EXPERIMENTAL STUDY ON MECHANICAL STRENGTH AND PERFORMANCE OF GIGANTACHOLA SCHORTECHINII BAMBOO (BULUH SEMANTAN) JOINTS

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By

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Finally, I am hoping that this dissertation could be a useful guide in improving the quality of the construction industry in Malaysia, especially in bamboo construction as new and green material. Thank you.

ABSTRAK

Kajian ini dijalankan untuk menyiasat sifat mekanikal dan jenis mod kegagalan untuk pelbagai jenis penyambungan untuk buluh *Gigantachola Schortechinii* atau dikenali sebagai Buluh Semantan. Dalam kajian ini, beberapa parameter seperti jenis sambungan, kedudukan sampel, dan sudut sampel telah diteliti. Kajian telah dijalankan ke atas 64 sampel, iaitu rasuk-tiang ortogon, rasuk-rasuk ortogon, rasuk-tiang sudut 30°, rasuk-rasuk sudut 30°, rasuk-tiang sudut 45°, dan rasuk-rasuk sudut 45°. Manakala jenis penyambung terdiri daripada mulut ikan, tali dan dowel, bolt dan nat, dowel, dan anchor bolt. Eksperimen telah dijalankan menggunakan Mesin Pengujian Universal Shimadzu (UTM). Ujian ini mengikut piawaian antarabangsa, ISO 22156; Struktur buluh- Batang buluh- Reka bentuk struktur. Hasil daripada kajian ini menunjukkan, bahawa penyambung tradisional, mulut ikan adalah yang paling kuat diikuti oleh tali dan dowel, bolt dan nat, dowel, dan anchor bolt dalam setiap kedudukan dan keadaan. Dari perspektif industri pembinaan, kajian ini penting untuk memperkenalkan buluh sebagai bahan binaan baharu dan hijau di Malaysia

ABSTRACT

This study was conducted to investigate the mechanical properties and type of failure mode for various types of *Gigantachola Schortechinii* bamboo or known as Buluh Semantan joints. In this study, several parameters such as the type of joints, the sample's position, and the sample's angle were examined. The study was carried out on 64 samples, which are orthogonal beam-column, orthogonal beam-beam, angular 30° beam-column, angular 30° beam-beam, angular 45° beam-column, and angular 45° beam-beam. While the type of joints consists of a fish mouth, rope and dowel, bolt and nut, dowel, and anchor bolt. The experiment was carried out using Shimadzu Universal Testing Machine (UTM). This test followed the international standard, ISO 22156; Bamboo structures- Bamboo culms- Structural design. The results showed that the traditional joint, fish mouth is the strongest followed by rope and dowel, bolt and nut, dowel, and anchor bolt in every position and condition. From the construction industry perspective, this study is important to introduce bamboo as new and green construction material in Malaysia.

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LIST OF ABBREVIATIONS

NTFPs	Non-Timber Forest Products
CO_2	Carbon Dioxide
UTM	Universal Testing Machine
LVDT	Linear Variable Displacement Transforms
MOE	Modulus of Elasticity
MOR	Modulus of Rupture

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CHAPTER 1

INTRODUCTION

1.1 Background of the study

Over the last two decades, bamboo has been increasingly recognized as one of the major non-timber forest products (NTFPs) of the world (Rana et al., 2010). Bamboo can be used for a huge variety of building purposes from building superstructures such as columns, beams, and rafters to interior and exterior finishes such as walls, flooring, and furniture. Traditional bamboo huts are home to more than a billion people. The nipa hut or known as Bahay Kubo is an example of a bamboo housing structure that is usually found in the Philippines (see Figure 1-1). It is constructed with bamboo poles which are used to support the structure and the walls of the house are composed of split and woven bamboo.

Figure 1-1: The nipa hut or Bahay Kubo (Photo adapted by the author from Google Image)

Bamboo is used as a construction material in these low-cost homes, although little is known about its function and structural characteristics. Bamboo is not employed as raw building material by architects and engineers due to lack of engineering data, limitation of building codes and regulations as well as its reputation which is still underrated as a ‘poor man's material’ and due to a lack of skilled labor. According to Bhode et al. (2014), bamboo should be employed in high-rise buildings because of its versatility, which could help to overcome the stigma of a poor man's wood. Bamboo is not a new material in the construction sector. As a result, it has been employed for centuries, particularly by people who live in areas where bamboo grows organically and abundantly. Bamboo, along with lumber, was once used as a construction material, particularly in Malaysia and Indonesia. Bamboo construction skills and tools have been passed down through the generations.

