EXPERIMENTAL STUDY ON MECHANICAL STRENGTH AND PERFORMANCE OF GIGANTOCHLOA LIGULATA BAMBOO (BULUH MATA RUSA) JOINTS

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SCHOOL OF CIVIL ENGINEERING
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By

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I hereby declare that all corrections and comments made by the supervisor(s)and examiner have been taken into consideration and rectified accordingly.

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ABSTRAK

Buluh telah menjadi suatu bahan binaan yang sering digunakan disebakan oleh keaslian, kualiti seni bina dan daya tarikannya. Buluh secara meluas dianggap sebagai salah satu sumber hutan bukan kayu yang paling penting kerana dapat memberi manfaat sosioekonomi yang besar hasil daripada penghasilan produk yang diperbuat daripada bahan tersebut. Walaupun buluh menyumbang banyak faedah kepada sector pembinaan, ia masih belum banyak kajian yang mengkaji hubungan antara keserasian sambungan dan kealakuan mekanikalnya. Sebagai tindak balas, kajian ini membuat penyiasatan terhadapkekuatan mekanikal dan prestasi sambungan buluh daripada spesies *Gigantochloa Ligulata*. Jenis sambungan buluh yang digunakan dalam kajian ini ialah bahagian tiang ke rasuk dan rasuk ke rasuk dengan sambungan ortogonal dengan pelbagai jenis penyambung iaitu pin, taki dan pin, bolt dan nat, bolt sauh, dan mulut ikan. Ujian yang digunakan ke atas sampel untuk mendapatkan beban maksimum dan pesongan ialah ujian beban statik. Semua proses dalam penyediaan dan pengujian sampel dilakukan dengan teliti untuk memastikan ketepatan data. Berdasarkan hasil, sambungan mulut ikan memberikan prestasi sambungan terbaik dengan beban maksimum tertinggi. Mod kegagalan yang diperhatikan bagi sampel sambungan ialah pembelahan, ricih keluar, lengkok dan lenturan bolt.

ABSTRACT

Bamboo has become a fairly common building material because of its originality, architectural qualities, and attractiveness. Bamboo is widely regarded as one of the most important non-timber forest resources due to the considerable socioeconomic benefits of products made from the material. Even though the bamboo contributes many benefits to the construction, there haven't been many studies examining the relationship between joints' compatibility and their mechanical behaviour. As a response, this study makes an investigation on the mechanical strength and performance of bamboo joints from the species *Gigantocholoa Ligulata*. The type of bamboo joint used in this study is column to beam and beam to beam section of orthogonal joint with various type of connections which is dowel, rope and dowel, bolt and nut, anchor bolt and fish mouth connection. The test used on the samples to get maximum load and deflection is static load test. All of the process in sample preparation and testing was done carefully to ensure the accuracy of the data. Based on the result, the fish mouth connection gives the best joint performance with the highest maximum load. The observed failure modes of the joint samples were the splitting, shear out, buckling and bolt bending.

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LIST OF ABBREVIATIONS

ISO	International Standardization for Organization
UTM	Universal Testing Machine
OCB D	Orthogonal Column to Beam Dowel
OCB RD	Orthogonal Column to Beam Rope and Dowel
OCB BN	Orthogonal Column to Beam Bolt and Nut
OCB AB	Orthogonal Column to Beam Anchor Bolt
OCB FM	Orthogonal Column to Beam Fish Mouth
OBB D	Orthogonal Beam to Beam Dowel
OBB RD	Orthogonal Beam to Beam Rope and Dowel
OBB BN	Orthogonal Beam to Beam Bolt and Nut
OBB AB	Orthogonal Beam to Beam Anchor Bolt
OBB FM	Orthogonal Beam to Beam Fish Mouth

CHAPTER 1

INTRODUCTION

1.1 Background of study

The majority of bamboo construction relates to the needs of rural communities in developing countries. As such domestic housing predominates and in accordance with their rural origins, these buildings are often simple in design and construction relying on a living tradition of local skills and methods. Other common types of construction include farms, school buildings and bridges. Further applications of bamboo relevant to construction include its use as scaffolding, water piping and formwork as shuttering and reinforcement for concrete (Sharma et al., 2014). Usually, the bamboo structure or building such as in the Figure 1 can be found a lot in Asia that has tropical climate (Mertens & Audrey, 2019).

