Microscopy Observation

Observations of SEM photographs in *figure 4.15* illustrated the untreated and alkaline treated bamboo fibers. *Figure 4.15* (A) pictured untreated bamboo fiber were together bonded by lignin and hemi-celluloses with different bonding level. Most lignin contents are condensed on fibers surfaces as illustrated here, in which the smoothest and softest pars are these components that stick on outer surface of bamboo fiber.

It is clear that this soften fleshy part of bamboo fiber can be a barrier for bamboo fiber being well bonded with adhesive, and if excess of these component is present with in the fiber, during loading, the composite laminate can be easily peeled or delaminated.

*Figure 4.15*(B) showed the hemi-cellulose and lignin contents decrement due to alkali treatment. It is clear that comparing (B) with (A), here, the surface is somehow clean from these lignin and cellulose components. The elimination of amorphous weak hemi-cellulose components from the bamboo fibers using alkali treatment may be responsible for good mechanical properties of the BGREC as elaborated before.

Through alkali treatment, removal of hemicelluloses, lignin, waxes, oils, and surface impurities from the fibre ensured and leading to reduction in the total weight of the fibre core, and hence lowering the density [14]. Similarly the presence of excess amount of lignin and cellulose in the fiber causes the fibers to loss of its stiffness, toughness and its light weight characteristics.

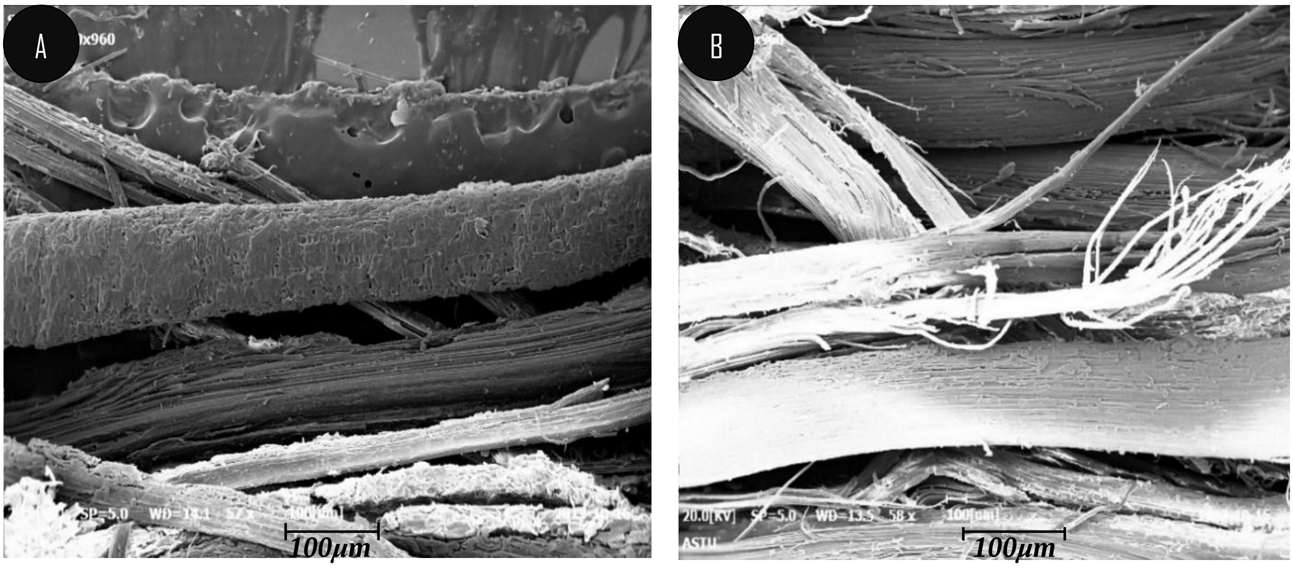


*Figure 4.15: SEM photographs of untreated & alkali treated bamboo fibers surface*

Furthermore, removal of these excess amount of lignin and hemicellulose, leads the bamboo fiber own a good adhesion properties during the bamboo fiber-epoxy-glass fiber bonding. So, the result obtained from experiment is due to the responsibility of this effect.

*Figure 4.16* shown a single untreated & treated bamboo fiber surface SEM observation under higher magnification scale. Here part (A) is untreated single fiber. The fatty components and impurities are stick on this fiber surface. In part (B) of the rubbed and hollowed surfaces are caused by removal of larger amount of the soluble substances (lignin, hemicellulose & impurities) from the fiber layer using the caustic soda.

