STUDY ON MECHANICAL PROPERTIES OF NODE AND INTERNODE FROM DIFFERENT PARTS OF *GIGANTOCHLOA LIGULATA* BAMBOO

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STUDY ON MECHANICAL PROPERTIES OF NODE AND INTERNODE FROM DIFFERENT PARTS OF *GIGANTOCHLOA LIGULATA* BAMBOO

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ABSTRAK

Dengan peningkatan populasi di seluruh dunia dan menyertai penggunaan sumber alam yang merosakkan alam sekitar, bahan alternatif dan lestari sedang diteliti untuk memenuhi permintaan manusia. Ciri-ciri buluh, seperti pertumbuhannya yang cepat, sifatnya yang dapat diperbaharui, dan kemudahan ketersediaan sebagai bahan mentah, memenuhi permintaan manusia untuk bahan binaan yang mesra alam. Buluh adalah salah satu tanaman yang paling cepat tumbuh di planet ini, dengan pelbagai spesies yang berukuran berbeza. Walaupun buluh telah digunakan sebagai bahan binaan selama ribuan tahun, namun tidak banyak kajian mengenai sifat mekanik buluh itu sendiri. Penggunaan buluh dalam pembinaan telah lama diabaikan kerana kurangnya pemahaman tentang sifatnya. Akibatnya, kajian ini menyajikan penyelidikan sifat mekanik nod dan internod dari pelbagai kedudukan tinggi (atas, tengah, dan bawah) spesies buluh yang terdapat di Malaysia. Dalam kajian ini, sifat mekanik spesies buluh *Gigantochloa Ligulata* ditentukan (mampatan, ricih, dan tegangan). ISO 22157 telah digunakan sebagai rujukan untuk menguji sifat mekanik batang buluh pada pelbagai ketinggian. Berdasarkan keputusan ujian, kekuatan mampatan dan ricih internod mengatasi nod. Dari bahagian bawah hingga ke atas batang buluh, bahagian nod untuk mampatan dan ricih menunjukkan kecenderungan yang semakin meningkat. Semua sifat mekanik menunjukkan arah aliran yang meningkat dari bawah ke atas batang buluh.

ABSTRACT

With exponential worldwide population increase and accompanying environmentally damaging consumption of natural resources, alternative and sustainable materials are being researched to meet human demands. Bamboo's features, such as its rapid growth, renewable nature, and ease of availability as raw material, satisfy the human demand for environmentally friendly building materials. Bamboo is one of the fastest-growing plants on the planet, with numerous species varying in size. Even though bamboo has been used as a construction material for thousands of years, there has been little research on the mechanical properties of bamboo itself. Bamboo's use in construction has long been overlooked due to a lack of understanding about its properties. As a consequence, this study presents an investigation of the mechanical properties of nodes and internodes from various height positions (top, middle, and bottom) of a bamboo species found in Malaysia. In this study, the mechanical properties of the *Gigantochloa Ligulata* bamboo species are determined (compression, shear, and tensile). ISO 22157 was used as a reference to test the mechanical properties of bamboo culms at various heights. Based on the test results, the compressions and shear strengths of internodes outperform those of nodes. From the bottom to the top of the bamboo culm, the nodal section for compression and shear exhibits an increasing tendency. All the mechanical properties show an increasing trend from bottom to top of the bamboo culm.

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LIST OF ABBREVIATIONS

ISO	International Standardization for Organization
BJA	Bamboo Jungle Adventure
CA-B	Copper azole type B
CA-C	Copper azole type C
UV	Ultraviolet light
T	Top
M	Middle
B	Bottom
MC	Moisture content

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Bamboo is the only grass with a growth rate of up to 60 cm or more in a single day. It is known as the fastest growing plant in this world. Research and studies prove that bamboo plays a significant role in the social, cultural, and economic sectors and is also a traditional building material in the construction industry. Bamboo is a lightweight, flexible, strong, high-tensile, and cheap alternative to other building materials such as steel. Therefore, bamboo can be used in a variety of projects (Bhonde et al., 2014).

Bamboo has been used widely as a building material since ancient times, especially by the people who live in the areas where bamboo grows naturally and abundantly. Back in the day, bamboo was used to build houses due to its inherent strength and flexibility. The aesthetics of bamboo also plays a role in the current world (Nurdiah, 2016).