Figure 1-2: Exterior wall made of bamboo (Photo adapted by the author from Google Image)

According to a study conducted by Siam et al. (2019), not all bamboo species are suitable for structural members. Only three (3) of the 13 varieties of bamboo evaluated were appropriate for structural element purposes. *Gigantochloa this*, also known as 'Buluh beting *Gigantochloa Scortechinii*, also known as 'Buluh Semantan', and *Dendrocalamus Asper*, also known as 'Buluh Betong', are examples of bamboos are usually used for structural elements. The fact that some bamboos are not included does not mean they cannot be used in the construction industry. Instead, bamboo with a small thickness, for example, can be utilized as an interior or external wall (see Figure 1-2), as well as for the roof, as 'anyaman' or known as 'pulapo'.

1.2 Problem statement

Climate change is a result of human activity. One of the industries that contribute to this issue is the construction sector. According to the United Nations Environmental Program, building and construction activities account for 36 percent of worldwide energy use and 39 percent of energy-related carbon dioxide emissions. Day-to-day energy use, such as lighting, heating, and cooling, contributes to the carbon footprint. The carbon footprint is further influenced by the manufacturing of building materials, the transportation of resources to job sites, and the actual construction process.

The design and equipment employed by the building must be energy efficient to produce a building with low or zero carbon emissions. For example, natural lighting is being used for the same purpose as artificial lighting, and mechanical ventilation is being substituted with natural ventilation. Bamboo is a natural product and the most environmentally friendly building material. Bamboo is a big grass (Manandhar et al., 2019). This is due to its grass-like capacity to regenerate making bamboo one of the fastest-growing plants in the world. Bamboo can also help to reduce carbon dioxide, and CO_2 emissions by storing more carbon dioxide than trees. Bamboo is marginally less expensive than timber in terms of cost-effectiveness. Together with high compressive strength, it offers a durable green building material in comparison to woods, brick, and concrete. Bamboo can be used to speedily build houses to recover from those disasters (Manandhar et al., 2019).

The major drawback of the usage of bamboo as a construction material is a scarcity of engineering data and building codes—the lack of data such as compression, tension, and limit oxygen index. Bamboo comes in over 1400 different species. Every bamboo has its unique traits and properties. Mechanical properties and density are the most significant criteria that need to be considered when determining the acceptability of structural elements. Not all bamboo is good for structural purposes. The goal of this research is to develop new engineering data to give insight into bamboo research and study and to investigate its behavior in a variety of joint conditions.

1.3 Objectives

This study aims to promote and commercialize bamboo as a unique and versatile construction material. The objectives of this study are as follows:

1. To evaluate mechanical strength in different types of bamboo joints and different types of joint material.
2. To evaluate the type of joint failure due to the application of static load.

1.4 Scope of research

This research focuses on bamboo as a building material that is used to create structures that are pleasant, durable, valued, precious, and attractive. In the laboratory, the maximum loads and deflection in each variety of bamboo will be determined by using proper procedures and standards.

1.5 Purpose of projects

The purpose of the project is:

1. To introduce the usage of bamboo in the construction industry.
2. To collect the engineering data regarding bamboo.

Moreover, the usefulness of this bamboo is for structural and non-structural uses.

1.6 Dissertation Outline

The dissertation is organized into five (5) 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 dissertation as well as gives an explanation of the purpose of this research being carried out and lastly to give 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 reviewed further 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 presented and 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: Conclusions 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 will discuss the bamboo plant as well as valuable bamboo research that has been published. This chapter discusses the mechanical and biological qualities of bamboo, as well as its appropriateness for use in construction. Aside from that, this chapter covers the source of the bamboo being used, as well as earlier applications of bamboo in the construction industry.

2.2 What is Bamboo ?

Bamboo (subfamily *Bambusoideae)* is a subfamily of tall treelike grasses belonging to the *Poaceae* family, with around 115 genera and 1,400 species. Bamboos can be found in tropical and subtropical to mild temperate climates, with the highest density and number of species found in East and Southeast Asia, as well as on islands in the Indian and Pacific oceans (Britannica). Grasses refer to the fact that if the bamboo is cut at the top, it would regrow like grass. Unlike trees, when the trunk is chopped down, it does not regrow and consequently, it will die. The bamboo employed in this study is *Gigantochloa Scortechinii*, also known as Buluh Semantan.

2.3 Anatomy, structure, and growth of Buluh Semantan

Buluh Semantan, also known as *Gigantochloa Scortechinii*, is a perennial clump-forming bamboo that can reach a height of 10 to 20 meters. The upright, thin-walled, woody culms have internodes up to 60 cm long and are 60-120 mm in diameter (Tropical). Commonly every bamboo had the same anatomy (see Figure 2-1). It is very important to understand the bamboo anatomy very well. In Malaysia, Buluh Semantan is widely used in construction. The culms are harvested regularly for a huge variety of purposes. It is commonly picked from the hood, although it can also be grown on a farm or in a community. Southern Thailand, Malaysia, and Indonesia are home to this variety of bamboo (Sumatra).