Figure 1: Traditional construction in Burma, Myanmar (Mertens & Audrey, 2019)

In addition, it can be used to create countless other things, such as bridges, rafts, towers, fences, water wheels, irrigation piping, traps, cages, tools, and weapons. Due to the significant socioeconomic advantages of bamboo-based goods, it is widely acknowledged as one of the most significant non-timber forest resources. As wood resources are depleting and limits are placed on cutting down natural forests, this is a replacement building material that is renewable, environmentally beneficial, and generally accessible (Raj & Agarwal, 2014).

Figure 2: Bamboo bridge (Kaminski et al., 2016)

Additionally, bamboo is utilised as a fire line in traditional woods due to its high silica content, as a windbreak, to cleanse urban waste water and reduce nitrate contamination, and to stabilise soil. It also removes carbon dioxide from the atmosphere. The shoots can be used for handicrafts, small-scale and cottage industry buildings and constructions, as well as other goods. In the manufacturing of truck bodywork and railroad carriages, it can also be utilised as a substitute for wood in the industrial products and transportation sectors. There are various sustainability benefits of using locally accessible and indigenous earth elements. (Kareem et al., 2018).

Figure 3: Bamboo crib wall (Tardio et al., 2018)

1.2 Problem statement

Nowadays, the use of bamboo as a construction material is very popular due to its architectural aspects, uniqueness and aesthetics. Over a billion people are thought to live in bamboo homes globally. More than 70% of homes in Bangladesh alone use non-processed bamboo culms in temporary wall and roof construction (Escamilla et al., 2019). Commonly, the construction of bamboo is applied based on traditional techniques. Therefore, there is a need to determine the mechanical properties of the bamboo in order to make sure all the structure members can be effectively constructed. There are around 1400 species of bamboo that exist in this world and each of them has its own properties and characteristics (Zhaohua & Wei., 2018).

Owing to the round shape, jointing is very difficult and cumbersome in bamboo. The reduction of diameter along the length is another limiting factor. Various types of engineered and tested jointing systems with appropriate materials need to be developed for effective structural load distribution and transfer. Not many studies have been done relating suitability of joints and their mechanical behaviour. Researchers need to include connection types with complete structural systems. Therefore, a lot of research and development of bamboo should be done, in order to recognize bamboo as a sufficiently resilient and structurally secure building material for the building industry (Manjunath, 2015).

1.3 Objectives

The objectives of this study are to,

1. To determine the mechanical strength of *Gigantochloa Ligulata* bamboo joint.
2. To determine the performance of different types of fasteners.
3. To evaluate the failure mode of bamboo joint sections with different types of fasteners.

1.4 Scope of studies

This study focuses on bamboo as a construction material as it is consistent in terms of strength and durability. Those terms play an important role in building structures. All of those terms will be proven by determining the mechanical properties of the bamboo joints by using appropriate standards and testing in the laboratory.

1.5 Dissertation outline

The thesis is organised into five chapters to ease the reader's 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 explains the purpose of why this research was 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.

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 bamboo plant studies as well as previously published bamboo research. This chapter focuses on the population of bamboo generally in the world and specifically in Asia. The bamboo growth and its physical properties also has been discussed in this chapter since the bamboo growth give a lot contribution to the existence of bamboo species in this world. Other than that, the preservation and sustainability of bamboo are also covered in this chapter since bamboo is widely used as a construction material.

2.2 Bamboo resources in Asia

Bamboos are quick-growing woody grasses that can be found in mixed or pure stands in the tropics and subtropics. Within the forestry and agroforestry systems, they can be grown in plantations, on homesteads, and on farms. Bamboos are cultivated for their long, hollow culms that can be used as whole or sectioned poles and provide softwood and fibre for processing; certain varieties also have edible shoots (Liese and Kohl, 2015).

Bamboo covers over 14 million hectares of the earth's surface, with 80 percent of that area being in Asia. South America and Asia-Pacific both have significant species richnesses, while Africa has the fewest species (Yeasmin et al., 2015).