In the 1980s, the bamboo plant sparked a great deal of interest as a construction material when the whole world faced a shortage of housing materials, especially timber. In the olden days, bamboo was used together with other natural building materials like wood, clay, lime, and grass. It is now mixed with cement and adhesives to produce strong and more aesthetically appealing materials compatible with current modern lifestyles. Since bamboo is a natural product, it will deteriorate over time. Proper treatment and industrial processes enhance the bamboo components to have a reasonable life span of 30 – 40 years (Manandhar et al., 2019).

Bornoma et al., (2016) stated that not all bamboo species are suitable for construction. Only a few bamboo species, such as Guadua bamboo and Moso bamboo, have the same strength ratio of steel and almost twice the compression to weight ratio of concrete. Bamboo species that have been used historically for construction have common characteristics such as a) grows abundance and relatively straight, b) slightly more resistant to insects and fungi, c) stronger and mature quickly within 3 to 5 years, and d) less susceptible to splitting. The basic properties of bamboos used structurally are a) dry density ranging from 500 kg/m3 – 800 kg/m3, b) culm height about 6 m to 25 m, c) nodal spacings about 250 mm to 500 mm, and d) diameter ranging from 50 mm to 20 mm (Kaminski et al., 2016).

1.2 Problem Statement

According to scientists and experts, human activities contribute to climate change. One of the industries that account for that issue is the construction industry. Buildings are account for up to a third of total global greenhouse gas emissions, primarily through the use of fossil fuels during their operational phase. Excessive emissions are a threat to the environment and may result in significant problems in the future.

Some construction materials, such as steel, are more difficult to be manufactured and contribute more to overall material consumption because they are non-renewable resources. Steel, cement, and glass processing require a relatively high temperature, which can only obtain with massive quantities of fossil-based energy. Switching from non-sustainable construction materials like steel and concrete to sustainable building materials like bamboo will significantly reduce the negative environmental impact.

Bamboo's usage in the construction industry should be expanded due to its advantages such as low cost, renewable, biodegradable, and easy-to-find environmentally friendly material. Besides, bamboo uses the least amount of energy in the manufacturing process, resulting in less pollution. Aside from that, bamboo is important for creating job opportunities and rising income levels in both rural and urban areas.

Many countries and organizations are focusing on bamboos to adapt their use according to technological advances. The natural properties of bamboo, such as round culms and varying diameters, restrict its use in construction. Advanced researches and engineered designs on bamboo have been able to overcome this issue by introducing bamboo composites. Ply-bamboo, laminated bamboo, bamboo scrimbers, and cross-laminated bamboo and timber are a few examples of bamboo composites.

1.3 Objectives

This study aims to promote and commercialize bamboo as a unique and versatile construction material.

1. To characterize the mechanical properties at node and internode of the bamboo species.

2. To compare and evaluate the mechanical properties of node and internode from the top, middle, and bottom parts of the bamboo species.

1.4 Scope of Research

This study highlights bamboo as a construction material that plays a significant role in constructions that are comfortable, durable, valuable, precious, and beautiful. Bamboo's physical and mechanical properties, such as moisture content, compression strength, shear strength, and tensile strength will be determined in the laboratory using the appropriate protocol and standards.

1.5 Dissertation Outline

The thesis is organized into five chapters to ease the viewing and understanding. The general description of each of the chapters is explained below.

Chapter 1: Introduction - This chapter contains information about the background of the study, the problem statement of the research, the research objectives, and the scope of research which briefly gives an overall understanding of this thesis as well as explains the purpose of why this research is carried out and gives an idea about the outcome of this research.

Chapter 2: Literature Review – This chapter provides a fundamental understanding of the research topic based on research papers and articles by scientists and experts. Information such as the anatomical properties of bamboo, the structural applications of bamboo, and others are well-reviewed in this chapter.

Chapter 3: Methodology – This chapter discusses the methods used to obtain data related to this research. Elements such as workflow and conducting experiments are described in this chapter.

Chapter 4: Results and Discussion – This chapter evaluates the results obtained from the previous chapter. The objectives of this thesis will be identified in this chapter.

Chapter 5: Conclusion and Recommendations – This chapter finalizes and summarizes the research including recommendations for future research and study in this field.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter discusses studies on bamboo plants and also previously published research on bamboo. This chapter thoroughly examines the biological structure of bamboo as well as the properties that make bamboo suitable for use in the construction industry. Aside from that, insect infestations on bamboo, treatment methods used around the world to combat insect attacks, and previous applications of bamboo in construction industries are all fully covered.