This bamboo's mechanical properties are unknown. Because the young shoots are bitter, they are rarely used as a vegetable. There are many uses for bamboo such as chopsticks, toothpicks, skewers, blinds, joss sticks, large baskets, poultry cages, and paper. In this study, the focus will be on the usage of this bamboo in construction.

With the popularity of the concept of sustainable development, green buildings have become the main development direction of future architecture. They are currently attempting to construct magnificent structures out of bamboo. Numerous Bamboo hotels, for example, may be found in Bali, Indonesia, while many Bamboo mosques can be seen in Malaysia. To assess the bamboo's fitness for the planned objectives, it is crucial to understand its basic anatomical, physical, and mechanical features.

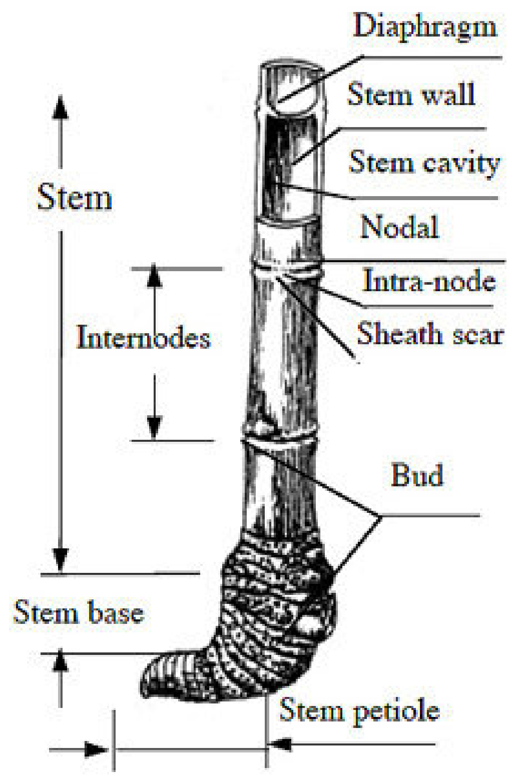

Figure 2-1: Bamboo anatomy (Photo adapted by the author from Google Image)

2.3.1 Physical Characteristics

The physical traits of the bamboo species were frequently used to identify it in the field. The physical feature information is significant since it speeds up the identification of bamboo specimens that have a distinct species identity. Culm height, internode length, and culm wall thickness are all essential qualities that need to be taken into account. The above criteria can be used to identify whether bamboo end products are appropriate.

According to Siam et al. (2019), *Gigantochloa Scortechinii*, or Buluh Semantan, has a culm height of 21 m, internode length of 42 m, a culm wall thickness of 10 mm, a density of 641 kg/m^3, modulus of rupture of flexural strength 125 N/mm^2, and modulus of elasticity 10,039 N/mm^2. Because of these properties, bamboo can be utilized for furniture, parquet (Figure 2-2), and structural purposes.

Figure 2-2: Bamboo parquet (Picture adopted by the author from Google Image)

2.3.2 Anatomical Properties

Vascular bundle types I, II, III, and IV are the four (4) basic types of vascular bundles. Type I vascular bundles are found in monopodial bamboo species, while type II, III, and IV vascular bundles are found in sympodial bamboo species (Siam et al., 2019). Type III was assigned to *Gigantochloa scortechinii* (see Figure 2-3). The open form of Type III vascular bundles can be detected in the middle and inner parts of the bamboo. The four fiber sheaths are self-contained, and the vessel, sieve tube, and phloem are all finely grained, resembling the morphology of certain bamboo species (Li et al., 2021).