Alkali treatment is believed to have cleared the micro-pores in fibres and roughened the fibre surface. Higher NaOH concentration could have cleaned the fibre even more thoroughly [14]. Study of [14, 27] reported that alkalization cleans and makes the fibre surface look smooth, but the fibre surface is actually roughened as shown in figure *4.15*(B).

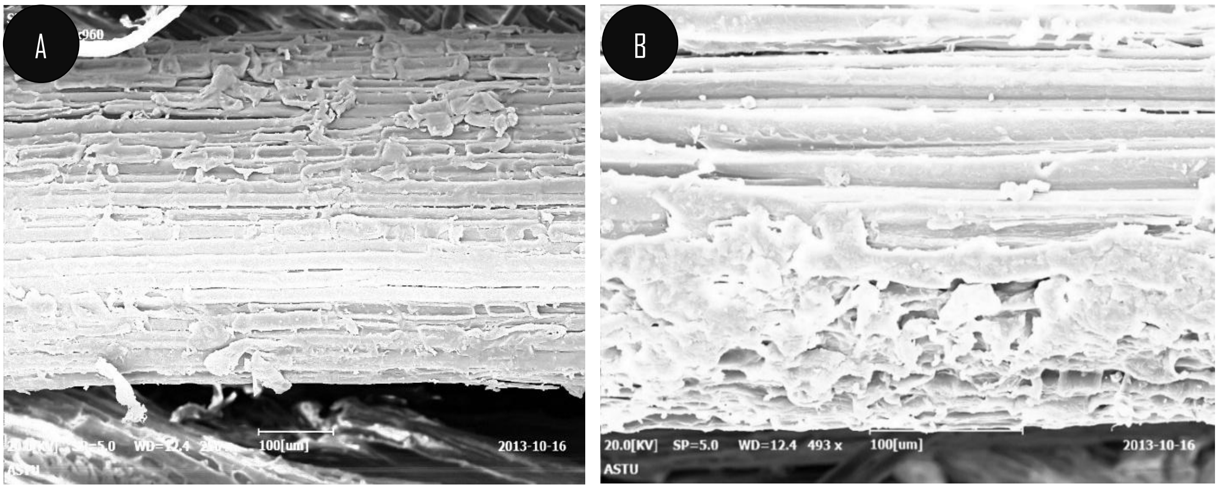


*Figure 4.16: SEM photographs of untreated & 5% treated single bamboo fiber surface.*

*Figure 4.17* illustrated the tensile specimens' surface morphology before tensile loading.

In part (A), the outer surface is observed at 1.0kx (1000 times) magnification, and several hollow structures are observed. However all of these holes are not voids. Rather many of them are scratched parts by peel ply materials during fabrication. Only few of them are voids as clearly shown on the figure. This probably caused by fabrication process. During vacuum bagging process, a very little amount of vacuum pressure drop (around 0.015%) were observed. This makes a chance to form a few micro-bubbles inside the laminate due to incomplete evacuation of air from the perimeter of the mold, and finally micro-holes are formed after solidification. Beside this, at this higher resolution level, the amount of voids is almost insignificant.

Moreover part (B) of this figure illustrated that bamboo and E-glass fibers are completely embedded and covered by epoxy which is visualized at 3.0kx magnification.

In fact, all of these photographs conclude that the BGREC were well fabricated and have good homogeneity with minimum porosity.