2.2 Anatomy, Structure, and Growth

Bamboo grows everywhere and on almost every continent except in cold climates. About 1400 bamboo species are thought to have been discovered, with even many more still being discovered (Bamboo Anatomy and Growth Habits, 2016). Bamboos are in a variety of colors. Although green is the most common color, it may also be yellow, orange, brown, striped, or even black (Akinlabi et al., 2017). Bamboo is arborescent grass that belongs to the family *Gramineae* (*Poaceae)*, subfamily (*Bambusoideae*) (Hidalgo-López, 2003). The two main anatomical features of a bamboo plant are the underground rhizome system and the culm which, are widely used in the construction industry (Richard, 2013).

2.2.1 The Bamboo Culm

Culms, which grow from shoots that emerge from buds, are the most visible characteristic of a bamboo plant. Depending on the species, culms can differ in size, shape, color, and even smell. The culm has three main constituents, namely stem, stem base, and stem petiole (Anokye et al., 2016; Akinlabi et al., 2017). Culms of certain bamboo species take about 2 to 6 years to maturity. Researches and studies show that the maturity of bamboo varies by species, and it can attain hardwood-like characteristics earlier than hardwood which takes about 5 to 10 decades to mature (Akwada & Akinlabi, 2015).

Ghavami, (2005) states that the bamboo culm is a cylindrical shell that is divided at the nodes by transversal diaphragms. The space between nodes is known as internode. The nodes are made up of cells that are traverse-oriented while the internodes are made up of cells that are axially oriented (Bornoma et al., 2016). Within the internodes, the cellulose fibers and vascular bundles run parallel to the length of the culm, yet converge at the nodes, with some passing through the nodal diaphragm. For natural efficiency, these fibers are approximately six times abundant on the outside of the culm, ensuring it is much denser and stronger (Kaminski et al., 2016).

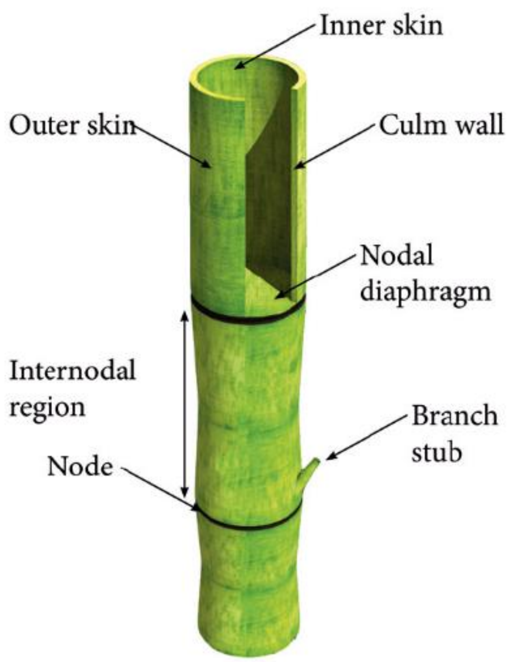

Figure 2. 1 Structure of a bamboo culm (Kaminski et al., 2016)

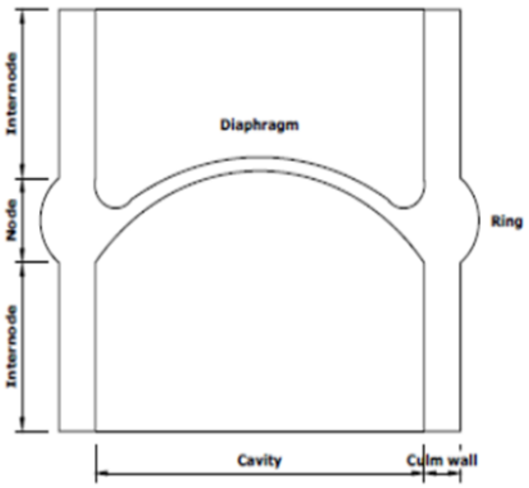

Figure 2. 2 Longitudinal sections of a bamboo culm (Anokye et al., 2016)

2.2.2 The Rhizomes

Bamboo plants propagate vegetatively or asexually through the branching of rhizomes and migrate underground to colonize new territories. The color of a healthy rhizome is typically slightly yellow or ivory, but other colors such as red, brown, grey, and purple are also possible (Hidalgo-López, 2003; Anokye et al., 2016). It has the role of nutrient storage and transportation as an organ. Culms depend on rhizomes for their growth, vigor, and spacing on the ground.