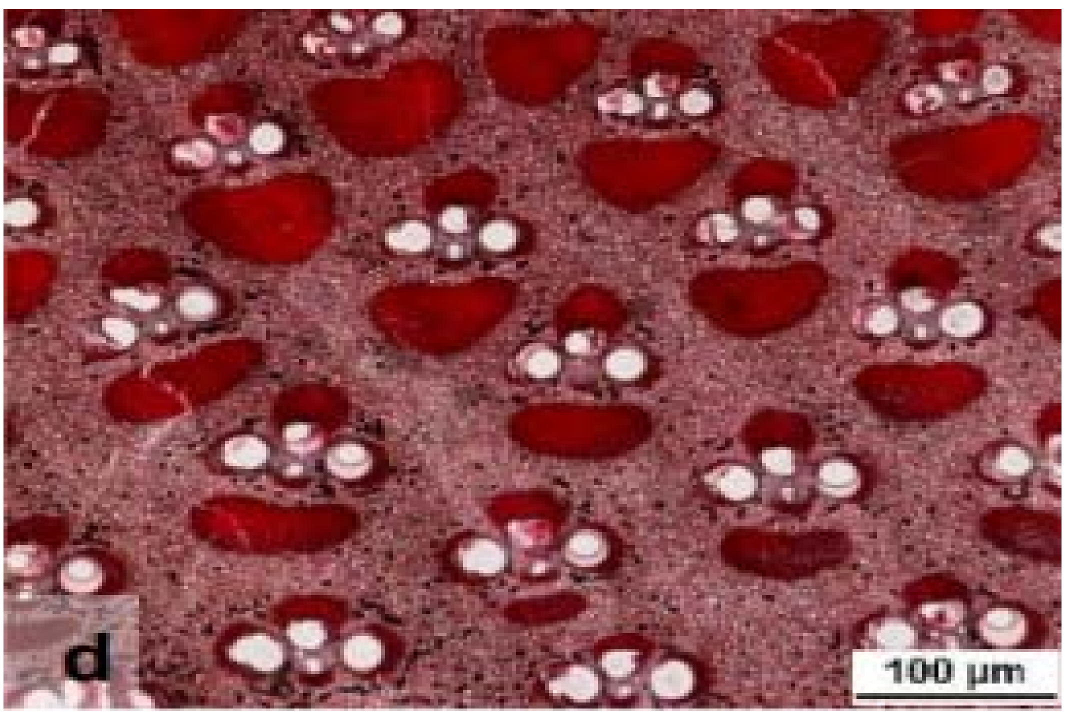

Figure 2-3: Vascular bundle of Gigantochloa Scortechinii (Siam et. al, 2019)

Although fiber length is commonly associated with internode length, research undertaken by Siam et al. (2019) demonstrates that fiber length is not correlated with internode length. From all the species studied, fiber length, width, thickness, and lumen diameter decreased significantly (P 0.05) from the base to the top of the culm. According to the findings, the largest mean percentage of vascular bundles was found at the top of the bamboo culm, followed by the middle, and the lowest at the bottom. This could be owing to the bamboo culm's thinning towards the top. *Gigantochloa Scortechinii* has a Runkel Ratio of 3.53 and an aspect ratio of 170.68.

The Runkel ratio is the proportion of the thickness of the cell wall to the diameter of the lumen. A pulp raw material can be used for fibers having a Runkel ratio of less than or equal to one (Sugesty et al., 2015). A fiber with a greater than one Runkel ratio is deemed substandard. Secondary fiber raw material is defined as fiber with a Runkel ratio of one. *Gigantochloa Scortechinii* has multiple classifications. The higher the Runkel ratio, the stiffer the fiber and the less flexible it is. For papermaking, the aspect ratio of pulp fiber should be less than 100. The aspect ratio of *Gigantochloa Scortechinii* was 170.68. Aspect ratios larger than 100 and longer fiber imply strong pulp raw material suitability and a higher Runkel ratio.

2.3.3 Density, Shrinkage, and Mechanical Properties

The value modulus of rupture or flexural strength of *Gigantochloa Scortechinii* was 125 N/mm^2, and the modulus of elasticity was 10,039 N/mm^2. Based on this information, this type of bamboo has a greater structural potential. The density and proportion of the vascular bundle influenced the increase in flexural strength and modulus of elasticity. It also has a higher density and thicker culm walls to sustain this. The density of bamboo culms grew from the base to the top, and this is true for all varieties of bamboo. This could be due to the larger value of vascular bundles, as well as the rise in silica concentration from the bottom to the top. The presence of more sclerenchyma fibers at the top of the body may also have a role.

The presence of more sclerenchyma fibers at the apex of the bamboo culm may also contribute to the culm's high density. From the base to the top of the bamboo culm, the shrinkage value decreases. This could be related to a lesser number of vascular bundles and a higher initial moisture content. The moisture content in *Gigantochloa Scortechinii* is usually at 10%-13%. The moisture content will greatly affect the mechanical properties of the bamboo (Taylor *et al.*, 2015).

2.3.4 The role of the nodes

A hollow, tubular culm with periodic nodes, an interior diaphragm, and an exterior ridge (see Figure 2-4) make up the bamboo plant's stem. The nodes have a biomechanical function, preventing failure by making the tube stiffer and stronger (Taylor *et al.*, 2015). During growing, bamboo nodes increase the slender bamboo culm's stiffness and stability. Additionally, it aided to stop failure brought on by local buckling. The node had made some mechanical properties changes which are stiffness, strength, and toughness.