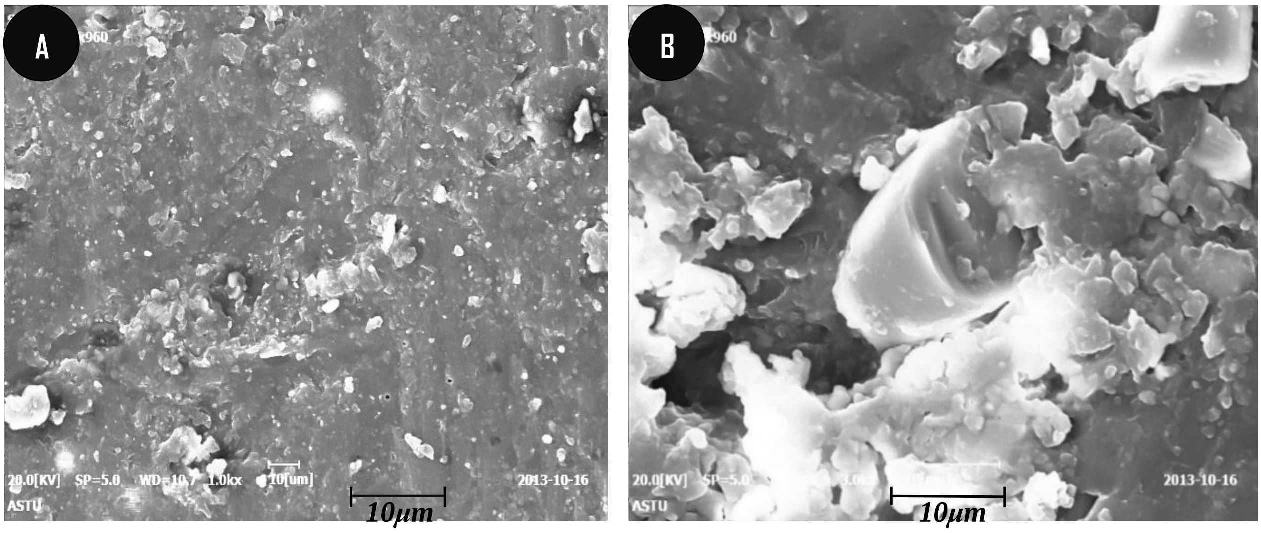


*Figure 4.17: SEM photographs of tensile surface at 1000X & 3000X magnification*

The final SEM observation is tensile fractured surface of BGREC specimen, which is pictured in *figure 4.18*. Part (A) of this photograph, is the axial view BGREC fractured surface; and easily we can visualize that a linear distribution of fibers in the adhesive. However a few spaces are observed. This is actually probably caused by an excess of resin squeezed from by vacuum pump during solidification, which causes shortage of resins between two adjacent fibers or caused by reasons mentioned for *figure 4.17* (A) above. And these points might responsible for initiation of tensile fracture to begin during loading.

Similarly, the SEM photograph (B) of lateral view of BGREC fractured surface shows the source of the cracks and their subsequent propagation. The fiber pull out indicate that there were perfect bonding among the bamboo fiber, E-glass fiber and epoxy as observed on the lateral surface of the specimen at 541x magnification.

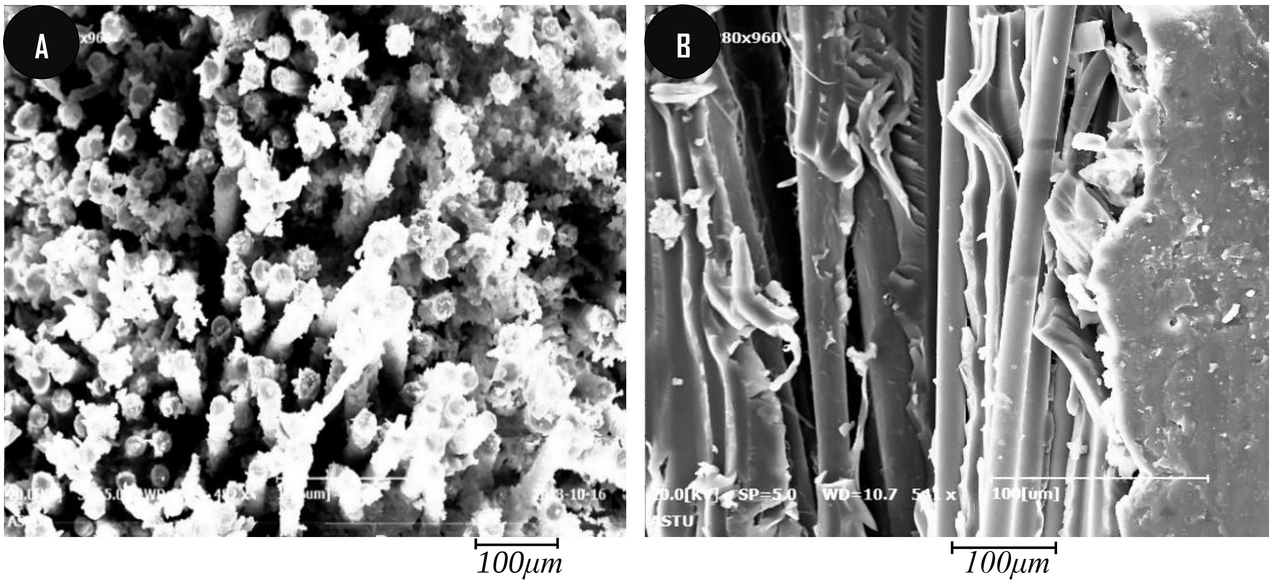


*Figure 4.18: SEM photographs of tensile fracture surface at different views*

# CHAPTER 5: CONCLUSSION AND RECOMMENDATION

## 5.1. Conclusion

The three years old bamboo fiber was extracted manually from Ethiopian bamboo '*Yushania Alpina'* species, and then alkaline treatment was carried out.

