STRENGTH PROPERTIES OF BORON-BASED TREATED CROSS - LAMINATED BAMBOO (*Gigantochloa scortechinii)* WITH DIVERSE LAYUP PATTERNS FOR STRUCTURAL APPLICATION

By

NORHAZAEDAWATI BINTI BAHARUDDIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

May 2024

IPTPH 2024 5

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

STRENGTH PROPERTIES OF BORON-BASED TREATED CROSS - LAMINATED BAMBOO (*Gigantochloa scortechinii)* WITH DIVERSE LAYUP PATTERNS FOR STRUCTURAL APPLICATION

By

NORHAZAEDAWATI BINTI BAHARUDDIN

May 2024

Chairman : Balkis Fatomer binti A. Bakar, PhD
Institute : Tropical Forestry and Forest Products

Bamboo is an alternative material that has been used across several industries, notably in construction applications. In this application, bamboo needs to be treated with a preservative solution to increase its durability and, more significantly, to guard against insects and fungi. Despite these beneficial uses, the effect of preservatives on mechanical qualities deserves further attention and investigation, primarily when used in structural applications. The utilisation of bamboo in construction is facing challenging due to its lack of section uniformity, unstable bearing strength brought on by the hollow section and the demand for constructing dependable and ductile connections. This makes it difficult to ensure that the structures comply with the standards for industrialised mass production. Therefore, it is important to develop bamboo forms that are better suited to current structural applications through lamination methods. However, various fabrication designs for laminated panels and orientations of bamboo strips require further investigation, peculiarly for structural use. Inspired by cross-laminated timber, this study focuses on the manufacture of cross-laminated bamboo (CLB) from *Gigantochloa scortechinii* to investigate its strength performance for potential usage in structural applications. Bamboo was treated with boron-based preservatives to evaluate its physical, mechanical, and adhesion properties. The fabrication of CLB was conducted to determine the bonding properties of these preservative treatments. Additionally, bamboo was manufactured into three types of layup patterns to evaluate their impacts on the mechanical properties of CLB. This study showed that preservative treatment had no significant impact on the dimensional stability and strength characteristics of bamboo strips; however, CLB treated with CCB demonstrated superior performance compared to boron, achieving values of 184.34 N/mm^2, 22417.10 N/mm^2 and 80.97 N/mm^2 for modulus of rupture (MOR), modulus of elasticity (MOE), and compression, respectively. The results furthermore demonstrated a notable change in the adhesion characteristics after treatment. Likewise, the investigation revealed that bonding qualities enhanced through treatment and higher spread rate, with CCB preservative at a rate of 300 g/m^2 yielded the most remarkable improvement in shear strength. Layup patterns were observed to influence the mechanical properties of CLB, with Type 3 (Vertical-Horizontal-Vertical) exhibiting the highest bending and compressive strengths, with values of 55.25 N/mm^2 and 55.69 N/mm^2, respectively. The disparities were influenced by various possibilities such as orientation direction, anatomical structure and thickness of the CLB. The most prominent failure modes in bending were observed to be rolling shear, glue line, compression and tension, and three failure modes, including crushing, splitting, and shear, have been reported in compression.

Keywords: cross-laminated bamboo, layup patterns, mechanical properties, preservative treatment, structural applications

SDG: GOAL 9: Industry, Innovation and Infrastructure

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

SIFAT KEKUATAN BULUH BERLAMINA SILANG DENGAN RAWATAN BERASASKAN BORON (*Gigantochloa scortechinii)* PELBAGAI CORAK SUSUN ATUR UNTUK APLIKASI STRUKTUR

Oleh

NORHAZAEDAWATI BINTI BAHARUDDIN

Mei 2024

Pengerusi : Balkis Fatomer binti A. Bakar, PhD
Institut : Perhutanan Tropika dan Produk Hutan

Buluh merupakan bahan alternatif yang sering digunakan dalam beberapa industri, terutamanya aplikasi binaan. Dalam aplikasi ini, buluh perlu dirawat dengan bahan pengawet untuk meningkatkan ketahanan dan perlindungan daripada serangga dan kulat. Disebalik penggunaannya yang bermanfaat, kesan bahan pengawet ke atas kualiti mekanikal perlu diberi perhatian dan penyiasatan lanjut, terutamanya apabila digunakan dalam aplikasi struktur. Penggunaan buluh dalam pembinaan menghadapi cabaran kerana ketidakseragaman bentuk, ketidakstabilan kekuatan galas disebabkan oleh strukturnya yang berongga dan kekangan untuk membina sambungan diantara satu sama lain. Ini menyukarkan untuk memastikan strukturnya mematuhi piawaian untuk pengeluaran secara besar-besaran. Oleh itu, adalah penting untuk membangunkan bentuk buluh yang lebih sesuai untuk aplikasi struktur melalui kaedah laminasi. Walau bagaimanapun, terdapat pelbagai reka bentuk fabrikasi panel berlamina dan orientasi bilah buluh yang memerlukan penyiasatan tambahan khususnya apabila ia digunakan sebagai aplikasi struktur. Diilhamkan daripada kayu berlamina silang (CLT), kajian ini memberi tumpuan kepada pembuatan buluh berlamina silang (CLB) daripada *Gigantochloa scortechinii* untuk mengkaji prestasi kekuatan bagi potensi kegunaan sebagai aplikasi struktur. Dalam kajian ini, buluh dirawat menggunakan bahan pengawet berasaskan boron untuk menilai sifat fizikal, mekanikal dan lekatan. Fabrikasi CLB dilaksanakan bagi menentukan sifat ikatan pengawet. Selain itu, buluh diproses kepada tiga jenis susun atur untuk menilai kesannya terhadap sifat mekanikal ke atas setiap CLB. Kajian ini menunjukkan bahawa rawatan pengawet tidak memberi kesan yang ketara terhadap kestabilan dimensi dan ciri-ciri kekuatan buluh bilah; walau bagaimanapun, CCB menunjukkan prestasi yang unggul berbanding boron iaitu 184.34 N/mm^2, 22417.10 N/mm^2 dan 80.97 N/mm^2 bagi kekuatan pecah (MOR), kekuatan lenturan (MOE) dan mampatan. Keputusan turut menunjukkan bahawa terdapat perubahan yang ketara terhadap ciri-ciri lekatan selepas rawatan. Begitu juga kajian mendedahkan bahawa kualiti ikatan meningkat melalui rawatan dan kadar penyebaran gam tertinggi, iaitu CCB pada kadar penyebaran 300 g/m^2 menghasilkan peningkatan yang luar biasa dalam kekuatan ricih. Corak susun atur diperhatikan mempengaruhi sifat mekanikal CLB dengan Jenis 3 (Menegak-Mendatar-Menegak) menunjukkan nilai tertinggi dalam kekuatan lentur dan mampatan iaitu 55.25 N/mm^2 dan 55.69 N/mm^2. Perbezaan keputusan ini dipengaruhi oleh pelbagai faktor, antaranya ialah arah orientasi bilah buluh, struktur anatomi buluh dan ketebalan CLB. Mod kegagalan yang paling menonjol dalam ujian lenturan adalah gulung ricih lapisan, kegagalan garisan perekat, mampatan dan tegangan. Manakala tiga mod kegagalan terhadap ujian mampatan yang diperhatikan adalah kegagalan hancuran, pemisahan dan ricih.