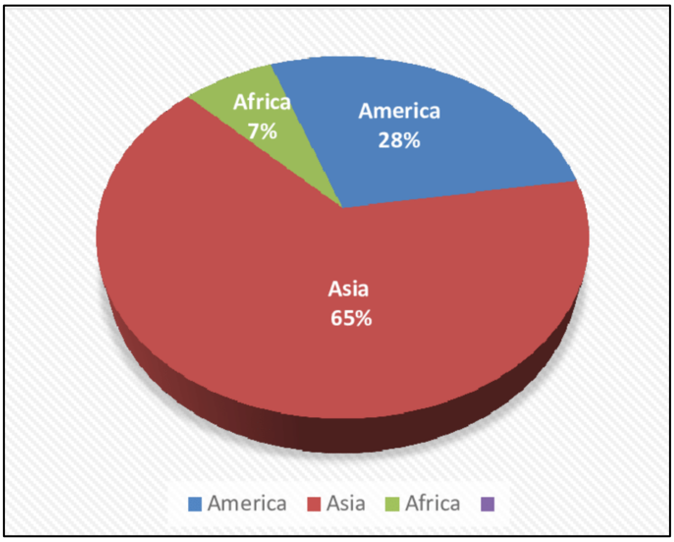

Figure 4: Bamboo resources according to continents (Anokye, 2016)

2.3 Bamboo growth

Bamboo grows in clusters by nature. Bamboo grows in two different ways: monopodial bamboo and sympodial bamboo. In a thin layer of soil, monopodial bamboo roots spread horizontally. New shoots grow away from the parent plant at a considerable distance. Most regions with temperate climates, including Japan, China, and Korea, are home to monopodial bamboo. Bamboo sympodial roots develop very closely to the parent plant, generating a clump of many stems or canes. Most often, it can be found in tropical regions like Southeast Asia and South America (Nurdiah, 2016).

According to Winkler et al. (2016), dwarf bamboo (S. Kurilensis) invasion above and below tree line was significantly influenced by soil drying rates, with growth rates declining in areas that dried more quickly. Dwarf bamboo increases its allocation to underground structures in response to competition and climatic stress. It seems that this species' success is largely attributed to its high physiological and morphological adaptability to soil moisture levels brought on by snowmelt in different habitats.

According to Lima et al. (2012), the bamboo *Guadua Tagoara* favours clay-rich soils and is more invasive due to its potential to generate greater physiological (heat and light stress) and physical (wind- and bamboo-induced damage) stress (Xu et al., 2019).

Bamboo plants can be found in a variety of ecological environments, such as temperate deciduous forests, coniferous forests, lowland tropical forests, hilly forests, understory, moist forests, grasslands, and many more. They are mostly spread throughout the tropics and subtropics via natural occurrences and agricultural agriculture (Akinlabi et al., 2017).