Experts say that Pachymorph (sympodial) and Leptomorph (monopodial) are two types of rhizomes in bamboo species (Akinlabi et al., 2017). Richard, (2013) states that the rhizome system can stabilize soil as well. Bamboos have been used to discourage riverbank erosion and thus defend villages in the past.

2.3 Mechanical Properties of Bamboo

Mechanical properties of a material are important because they define the range of utility and services that the material can provide. As a result, documenting the mechanical properties of bamboos is extremely important, as they are an alternate source of sustainable construction material in today's world (Salzer et al., 2018).

Compressive strength, shear strength, and tensile strength are three common properties of bamboo that make it suitable to be used as a construction material. Bamboo's high compressive strength and light weight make it the most widely used building material of timber. When bamboo is heated to a high temperature, it is also easy to shape, and once cooled or dried, it retains the shape (Zhang et al., 2019).

The resistance of a material to breaking or splitting under stress is known as tensile strength. In this case, tests have shown that bamboo structures have a higher tensile strength than other materials. This is due to bamboo's molecular structure, which is more tightly packed than materials like steel (Nordahlia et al., 2019).

However, when it comes to construction technology, the durability of bamboos is not one of its best qualities. Since bamboo is a natural biodegradable plant, it is more susceptible to insect and fungi attack and may degrade in the presence of water (Nordahlia et al., 2019).

Advanced innovations are now on the horizon with a solution to this bamboo flaw. Bamboo's resilience can be increased by using proper preservation methods such as chemical treatment, soak and diffusion, and pressure impregnation. Modern engineered bamboo composites such as bamboo scrimbers and laminated bamboo are also an alternate solution for this problem (Xiao et al., 2018).

2.4 Bamboo Insect Infestation

The bamboo plant is a natural resource that photosynthesizes to produce its food. Bamboo differs from other plants in that it develops quickly when exposed to direct sunshine for an extended time. Because of the availability of starch and other carbohydrates, bamboo, like practically any other plant, is vulnerable to insect attacks. Insect infestations on bamboo not only harm its look but also have major consequences for its mechanical properties (Varma & Sajeev, 2015).

More than 800 species of bamboo-infesting insects have been documented in Asian countries. However, barely a few countries have recognized this threat to the bamboo industry. These bamboo-infesting insects attack both live bamboos and bamboo culms that have been harvested. Attacks on live bamboos, particularly on the leaves, limit the plant's ability to photosynthesize, resulting in a loss of strength, growth, and survival (Varma & Sajeev, 2015).

Figure 2. 3 Insect infestation on bamboo culm (Chavan & Attar, 2013)

2.4.1 Damages from Beetles

Bamboo plant has large pores and contain high concentrations of starch. Unfortunately, certain beetles are drawn to the starch in bamboo and lay their eggs within the culm. The most common beetle that is drawn by bamboo is known as Powder-post beetles. Powder-post beetles can consume the entire bamboo culm, leaving only a thin outer shell behind when they exit. The appearance of powdery dust coming from the holes indicates an ongoing bamboo insect infestation by the Powder-post beetles and larvae. This beetle's larvae eat along the culm and eventually through the culm walls to escape, producing little round or oval exit holes between 1mm and 6mm in diameter, which might create a false impression when assessing the severity of damage for repair work (Kaminski et al., 2016; Varma & Sajeev, 2015).

Figure 2. 4 Visible exit holes due to beetle damage (Kaminski et al., 2016)

2.4.2 Termites Attack

Termites are ant-like insects that live in colonies and consume plant matter. Infestation of termites and the resulting damage has been a major issue in the establishment of most bamboo species. Termites generally infest roots and lower portions of bamboo culms (Shanbag et al., 2017). Termites live in well-organized colonies with populations ranging from thousands to millions of individuals and hence they can cause rapid damage to bamboo plants and structures. Termites are classified into two types: subterranean termites and dry wood termites. When subterranean termites come into touch with bamboo, they extend above the earth in tube-like runways comprised of soil and faeces. The gnawing occurs within the bamboo culm (Kaminski et al., 2016).