Next to that, bamboo & E-glass reinforced epoxy hybrid composite was manufactured and its mechanical performance is determined using laboratory experiment.

All the numerous experimental tests result gathered an important information about the bamboo & E-glass fiber composites and the best process formulations. Moreover such tests constitute fundamental confirmation of the reliability of the material and of its usage in wind power turbines blade shells fabrication.

In order to achieve the goal of this study, a lot of work was performed and the following conclusions are drawn.

- The tensile, shear, flexural and compressive properties of BGREC composites depends fundamentally on the amount of layers in a laminate, angle and orientation of lamina and bamboo to E-glass fiber percentage present.
- The surface morphology of bamboo fibers experiences substantial changes during alkaline treatment. Beneficial effects of surface fiber treatment occurred for BGREC within 5% caustic soda.
- A three years old of extracted bamboo fiber is good enough to use it as reinforcement in a super structural fibers.
- Different mechanical properties of BGREC were determined from different bamboo to E-glass fiber percentage of 45% total fiber volume.
- In some cases the stress/strain behavior of the BGREC is observed linear and in some other cases highly non-linear.
- An optimum strength and high modulus of elasticity, (i.e. good stiffness) is obtained from bamboo to E-glass fiber ratio of 50:50.

## 5.2. Recommendation

The primary function of the shells is to provide the aerodynamic shape. They also play a structural role in stiffening and strengthening the spar, particularly to resist torsion (twisting) loads. Structures loaded in torsion experience pure shear loading, so just like the spar shear webs, the shells have a high proportion of fibres running diagonally [2, 4].

Usually, the cross-section of the shells are significantly wider than the spar in order to provide edgewise bending stiffness. Edgewise bending is primarily due to the blade's own weight.

According to [1, 2, 4, and 5], wind is also another source of blade shell loading. Lift causes bending in the flapwise direction (out of rotor plane) while air flow around the blade cause edgewise bending (in the rotor plane). Flapwise bending involves tension on the pressure (upwind) side and compression on the suction (downwind) side. From this aspect, the tensile, compressive and bending strength should be optimum to minimize failure of blade shell laminates.

Wei Tong and Yosif said that the leading and trailing edge that are unsupported by inner web is constructed from carbon fiber, in which its stiffness is two times more than glass fibers, but other part is constructed from glass fiber (fabric and chopped).

Moreover in order to resist torsional loading, the shell is constructed from ±$45^0$ laminate of fiber glass. From this points of view, the result obtained from the ±$45^0$ offset tensile test in this study is much better than research conducted by [35].

In the same way many researchers conducted on wind turbine blade design around the world supposed that most of the time, materials used for the shell of wind turbine blade is glass fiber. From this regard, it is possible to conclude that result output of this BGREC material can be hopefully has a potential to substitute fiber glass alone composite. Even many researches proposed that materials for wind turbine blade skin is to be chopped glass fiber, which has lower mechanical strength than result obtained from BGREC [13, 24]. Beyond this, there is no any research conducted on wind turbine blade shell materials alone in before. Furthermore, a bamboo to E-glass ratio of 50:50 has an enough potential to be used as turbine blade shell materials from its optimum strength, super higher modulus of elasticity points of view, & even from cost point of view, in which half of the E-glass fiber is replaced by bamboo fiber.

However, the bamboo fiber has weaker side in its moisture absorption. But, this property can be improved by chemical application and by using it as inner part of the hybrid composite, in which this study also conducted in this fashion.

## 5.3. Future work

From different aspects, working on natural materials as composite have several advantages. From this point of views, regarding BGREC's several things can be made and improved in the future in which this study couldn't addressed.

So the following research areas are recommended for future studies.

- Finding of different bamboo fiber extraction processes.
- Finite element analysis for BGREC through determining material parameters.
- Effect of different fabrication techniques on BGRECs
- Improvement of moisture absorption of bamboo based composite for indoor/ outdoor applications.
- Effects of tab presence on tensile, shear and compressive strength
- Fracture and fatigue analysis of BGRECs
- Design of natural fibers extraction processing machine.