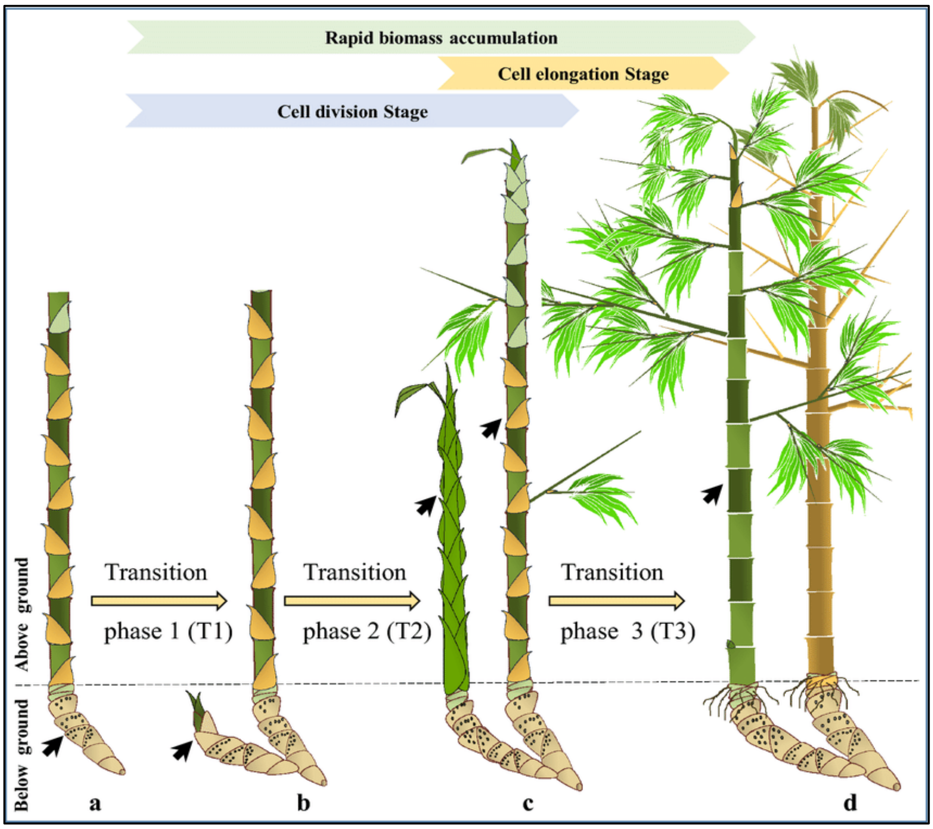

Figure 5: Stages of bamboo development. a) Dormant rhizome (DR), b) Growing rhizome (GR), c) Growing shoots of different height (GS), d) Mature shoot (MS) (Basak et al., 2021)

2.4 Properties of bamboo

In the field, a bamboo species is typically identified by first examining its morphological traits. The physical traits that distinguish one species of bamboo from another, such as culm height, internode length, and culm wall thickness, should be noted since they help identify bamboo specimens more quickly. It can also be used to select the appropriate final products based on the physical properties of bamboo species, such as culm wall thickness, internode, and culm length (Siam et al., 2019).

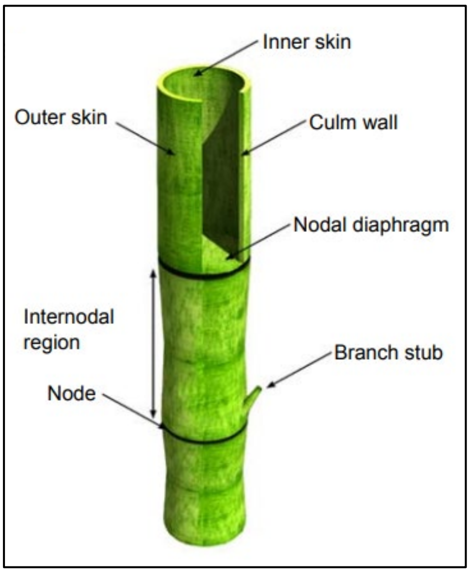

Figure 6: Bamboo culm section (Trujilo & Lopez, 2020)

Gigantochloa Ligulata also known as *Buluh Mata Rusa* can reach culm heights of up to 18 meters. Its internode length and culm wall thickness were measured at an average of 37 cm and 12 mm respectively. The bamboo has a pale green colour and occasionally has yellow stripes covered with sporadic dark brown stiff hairs on the tops of its internodes. It also has very fine, much shorter white hairs (Lester, 2014).

2.5 Bamboo as construction material

Bamboo has a highly strong fibre that makes it a great building material. Bamboo has a tensile strength that is comparable to steel and a compressive strength that is two times greater than that of concrete. In addition to having a higher shear stress than wood, bamboo fibre also has a broader span. Additionally, bamboo may be bent without breaking. In comparison to steel, which has a tensile strength of 23,000 N per square inch, bamboo is regarded as one of the building materials with a very high strength. Although some designers and academics refer to irregular geometries as freeform, these shapes can be composed of several forms to create an irregular shape that resembles a spline curve (Nurdiah, 2016).

There are various applications of bamboo in building construction. It practically contributes towards the design of almost all the components of a building, starting from the roof to the foundation. The components include support structures, piers, walls, floors, roofs, and room dividers among other things. Other than that, bamboo can also be alternatively in constructing scaffolding. It is a very convenient material for high rise construction scaffolding since it has the properties of heavy load bearing capacity (Yadav & Mathur, 2021).

2.6 Bamboo preservation and drying

Construction projects utilising bamboo must go through a preservation process. The reason for this is that bamboo is susceptible to termite and fungus attack. Borax boric acid solution is typically used in construction to preserve bamboo using a variety of methods, including immersion, gravity or vertical soak diffusion, and injection using a compressor machine. Bamboo can live longer thanks to the effectiveness of borax and boric acid. However, the use of chemicals in the preservation process prompts a number of inquiries and discussions over the environmental effects of the waste water. As a result, numerous investigations into the preservation of bamboo using organic components have been carried out in an effort to identify a more environmentally friendly preservation technique (Nurdiah, 2016).