Figure 2. 5 Severe external damage from termite attack (Kaminski et al., 2016)

2.4.3 Fungal Attack

When bamboo is exposed to rain or placed in damp regions, fungal attack becomes a severe concern. When bamboo is relatively damp, or has a moisture content of 20% or higher, fungal attacks it aggressively. The bamboo will eventually decay because of this (Kaminski et al., 2016). Fungal attacks on bamboo gives an unpleasant view of its structure. The most visible impacts that we can see with our naked eyes are fungus patches and sooty mold. Small sucking insects like mealybugs, aphids, and scale insects generate sooty mold by secreting a sticky liquid called honeydew after infestation. This material swiftly transforms into a harmful fungus, resulting in unattractive black blotches on the culms (Schmidt et al., 2013; Wei, 2016).

Figure 2. 6 Fungal damage due to exposure to sun and rain (Kaminski et al., 2016)

2.5 Preservation and Treatment of Bamboo

Bamboos, like wood, are susceptible to biological degrading organisms, necessitating bamboo preservation procedures throughout storage and use. Bamboo preservation is the process of preserving bamboo. Bamboo's durability can be improved with proper preservative treatment. As a result, using bamboo after suitable preservative treatments is crucial (Sulaeman et al., 2018).

2.5.1 Bamboo Treatment using Boron

Boron salts are the most frequent non-fixing bamboo preservatives because they are effective against borers, termites, and fungi. Boron is a low-cost and effective barrier against insect infestation and fungal attack. It has insecticidal and fungicidal qualities while being safe for humans and animals. These boron salts are first dissolved in water before being soaked in it by bamboos. The evaporation of water after treatment, leaves the salts inside the bamboo, giving it the ability to resist fungal and insect attacks (Kaminski et al., 2016; Singha & Borah, 2017).

2.5.2 Treating using Copper induced Preservatives

Modern copper-based preservatives are substantially less harmful to humans than older versions as they no longer contain arsenic and chromium. Instead, they contain a mixture of copper, biocides, and occasionally boric acid. They're efficient against fungi, termites, and beetles, and because they're chemically well-fixed into the bamboo, they can be utilized outside and in contact with the ground (Yang, 2019; Gauss, 2020).

Copper azole type B and C (CA-B and CA-C) are the suggested forms of current copper-based preservatives for bamboo since they do not contain boron, which will leach out over time, and are less corrosive to steel than other forms. These copper-based preservatives are safe to use because the harmful chemical is fixed into the bamboo; however, the treated bamboo should not be burned at the end of its useful life because hazardous compounds may be released (Kaminski et al., 2016).

2.5.3 Conventional Preservation Methods

Water soaking, curing, smoking, and whitewashing are some of the most well-known traditional methods. Water soaking is one of the most common treatments since it is inexpensive and removes nutrients from the bamboo while also reducing insect and fungal attacks. These strategies give bamboo resistance to biodegrading agents, however the degree of success varies depending on the bamboo species, age, moisture level, nutritional content, and harvest time (Singha & Borah, 2017).

Unfortunately, all of these have a limited effect and are therefore not advised for permanent structural bamboo. They may only be suitable for extending the life of non-structural bamboo or for use in temporary structures. Painting or varnishing, for example, does not cling well to bamboo due to its smooth silica exterior surface, secondly, it breaks down quickly when exposed to UV light, and thirdly, as the bamboo shrinks and expands under various moisture levels, the paint crack and allows water in (Kaminski et al., 2016).

2.6 Structural Applications

Bamboo is an environmentally friendly material that can be used in the construction industry (Bansal & Zoolagud, 2002; Paudel, 2008). Bamboo contributes quite significantly to the economy in some developing countries such as Africa, Asia, and South America (Das et al., 2012; (Akinlabi et al., 2017). Bamboos have a lot of benefits such as regulate the water cycle, capture carbon dioxide, easy to handle, and help in preventing soil erosion (Lugt & Dobbelsteen, 2006; Archila-santos et al., 2012; Dhillon & Wuehlisch, 2012).

Nowadays, bamboo is being alternative material in replacing common materials in construction especially wood which has similar properties (Kaur & Pant, 2016). In terms of its strength, bamboo has an advantage on axial resistance and has natural nodes along its length in various lengths which improve stiffness and stability of slenderness (Bansal & Zoolagud, 2002; Taylor et al., 2015). Bamboo is also known as the anisotropic material where it is very strong in the axial direction but weak in perpendicular to grain direction (Kaminski et al., 2016).