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# Appendix A: Graphs

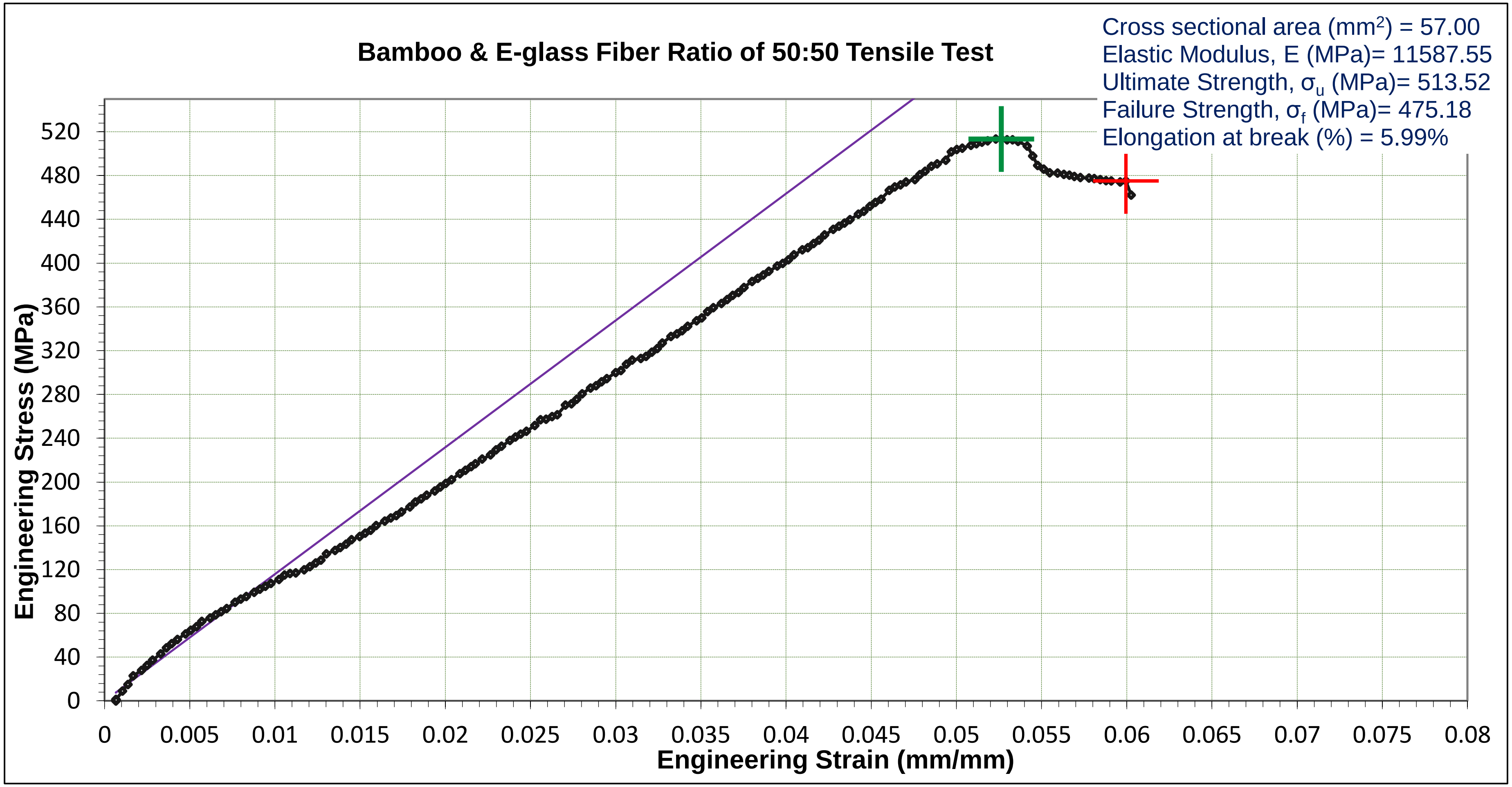

*Figure A.1: Engineering Stress vs. Engineering