2.7 Sustainability of bamboo

Bamboo as a building material has been extensively discussed and examined since concerns about global warming and sustainability first surfaced. Bamboo is a popular building material among some architects and builders nowadays. Due to deforestation, high-quality wood for construction is becoming hard to come by. Additionally, it takes a while for wood to regenerate and become suitable for use as building material. While this is going on, bamboo can be harvested in just 3 to 5 years. Bamboo has the potential to release oxygen into the air when it is planted, something industrial materials like steel, plastic, and concrete are unable to do. These factors have led to widespread recognition of bamboo as a sustainable building material (Nurdiah, 2016).

2.8 Mechanical properties

The variety of functionality and services that a material may offer is determined by its mechanical properties, which are significant. As a result, it is crucial to record bamboo's mechanical properties because they are a new alternative to wood as a sustainable building material.

Three common characteristics of bamboo that make it suitable for use as a construction material are its compressive strength, shear strength, and tensile strength. With it's low weight and great compressive strength, bamboo is the most popular type of timber used for construction. Bamboo is easy to shape when heated to a high temperature, and it keeps that shape after cooling or drying.

Based on previous research conducted by Devandran (2021), the mechanical properties of *Gigantochloa Ligulata* bamboo have been determined by referring to standard ISO 222157 as stated in the Table 1 below.

Table 1: Mechanical properties of Gigantochloa Ligulata bamboo

Property	**Height position**	**Node**	**Internode**
Compressive strength (N/mm^2)	Top	86.73	92.31
	Middle	83.87	96.75
	Bottom	73.63	88.41
Shear strength (N/mm^2)	Top	32.53	29.51
	Middle	31.82	28.08
	Bottom	30.43	24.93
Shear strength (N/mm^2)	Top	76.31	96.89
	Middle	63.85	88.55
	Bottom	71.30	83.89

2.9 Summary of chapter

In this chapter, there are several bamboo related literature reviews that explain about the information of existing of bamboo resources around the world, bamboo growth, properties of bamboo, bamboo as construction material, bamboo preservation, bamboo sustainability and mechanical properties of bamboo.

Asia has the largest bamboo resources in this world. The great bamboo resources are affected by its growth that known as a quick-growing woody grasses. The bamboo growth also depends on the climate. The suitability of bamboo growth to tropics and subtropics climate, makes the continent of Asia has the greatest bamboo resources. Besides, bamboo has many species that typically identified by examining its properties such as culm height, internode length and culm wall thickness.

Use of bamboo as a construction material has been focussed nowadays due to it's suitability and greater strength in tensile and compression. It practically contributes towards the design of building components. Even though the bamboo has great strength, it also needs to be treated in order to prevent from termit attack by soaking the bamboo into borax and boric acid. With the wide use of bamboo as construction material, the sustainability of bamboo should be concerned to prevent global warming issue.

CHAPTER 3

METHODOLOGY

3.1 Overview

This chapter will explain the strategies and methods adopted by this study. This chapter will mention every component involved in conducting this study starting from the preparation of the sample until the technique used for testing. The tools and methods used in sample preparation are briefly discussed. The testing procedure for all the tests conducted for each sample is explained in accordance with the relevant guideline, ISO 22157.

3.2 The flow of the experimental work

The workflow of this study is represented in Figure 7. The workflow of this study can be divided into three stages which are; determination of materials and sample preparation, testing of sample and data and result analysis.

In the first stage, the type of bamboo used for this investigation was selected. The preparation of all samples was conducted in this phase. In the second stage, all samples were tested in accordance with the relevant guideline, ISO 22157. All the testing was conducted to determine the mechanical properties of each sample. Lastly, in the third stage, all the results and data obtained from the testing from stage 2 were recorded and analysed.