However, bamboo is commonly used in houses, bridges, trusses, and scaffolds (Chung & Yu, 2002; Correal, 2016). There were also many examples of beautiful aesthetic structures made of bamboo around the world. For example, Carolina Zuluaga designed the Residential Ensemble in Carmen de Apicala, Colombia using bamboo to form the walls, floor slabs, and roofs, as well as their balconies, windows, and doors. In

Darmstadt, Germany, there is an office building with a timber roof that rests on 33 internally arranged bamboo columns which were designed by Susanne Korner and Tilman Schaberle (Minke, 2016).

Figure 2. 7 Residential unit in Carmen de Apicala, Colombia (Minke, 2016)

Figure 2. 8 (a) Timber roof construction and (b) bamboo columns in an office building, Germany (Minke, 2016)

2.7 Summary of Chapter

In this chapter, we will gain a thorough grasp of the anatomical characteristics of bamboo that contribute to its suitability as a building material. Bamboo culms are a common material used in the building industry, where it has essentially identical properties to lumber. The rhizome promotes prolific growth of bamboo within a few years, addressing bamboo as sustainable in terms of resource availability.

Furthermore, we have learned about bamboo's mechanical properties, such as its capacity to endure compressive, shearing, and breaking owing to tension, since they are considered an alternate source of sustainable construction material in today's world. Moreover, the structural application of bamboo in the construction industry, as well as its drawbacks due to insect infestation and other issues, allows us to use bamboo in a more sustainable and environmentally friendly manner.

CHAPTER 3

METHODOLOGY

3.1 Overview

The strategies and procedures utilized to attain the study's goals are described in this chapter. The tools and methods used in specimen preparation for each test are briefly discussed. The testing techniques for all of the tests conducted in this study are explained in accordance with the relevant guideline, ISO 22157.

3.2 The Flow of the Experimental Work

The workflow of this study is depicted in Figure 3.1. The progress of this study can be divided into four stages. The bamboo species that will be investigated is chosen at the outset.

The specimens for the mechanical tests will be prepared according to the International Organization for Standards (ISO)-22157 standard design. The physical properties of the specimens, such as external diameter, wall thickness, and moisture content, will be measured in the second stage.

In the third stage, a few experiments will be performed on the prepared specimens to determine their mechanical properties in accordance with ISO 22157. Finally, the results will be evaluated, and relevant comparisons will be made.