Strain curve of 50:05 ratio*

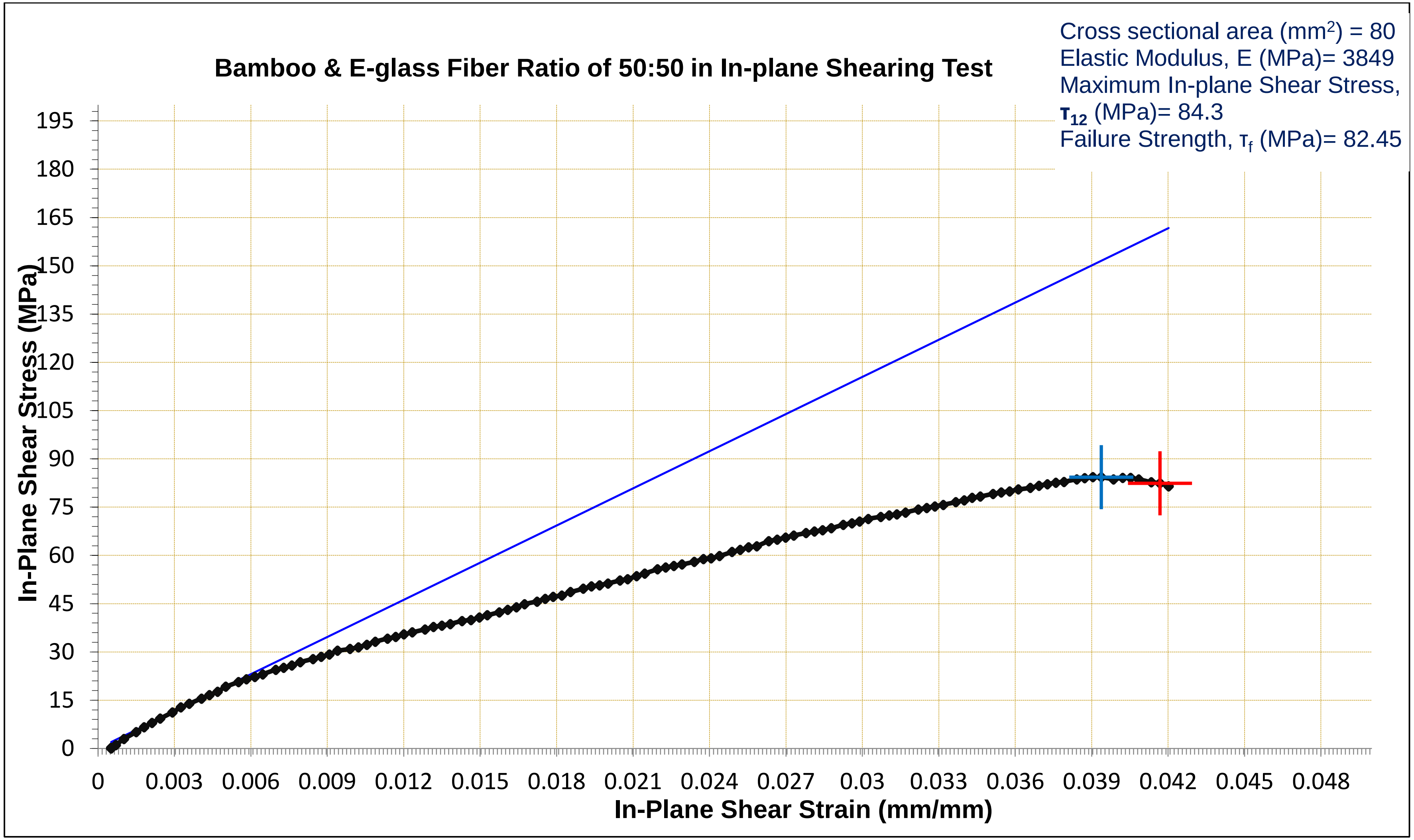

*Figure A.2: In-Plane Shear Stress vs. In-Plane Shear Strain curve of 50:50 ratio*