Figure 2-4: The external ridge and the fibrous structure near the node (Taylor *et al.*, 2015)

Stiffness is the ability to resist deformation under applied forces. It is important for any plant with an upright growth habit. When the bamboo grows, the force due to its weight may cause it to become permanently bent reducing access to light. The nodes had little if any effect on the bending stiffness. The average stiffness increased by only 10% (Taylor *et al.*, 2015) and this was not significant. Strength is the amount of force or stress needed to cause failure. Stress can be occurred in several different ways and is more difficult to access. There are three possible failure modes, which are transverse fracture, buckling, and longitudinal splitting. A transverse fracture occurs when maximum stress reaches the tensile or compressive strength of the material. The node cannot improve strength if a failure occurs by transverse fractures node can be very effective in resisting buckling mode, due to its internal diaphragm which prevents ovalisation. By longitudinal splitting, the culms tended to fail suddenly, and it was difficult to determine whether the failure was initiated at a node or not. Toughness means the ability to resist crack. It was hypothesized that nodes may act to make crack propagation more difficult. As a result, the split may tend to stop at nodes rather than running the whole length of the culm (Taylor *et al.*, 2015).

Table 2-1: Mechanical properties of Gigantachola scortechinii bamboo split at node and internode at three height positions (Hamdan *et al.*, 2009)

Position	Node			Internode		
	Green		Air dried	Green		Air dried
	Mean	Adjusted	Mean	Mean	Adjusted	Mean
			MOE (N mm^{-2})			
Basal	6969 (1507)	7787 a	10647 a (2509)	10036 (1335)	9676 a	13442 a (1712)
Middle	7254 (1761)	7462 ab	12048 a (2455)	9005 (2131)	8117 b	15164 b (2570)
Top	8116 (1979)	6883 b	12009 a (2629)	9931 (2870)	7948 b	15032 b (2914)
			MOR (N mm^{-2})			
Basal	84.4 (20.7)	82.4 a	123.3 a (29.3)	85.8 (12.4)	81.5 a	151.2 a (24.5)
Middle	79.9 (17.7)	79.9 a	135.0 a (32.3)	92.9 (23.7)	82.4 a	149.6 a (35.5)
Top	87.4 (22.3)	74.5 a	129.2 a (31.0)	97.6 (20.7)	80.4 a	155.8 a (32.7)
			Compression (N mm^{-2})			
Basal	29.8 (4.7)	31.3 a	85.6 a (10.2)	34.2 (6.3)	39.3 a	73.9 a (5.9)
Middle	28.6 (4.8)	30.7 a	70.7 b (10.2)	34.7 (5.3)	37.0 a	73.5 a (6.8)
Top	31.5 (3.9)	29.2 a	72.3 b (17.2)	39.6 (6.2)	36.7 a	76.0 a (10.12)

Table 2-1 above shows the result of the Modulus of elasticity (MOE), Modulus of rupture (MOR), and compression strength of *Gigantachola scortechinii* bamboo between node and internode. From the table, the value for MOE and MOR at the internode was relatively higher than at the node. Overall, the internode had higher compressive strength than the node. Under a uniaxial load, the bamboo's node and internode displayed various failure modes. The crack at the node tended to start at the bottom end, shear perpendicularly upward, and end below the nodal region. For the internode, however, it started with the culm wall being crushed from the bottom up, followed by shear splitting that spread above the crushed area upward. The presence of a node diaphragm in bamboo seems to prevent failure to cross-sectional flattening.

2.4 Bamboo preservation and drying

For utilizing bamboo must go through a preservation process. The reasons behind this are to increase termite and fungus resistance. Various techniques, including immersion, gravity or vertical soak diffusion, and injection using a compressor machine, are frequently employed in construction to conserve bamboo. Because of the efficiency of borax and other chemicals, bamboo can live longer. From the experiment that was conducted by Daud et al. (2018) moisture content and density increase when *Gigantochloa Scortechinii* bamboo is treated (see Table 2-2).

Table 2-2: Result of moisture content and density (Daud et al., 2018)

Section	Moisture Content (%)		Density (kg/m³)	
	Untreated	Treated	Untreated	Treated
Bottom	15.79	25.93	608.00	785.45
Middle	12.50	23.08	610.98	832.00
Top	11.11	16.00	716.42	869.57
Mean	13.13	21.67	645.13	829.01

While for the compression test the strength is increased when the bamboo is treated with boric acid. The result for treated bamboo (see Table 2-3) is higher compared to untreated bamboo (see Table 2-4).