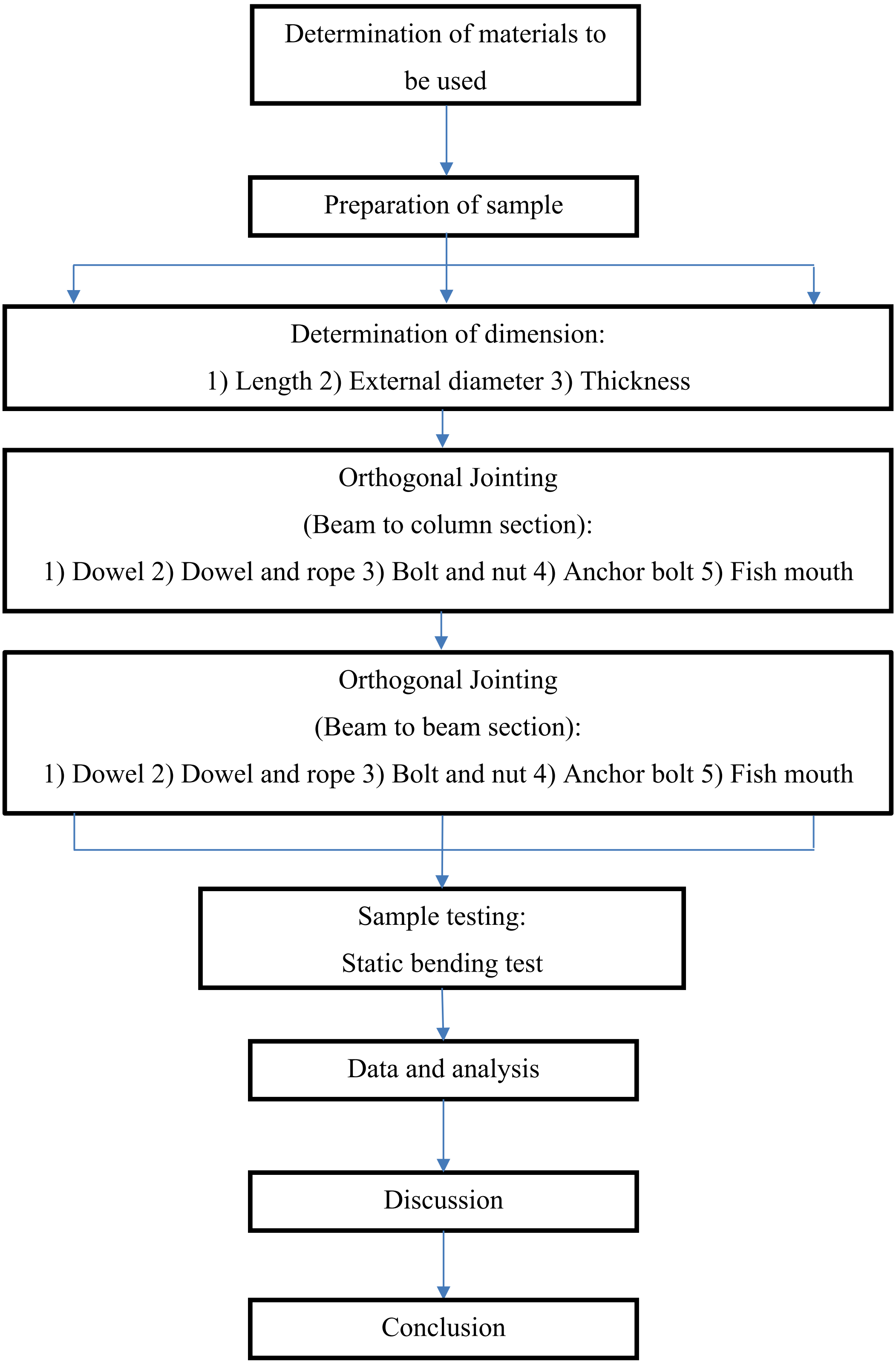

Figure 7: Flow chart of workflow of this study

3.3 Materials and preparation of sample

The bamboo species used in this study is *Gigantochloa Ligulata* sourced from Bentong, Pahang. The bamboo specimens used were of good quality and had straight culms. All of the bamboo specimens were obtained in one batch at the same location in order to maintain the characteristics of bamboo species.

3.3.1 Bamboo selection

The selection of bamboo was conducted with some criteria in mind. The bamboo was selected according to the height, diameter and maturity of bamboo. The selection of bamboo was also conducted by concerning the good condition of bamboo with no broken, damaged or discoloured bamboo. The bamboo used in this study was treated bamboo. The bamboo treatment process was done by soaking the bamboo with boric acid solution for 3 weeks and then going through a drying process for 3 weeks as well, to make sure the bamboo was completely dried and turned yellowish from its original colour.