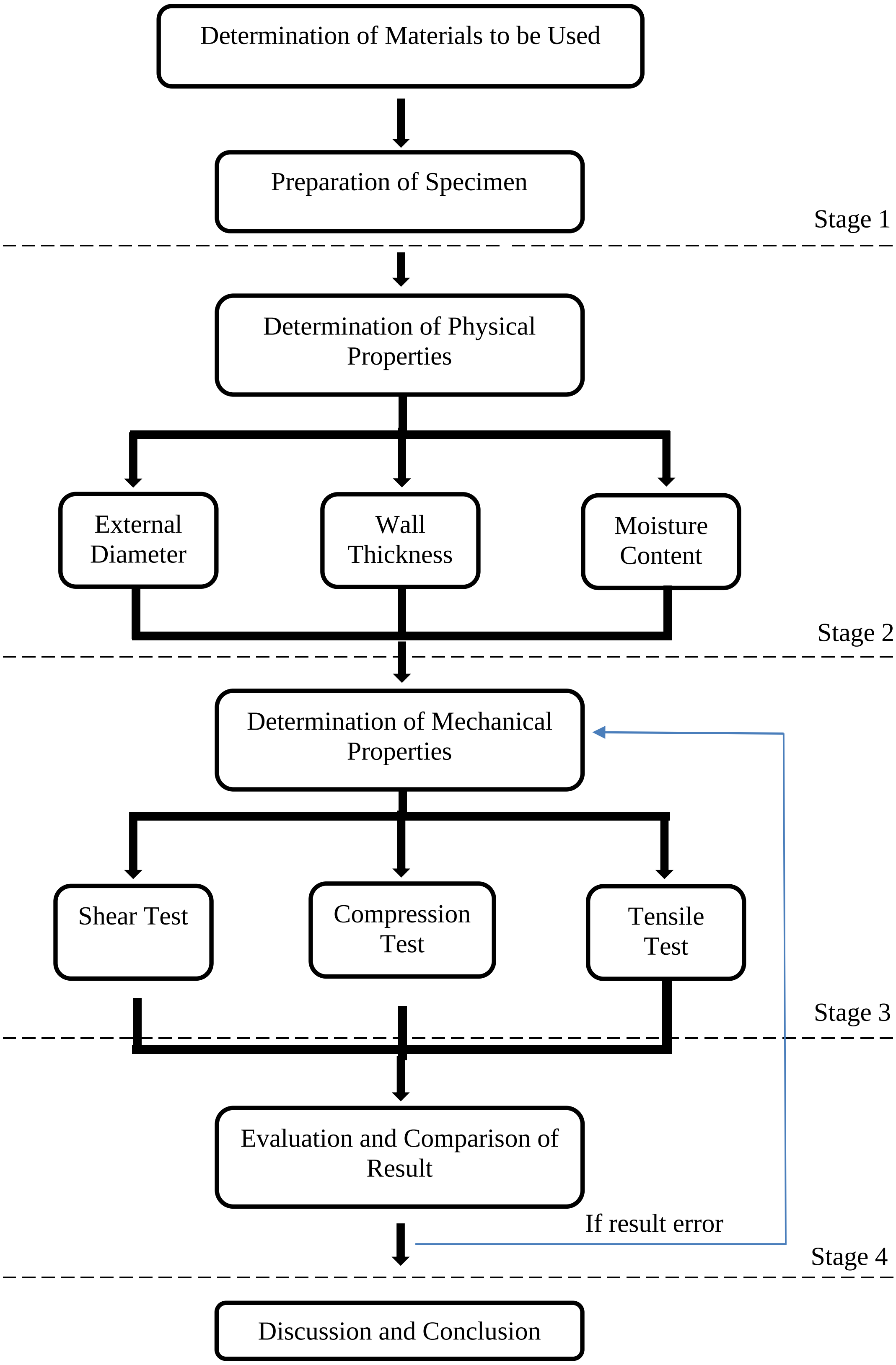

Figure 3. 1 Flow chart of the methodology

3.3 Materials and Preparation of Specimen

The study uses the bamboo species *Gigantochloa Ligulata* for all compression, shear, and tensile testing under ISO 22157. The Bamboo Jungle Adventure (BJA) company provides the bamboo species for this research study. The bamboo culms were up to 2 meters long with the presence of minimal three nodal sections. For each test, specimens are prepared from three bamboo culms from the top, (T), middle (M), and bottom (B) parts. It is ensured that each set of culms (T, M, and B) were taken from the same plant and marked with letters T, M, and B respectively. Following the completion of each test, the specimens are used to determine the moisture content.

3.3.1 Compression and Shear Test Specimen Preparation

Each compression and shear test requires a total of 54 specimens, 27 of which are nodal sections and the remaining 27 are internodal sections. According to ISO 22157, the length of each specimen is set to be constant to its external diameter. Figure 3.2 depicts the machine that was used to cut the culms to prepare the specimen for testing in the laboratory.

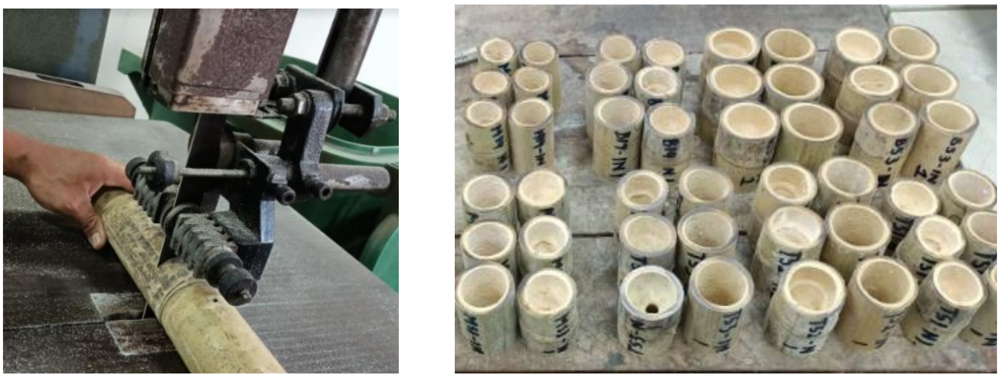

Figure 3. 2 Progress of culm cutting (left) and prepared specimens (right)

Machines like the one shown above are more likely to be suitable since they offer the specimen nice and flat end surfaces. The use of a handsaw may result in a nonuniform and rough surface, doubling the work required to modify the specimen again. After the samples are prepared, parameters such as height, external diameter, and wall thickness for each specimen are recorded.