Table 2-3: Result of compression strength for untreated bamboo (Daud et al., 2018)

Section	Wall Thickness (mm)	Untreated Bamboo Cross-Sectional Area (mm²)	Compression Strength (MPa)
Bottom	11.10	1583.38	19.96
Middle	17.40	2000.95	23.24
Top	27.30	2290.24	23.80
	Mean		22.33

Table 2-4: Result of compression strength for treated bamboo (Daud et al., 2018)

Section	Wall Thickness (mm)	Treated Bamboo Cross-Sectional Area (mm²)	Compression Strength (MPa)
Bottom	10.09	1439.86	31.74
Middle	12.96	1630.44	34.71
Top	19.25	1893.55	36.60
	Mean		34.35

Table 2-5: Result of shear strength for untreated bamboo (Daud et al., 2018)

Section	Wall thickness (mm)	Height (mm)	Shear Strength (MPa)	
			Node	Internode
Bottom	7.30	92.80	4.28	4.10
Middle	8.20	91.00	4.56	4.25
Top	9.40	87.40	5.69	5.45

Table 2-6: Result of shear strength for treated bamboo (Daud et al., 2018)

Section	Wall thickness (mm)	Height (mm)	Shear Strength (MPa)	
			Node	Internode
Bottom	10.54	126.08	3.67	3.54
Middle	11.18	123.12	4.61	3.94
Top	12.52	113.02	5.21	4.98

From Table 2-6 and Table 2-5, the shear strength is not affected when bamboo is treated with boric acid. In a conclusion, boric acid only affected the compressive and moisture content of the bamboo.

2.5 Structural Application

Today, the manufacture of primary construction materials, such as concrete and steel, is a significant source of carbon dioxide (CO_2) emissions, making the construction industry a significant polluter. Bamboo, on the other hand, is a promising structural material that is not only a renewable source, fast-growing, and robust, but also has a low carbon impact (Bhagat et al., 2021). Bamboos have many advantages, including managing the water cycle, collecting carbon dioxide, being easy to handle, and aiding in soil erosion prevention. There are at least 13 different types of bamboos in Malaysia. Bamboo has a greater chance of being the most environmentally friendly building material. Cement or glue can be used to create a material that is much stronger and more aesthetically beautiful to fit into today's lifestyle (Manandhar et al., 2019)

In Malaysia, the use of bamboo as a construction material is not new. Bamboo was used as a beam, column, plank, wall, and roof in the old house at the time. This style of home can still be found in the "Orang Asli" community, which has abundant resources. Unfortunately, compared to China, Malaysian research on bamboo as a construction material is very limited. Bamboo is the most similar substance to wood. It possesses mechanical qualities that are similar to those of wood (Sharma et al., 2015).

Bamboo is less expensive than wood in terms of cost-effectiveness. According to the findings, engineered bamboo possesses mechanical qualities that are comparable to those of other structural materials such as lumber and raw bamboo (Sharma et al., 2015). This could be owing to the bamboo fibers' longitudinal strength; both bamboo scriber and laminated bamboo have improved qualities parallel to the grain, except for stress parallel to the grain. The strength perpendicular to the grain is much lower than the strength parallel to the grain, just as it is in lumber. According to a study conducted by Sharma et al. (2015), both scriber and laminated bamboo products have qualities that are comparable to or better than Douglas-fir wood.

Even the potential of bamboo as a structural element is more promising and widely studied, but the uses of bamboo are hampered by the lack of engineering data and mechanical properties, and appropriate building codes. This problem becomes a barrier that makes engineers and architects overlook the usefulness of bamboo. However, several countries start to develop standards for bamboo such as China, Colombia, Ecuador, India, Peru, the USA, and international (see Table 2-7).

Table 2-7: Existing structural bamboo standards and code (Gato´o et al., 2014)

Country	Code	Standard
China		JG/T 199: Testing method for physical and mechanical properties of bamboo used in building (PRC MoC, 2007)
Colombia	*Reglamento Colombiano de Construcción Sismoresistente* – chapter G12 Estructuras de Guadua (Guadua structures) (ICONTEC, 2010)	NTC 5407: Uniones de Estructuras con *Guadua angustifolia* Kunth (Structural unions with *Guadua angustifolia* Kunth) (ICONTEC, 2006) NTC 5525: Métodos de Ensayo para Determinar las Propiedades Físicas y Mecánicas de la *Guadua angustifolia* Kunth (Methods and tests to determine the physical and mechanical properties of *Guadua angustifolia* Kunth) (ICONTEC, 2007)
Ecuador	*Norma Ecuatoriana de la Construcción* – chapter 17 Utilización de la Guadua Angustifolia Kunth en la Construcción (Use of *Guadua angustifolia* Kunth in construction) (INEN, 2011)	INEN 42: Bamboo Caña Guadua (bamboo cane Guadua) (INEN, 1976)
India	*National Building Code of India*, section 3 Timber and bamboo: 3B (BIS, 2010)	IS 6874: Method of tests for round bamboos (BIS, 2008) IS 15912: Structural design using bamboo – code of practice (BIS, 2012)
Peru	Reglamento Nacional de Edificaciones, Section III. Code E100 – Diseño y Construcción con Bamboo (ICG 2012)	
USA		ASTM D5456: Standard specification for evaluation of structural composite lumber products (ASTM, 2013)
International		ISO 22156: Bamboo – structural design (ISO, 2004a) ISO 22157-1 Bamboo – determination of physical and mechanical properties – part 1: requirements (ISO, 2004b) ISO 22157-2: Bamboo – determination of physical and mechanical properties – part 2: laboratory manual (ISO, 2004c)