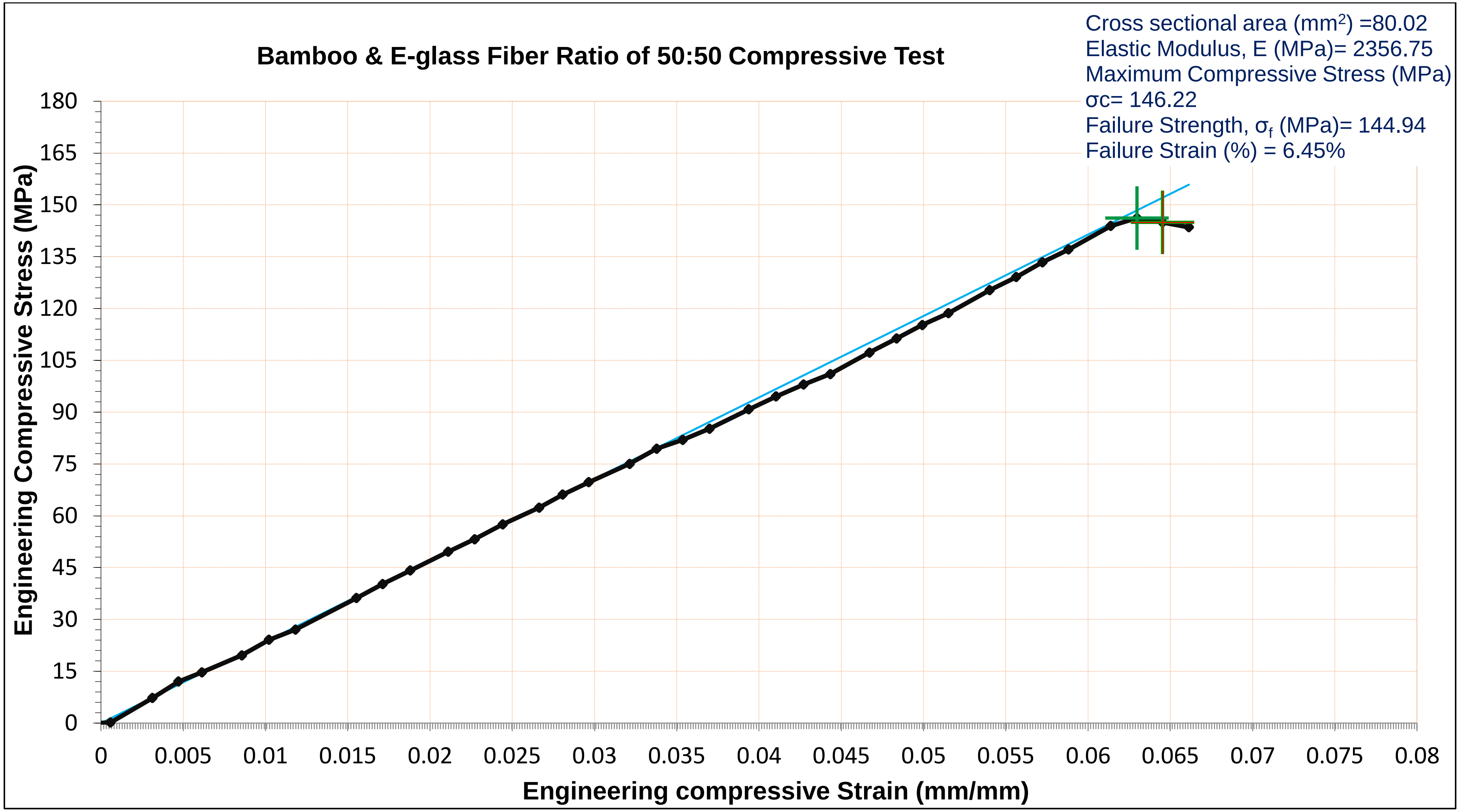

*Figure A.3: Compressive Stress vs. Compressive Strain curve of 50:50 ratio*

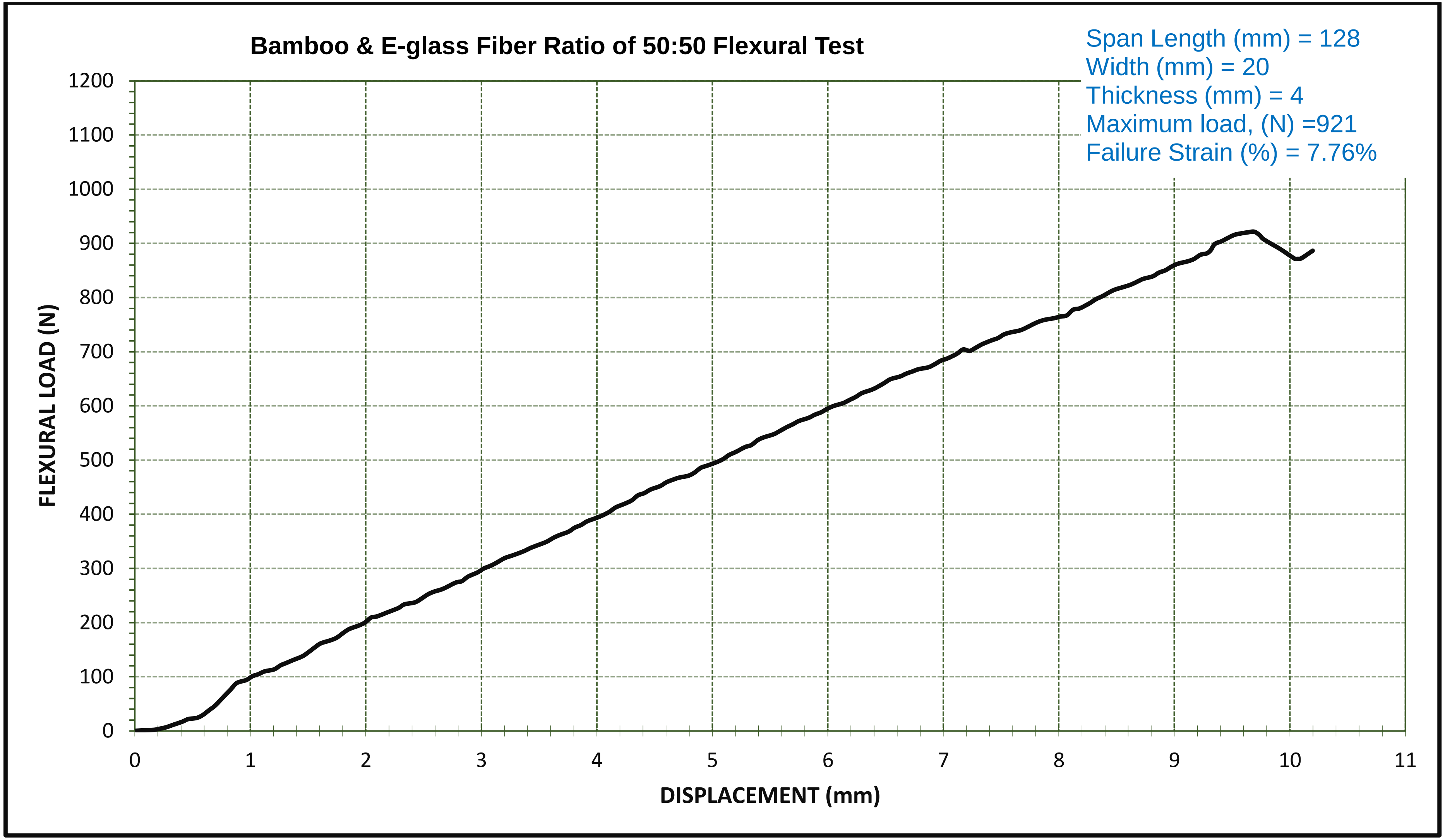

*Figure A.4: Flexural Load vs. Flexural Displacement curve of 50:50 ratio*

# Appendix B: Mechanical Properties of Materials

Mechanical properties of unidirectional E-glass fiber, epoxy and hardener.

## Unidirectional E-Glass fiber

Technical Data

| | |
|---|---|
| Color | white |
| Normal thickness | 0.35mm |
| Weight (g/m$^2$) | 420 ± 5 |
| Weave type | Plain |

Typical properties of unidirectional E-glass fiber

*Table B.1: Typical properties of unidirectional E-glass fiber*

| **Mechanical Properties** | **Value** | **Test Method** |
|---|---|---|
| Density (gm./cc) | 2.57 | |
| Tensile strength (MPa), *@ 23$^0$C* | 1725 | ASTM |
| Young's modulus (GPa), *@ 23$^0$C* | 72.3 | ASTM |
| Refractive Index | 1.557 | |
| Thermal Coef. Of Expansion Range | 5.4 x 10$^{-6}$ in./in./° C | |
| Elongation | 4.8% | |

[Source: Manufacturer is not known, procured by Dejen Aviation Industry (DAVI), Bishoftu, Ethiopia]

**System 2000 Epoxy Resin and System 2060 hardener**

Product Specifications

| | **Hardener 2060** | **ASTM Method** |
|---|---|---|