3.3.2 Tensile Test Specimen Preparation

When contrasted to compression or shear tests, this test requires a distinct way of specimen preparation. A total of 54 specimens with 27 nodes and 27 internodes are prepared for the tensile testing. All specimens are cut into a dog-bone shape with a gage length of 100 mm and a total length of 200 mm, and the average thickness and width are recorded.

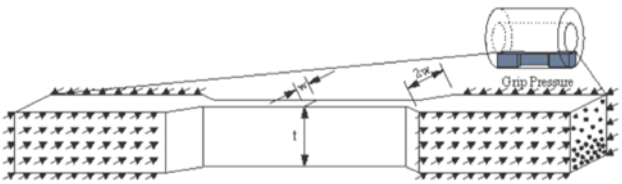

Figure 3. 3 Ideal shapes of tensile specimen

First, using the machine indicated in Figure 3.2, the round bamboo culm is sliced into four rectangular shapes. The rectangular specimen is then manually shaped into a dog-bone shape using a chisel and hammer. A wood rasp is used to smooth the surface.

3.4 Testing Procedures

According to ISO 22157, the specimens for testing are taken from the top, middle, and bottom sections of the bamboo culms. After being cut to the appropriate sizes, the specimens are labelled systematically. Few parameters such as the specimen weight, external diameter and wall thickness are recorded before proceeding with mechanical tests.

3.4.1 Moisture Content

Moisture content is an important property of bamboo. It causes the bamboo to shrink and expand. The oven-dry test is used to determine the moisture content of the prepared specimens. The specimens were dried for 24 hours at 103 ± 2° C in an oven. After 24 hours, the mass of the specimens is recorded at regular intervals of 2 hours until they reach a relatively constant weight. The moisture content is then calculated by substituting the values into the following equation.

$$MC = \frac{W_i - W_{oven-dry}}{W_{oven-dry}} \times 100 \qquad 3.1$$

Where,

MC = Moisture Content, in %

W_i = Initial weight of the specimen, in mm

$W_{oven-dry}$ = Oven-dry weight of the specimen, in mm

3.4.2 Compression Test

One of the most essential qualities of bamboo as a construction material is its compressive strength. Awalluddin et al., (2017) states that bamboo strength varies according to age and species. It has also been discovered that the compressive strength of bamboos rises as they grow taller, as well as from the interior to the exterior parts of their culm.

Figure 3. 4 Universal testing machine

The test is conducted according to ISO 22157 (2004b). The compressive strength of the bottom part, middle part, and top part of the bamboo species are determined using the universal testing machine as shown in Figure 1. The prepared bamboo specimen is placed at the centre of the testing machine. A small load is applied continuously during the test to cause the movable head of the testing machine to travel at a constant rate. The failure of the specimen is observed and the maximum load to cause the failure is recorded. The ultimate compressive strength is then calculated using equation 3.2.

$$Compressive\ Strength\ (N/mm^2) = \frac{Maximum\ Load\ (N)}{Cross\text{-}sectional\ Area\ (mm^2)} \qquad 3.2$$

3.4.3 Shear Test

Shear strength refers to a material's ability to resist deformation caused by slippage in planes parallel to the applied stress. Shear strength is another important property of bamboo as a building material for withstanding downslope movement of earth materials and earthquakes. ‘Bowtie’ test is carried out by using the same universal testing machine that was used for the compression test with additional bowtie-shaped steel platens as shown in Figure 2. The test is carried out following the 221571:2004(E) (ISO 2004b) procedure.

Figure 3. 5 ‘Bowtie’ test set up

The prepared bamboo specimen is placed at the centre of the testing machine. A small load is applied continuously during the test to cause the movable head of the testing machine to travel at a constant rate. The failure of the specimen is observed, and the maximum load applied to cause the failure is recorded. The ultimate shear strength is then calculated using equation 3.3.

$$Shear\ Strength\ (N/mm^2) = \frac{Maximum\ Load\ (N)}{Thickness\ (mm) \times Height\ (mm)} \qquad 3.3$$