2.5.1 Bamboo connections

Bamboo is hollow and cylindrical, and thus it cannot be connected in the same way as wood. Nails and wires should also be used sparingly in bamboo construction because they can produce cracks and are ineffective (Bamboo Construction Source Book, 2013). Bamboo's characteristic round and hollow structure cause several issues during construction, particularly in terms of its connection (Manandhar et al., 2019). Traditional assemblies, metal connectors, and mortar filling are the types of joints used in bamboo buildings. Example of bamboo joints is fish mouth notch through bolt, cap bolt connection, longitudinal union, motar filled hole, and nails and wire (see Figure 2-5).

Attaching the end of a bamboo cane to a perpendicular cane is done with the ‘fish mouth’ cut (Bamboo Construction Source Book, 2013). The notched ‘flute peak’ should be used to connect the bamboo at an angle of 45 or 30 degrees. Threaded rods via bolts can be used to securely attach bamboo joints and bamboo to other materials. Galvanized steel threaded rods with nuts and washers, hardwood dowels, or smooth steel road may be used, depending on material availability and affordability (Construction Manual for Bamboo, 2012).

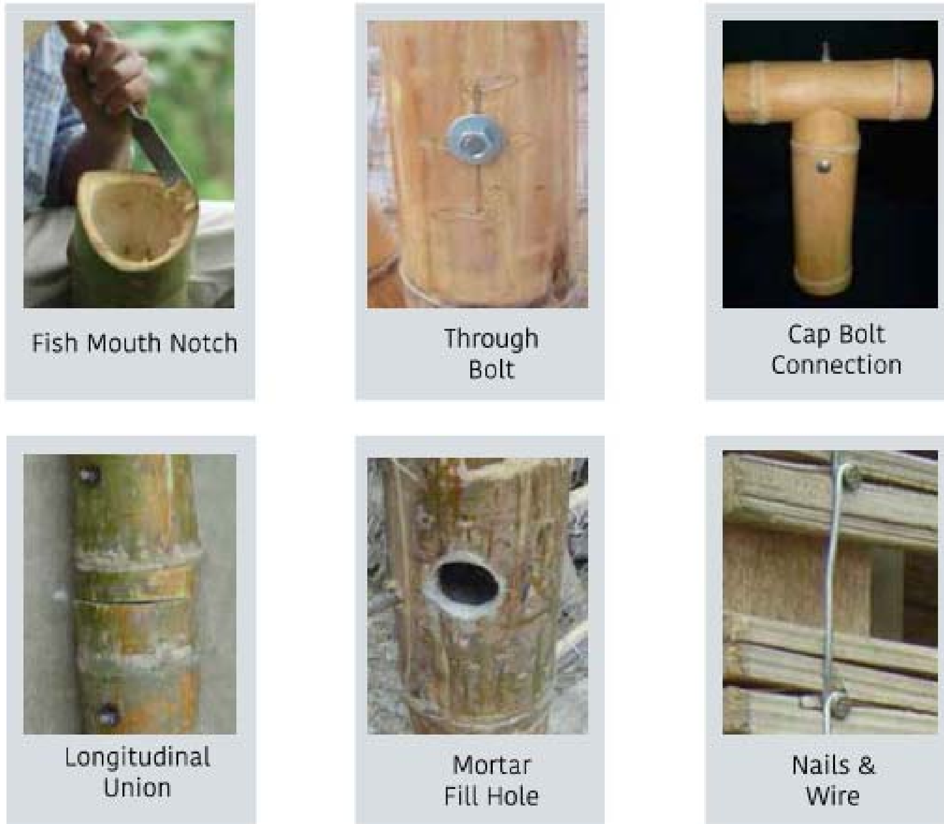

Figure 2-5: Type of connection (Construction Manual for Bamboo, 2012)

Lashing can also be used to keep a bamboo connection secure. A lashing is a rope, wire, or webbing arrangement with a connecting mechanism. Square lashing and shear lashing are two types of lashing techniques (Bamboo Construction Source Book, 2013). Lashing joint (see Figure 2-6) has characteristics of good adjustability and low price, but the construction of lashing is less efficient and time-consuming, and the performance of joints is greatly affected by human operation due to the flexible connection characteristics of lashing itself, the joint stiffness is insufficient (Hong et al., 2019).