| Color | Amber | Visual |
| Viscosity, @ 77° F, centipoise | 190-200 cps | D2393 |
| Density, lb./cu Inch | .0410 | D792 |
| Specific Gravity, gm./cc | 0.96 | D1475 |
| Specific Volume, cu. in./lb. | 25.0 | D792 |
| Mix Ratio, By Weight | 100 : 27 By Weight, or<br>3 to 1 By Volume | D2471 |
| Pot Life, 4 fl. Oz. Mass @ 77° F | 1 hour | PTM&W |

Typical Mechanical Properties of system 200 Epoxy Resin with its hardener

*Table B.2: Typical Mechanical Properties of system 200 Epoxy Resin with its hardener*

| **Mechanical Properties** | **Epoxy system 2000 with Hardener 2060** | | **ASTM Method** |
|---|---|---|---|
| | **Neat Resin(Unreinforced)** | **With Fiberglass** | |
| Flexural strength | 16,827 psi | 62,285 psi | D790 |
| Flexural modulus | | | |
| Tensile strength | 9828 psi | 45,170 psi | D638 |
| Tensile modulus | 418,525 psi | 2,620,000 psi | D638 |
| Thermal Coef. Of Expansion Range | $4.3 \times 10^{-5}$ in./in./° F | | D696 |
| Fiberglass Properties Derived with A 10 Ply Laminate, Hand Lay-up, Style 181 Glass Fabric, 55% Glass Content | | | |

[Source: Fiber Glast Development Corporation, 385 Carr Drive-Brookville, Ohio 45309, USA, procured by Dejen Aviation Industry (DAVI), Bishoftu, Ethiopia]