Figure 8: Drying process after soaked with boric acid

3.3.2 Determination of moisture content

The moisture content (MC) of all the bamboo samples was determined before beginning the construction of bamboo jointing samples. The moisture content was investigated by following clause 7.2 of bamboo standard ISO 22157, measuring moisture content by the electrical moisture content meter method. The moisture content of bamboo was measured by taking 3 readings and calculating the average. The measurement of moisture content was made by driving sharp probes into the wall from the side. The moisture meter was set up to Mode B, which is suitable to determine the moisture content of a group of woods, namely Keruing, white plar, beech, cedar and tola. Even though bamboo was not stated in the group of woods in Mode B, it can also be used for measuring bamboo moisture content. The measurement of moisture content by using moisture meter Mode B was compared with the oven-dry method which resulted in an error of less than 2%.

Figure 9: Moisture meter

3.3.3 Measurement of dimension

The dimensions of every sample, which are their thickness, external diameter and length were recorded precisely by using vernier calliper and measuring tape. The measurement of thickness, external diameter and length for every sample was done by referring to Kaminski et al., (2016) technical note shown in Figure 10 below. All the dimension measurements of samples were determined by calculating the average of the readings taken.

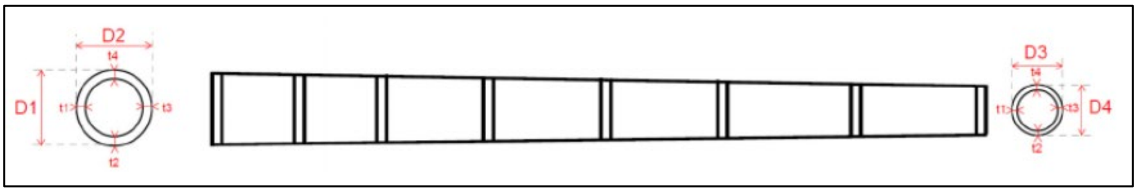

Figure 10: Measurement of external diameter and wall thickness of bamboo

Table 2 and 3 present the dimensions of bamboo samples used in this test.

Table 2: List of dimensions for orthogonal joint column to beam samples

Specimen	Diameter (mm)	Average (mm)	Thickness (mm)	Average (mm)
OCB D1 OCB D2 OCB D3	45.00 51.00 47.00	47.67	6.70 6.70 8.30	7.23
OCB RD1 OCB RD2 OCB RD3	38.00 39.00 44.50	40.50	6.00 7.70 6.70	6.80
OCB BN1 OCB BN2 OCB BN3	51.00 49.50 52.00	50.83	6.50 7.87 7.17	7.18
OCB AB1 OCB AB2 OCB AB3	51.00 49.50 52.00	50.83	7.00 5.93 7.13	6.69
OCB FM1 OCB FM2 OCB FM3	53.50 55.00 47.50	52.00	8.70 6.93 5.50	7.04

Table 3: List of dimensions for orthogonal joint beam to beam samples

Specimen	Diameter (mm)	Average (mm)	Thickness (mm)	Average (mm)
OBB D1	41.00		6.83	
OBB D2	45.00	42.33	6.67	7.39
OBB D3	41.00		8.67	
OBB RD1	43.50		5.17	
OBB RD2	39.50	43.67	7.00	6.72
OBB RD3	48.00		8.00	
OBB BN1	42.50		5.83	
OBB BN2	45.00	43.67	5.67	5.78
OBB BN3	43.50		5.83	
OBB AB1	41.00		5.00	
OBB AB2	48.00	42.07	5.83	5.50
OBB AB3	37.20		5.67	
OBB FM1	49.00		7.50	
OBB FM2	54.20	52.73	5.17	6.65
OBB FM3	55.00		7.27	

3.3.4 Bamboo joint

The type of joint that was used in this study is the orthogonal joint, which is divided into two sections; beam to column section and beam to beam section. All of the orthogonal jointing samples, including column to beam section and beam to beam section were connected with different types of fasteners which are dowel, dowel and rope, bolt and nut, anchor bolt and nut, and fish mouth. Three samples have been prepared for each type of joint connection. Total samples have been prepared for this study was 30 samples. The list of bamboo jointing samples prepared for this study are shown in Table 4.