Figure 2-6: Lashing joint (Hong et al., 2019)

Bolts are the most extensively used metal connectors, with strong economic performance, high construction efficiency, and easy, and dependable force transmission. This can be done by drilling holes sufficient for bolt diameter on the bamboo rod and then connecting the bamboo components with matching bolts and nuts. On this foundation, other types of bolt connections are optimized and improved. Bolt solves the difficult connection problem by using a simple connection method, but there are also some problems such as insufficient strength joints. The performance of bolted joints of raw bamboo structures around factors such as the end distance and diameter of the bolt and the different end distance and bolt diameter would affect the ultimate bearing capacity (Hong et al., 2019). Another type of bolt is a cap bolt cinch or anchored bolt can also be utilized for the fish mouth joint. It calls for two threaded rods: one with a thread on one end and a j-hook on the other (for tensioning) and another with a shorter length (for anchoring) (Construction Manual for Bamboo, 2012).

Mortar filling joints are to ensure the stiffness and stability of the joints. Several scholars put forward the joint forms which are strengthened by adding fillers into the bamboo cavity, and then connected by bolts and prefabricated metal connectors. Mortar filling had demonstrated the good mechanical properties and processability of mortar-injected joints. Cement mortar could improve the bearing capacity. It was found that the compressive strength of cement mortar played a decisive role in the bearing capacity of joints (Hong et al., 2019). The sheer capacity of the connection was increased and successfully prevent local splitting failure of the bamboo.

Bamboo is usually used in the length or split form (if necessary). Traditionally, only one tool, Dabiya (see Figure 2-7), has been used to complete this work. In Malaysia and Indonesia, Dabiya is known as “Pisau Pandai Buluh." The tool is a knife with sharp sections in a spherical shape. To account for the impact from above, the knife is likewise very thick. However, carpentering and modern powerful tools can also be utilized to speed up the process.

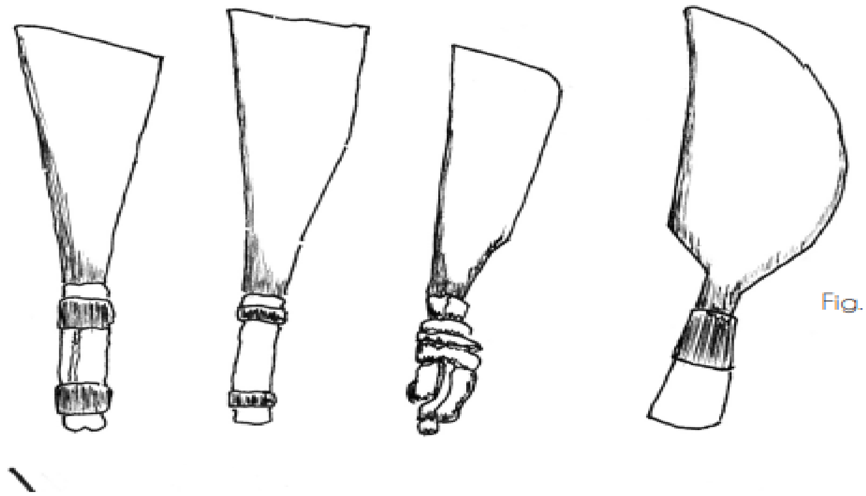

Figure 2-7: Traditional tools (Bamboo construction Source Book, 2013)

2.6 Fire resistance

The main challenge for bamboo is its fire resistance ability. Bamboo has properties that make it sustainable, but its fire behavior remains unknown (Mena et al., 2012). Bamboo is flammable and can catch fire easily. Most bamboo has an ignition temperature of 265 degrees Celsius (509 Fahrenheit), making it catch fire more easily than many other types of wood (Firefighter insider). Ignition temperature is the minimum temperature at which a volatile material will vaporize into gas and ignite without help from an external fire source. In comparison to timber which has an ignition temperature between 250 and 300 Celsius (482 and 572 Fahrenheit) (Firefighter insider), bamboo is a bit more flammable than most wood. Compared to cement, both materials are far away in terms of fire resistance, which is 900 to 1000 Celsius (1650-1830 Fahrenheit). Special treatment or engineered bamboo is needed to increase the ignition temperature if bamboo is to be employed as a structural member in the building.