Table 4: List of bamboo jointing samples

	Joint Section	
Type of Joint	**Colum to Beam**	**Beam to Beam**
Orthogonal Joint	• Dowel (3 samples) • Dowel and Rope (3 samples) • Bolt and Nut (3 samples) • Anchor Bolt and Nut (3 samples) • Fish Mouth (3 samples)	• Dowel (3 samples) • Dowel and Rope (3 samples) • Bolt and Nut (3 samples) • Anchor Bolt and Nut (3 samples) • Fish Mouth (3 samples)

All of the bamboo jointing samples were constructed appropriately by concerning the good quality aspect of bamboo jointing. The bamboo jointing samples were prepared by cutting them into parts from the whole culm length using a table saw. Each part was cut into pieces to have at least 1 internode with 2 nodes on both the upper and bottom sides of the culm.

Figure 11: Orthogonal joint

3.3.5 Type of fastener

3.3.5.1 Dowel

The size of the dowel that has been used is 8 mm. The dowel was constructed from the unused thick bamboo by reeding the bamboo and also by hitting the reeded bamboo using a wooden mallet hammer through an 8 mm hollow metal plate.

Figure 12: Dowel connection

3.3.5.2 Dowel and rope

By using the same size of dowel, which is 8 mm, the rope was also attached to the joint. The type of rope that has been used is nylon rope. The nylon rope is quite strong and may be stretched before returning to its original length. It has strong UV resistance and is resistant to sunlight, mildew, rot, and chemical exposure as well as ultraviolet deterioration (Gajbhiye & Kumar, 2014).

Figure 13: Rope and dowel connection

3.3.5.3 Bolt and nut

The size of the bolt and nut that have been used is 8 mm. The type of material for the bolt and nut is mild steel. The nut shape used is a hexagonal shape. Mild steel is a stable material to be used for fastener equipment with the formation of perlite that can retain its strength at higher temperatures (Shaheen et al., 2020).

Figure 14: Bolt and nut connection

3.3.5.4 Anchor bolt and nut

The application of the anchor bolt and nut is the same as the application of the bolt and nut. The difference is just the bolt. The anchor shape is at one end of the bolt. The size used for anchor bolts and nuts is 8 mm.

Figure 15: Anchor bolt and nut connection

3.3.5.5 Fish mouth

The fish mouth joint connection is connected by using bolt and nut same as in the sub-section 3.3.5.3.

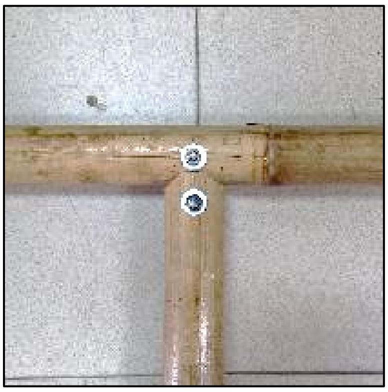

Figure 16: Fish mouth connection

3.4 Construction of sample

Since this study was focusing on traditional bamboo jointing, the construction of bamboo jointing was done based on the existing bamboo jointing used in building construction. The construction of a bamboo jointing sample was shown and guided by a professional person in bamboo construction. Both orthogonal joint sections, which are beam to column section and beam to beam section, were constructed with the same steps and procedure. All of the steps and procedures are as follows;

3.4.1 Orthogonal joint with fish mouth connection

1. The bamboo specimen was cut by using a table saw to have at least 1 internode and 2 nodes in a culm. One orthogonal joint sample was provided for two culms, one for horizontal culm and another one for vertical culm.
2. By using a circular saw, the top of the horizontal culm was cut to be a fish mouth shape close to a node. The fish mouth was cut and trimmed by using a knife according to the diameter of the horizontal culm to ensure the fish mouth had maximum contact with the horizontal culm.
3. A hole was made close to the node of the vertical culm by using a drill with a circular drill bit and trimming with a knife. The hole was made depending on the size of the smaller piece of bamboo that acts as a tie between both culms. The smaller piece of bamboo is called "bamboo putting".
4. The bamboo putting was fitted into the hole that had been drilled on the vertical culm and also slipped into the horizontal culm that has a fish mouth at the end to secure the joint between the horizontal and vertical culm.