Kata Kunci: aplikasi struktur, buluh lamina silang, corak susun atur, rawatan pengawet, sifat mekanikal

SDG: MATLAMAT 9: Industri, Inovasi dan Infrastruktur

ACKNOWLEDGEMENTS

IN THE NAME OF "ALLAH, MOST GRACIOUS, MOST MERCIFUL"

Alhamdulillah, all praises to Allah and His blessings in this successful completion of this thesis. I thank Allah for the abundance of possibilities, challenges, and resilience bestowed upon me, enabling me to complete this journey successfully. Firstly, I would like to express my heartfelt appreciation to my supervisors, Dr. Balkis Fatomer A. Bakar, Dr. Mohd Khairun Anwar Uyup, Dr. Lee Seng Hua and Professor Dr. Paridah Md Tahir, for their guidance and unwavering assistance in all time of research and writing of this thesis.

Secondly, I would like to thank the Malaysian Timber Industry Board (MTIB) and the Ministry of Plantation and Commodities for the opportunity, financial sponsorship, and facilities provided throughout the study. Additionally, to my director of division, Pn. Nor Liza Mat Yasok for the encouragement, and my technical colleagues, especially En. Mohd Rozemy bin Mohammad Ghazali for assistance during this research. I also want to express my sincere gratitude to the Forest Research Institute Malaysia (FRIM) and Universiti Teknologi MARA (UiTM) for their technical support and guidance.

Ultimately, the most profound appreciation and love goes to my lovely husband, En. Mohd Ridzuan Samsury, for his endless love, patience and support through thick and thin of this journey. Finally, sincere thanks to my parents, En. Baharuddin Adnan and Pn. Zainab Ahmad, sisters and families, for their encouragement and never-ending

prayers. May Allah bestow the aforementioned individuals with wealth and prestige throughout their life.

This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

Balkis Fatomer binti A. Bakar, PhD
Senior Lecturer
Faculty of Foresty and Environment
Universiti Putra Malaysia
(Chairman)

Paridah binti Md Tahir, PhD
Professor
Faculty of Forestry and Environment
Universiti Putra Malaysia
(Member)

Lee Seng Hua, PhD
Senior Lecturer
Department of Wood Industry
Universiti Teknologi MARA Jengka Campus
(Member)

Mohd Khairun Anwar bin Uyup, PhD
Senior Research Officer
Forest Research Institute Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 12 December 2024

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

°	Degree
° C	Degree Celsius
%	Percentage
ANOVA	Analysis of variance
BDB	Boil-dry-boil
cm	Centimetre
cm^{-1}	Reciprocal centimetre
CCB	Copper chrome boron
CLB	Cross-laminated bamboo
CLT	Cross-laminated timber
EMC	Equilibrium moisture content
FTIR	Fourier Transform Infrared Spectroscopy
g/m^2	Gram per square metre
Glubam	Glued laminated bamboo
GPa	Gigapascal
ha	Hectare
HCL	Hydrochloric acid
INBAR	International Bamboo and Rattan
Kg/m^2	Kilogram per square metre
Kg/m^3	Kilogram per cubic meter
Kg	Kilogram
kPa	Kilopascal
kN	Kilonewton
LBL	Laminated bamboo lumber
LVDT	Linear variable differential transformer

mm	Millimetre
m	Metre
MC	Moisture content
mL	Millilitre
Min	Minute
MOR	Modulus of rupture
MOE	Modulus of elasticity
MPa	Megapascal
N/mm^2	Newton per square millimetre
NDSR	Net dry salt retention
NOAH	Sodium hydroxide
PRF	Phenol resorcinol formaldehyde
pH	Potential of hydrogen
SEM	Scanning electron microscopy
USD	U.S. dollar
VP	Vacuum pressure
WPG	Weight percent gain

CHAPTER 1

BACKGROUND

1.1 Introduction

The bamboo-based industry is experiencing significant growth in terms of industrial development. In 2020, the global trade value of bamboo commodities reached USD 2.97 billion, with Asia dominating the share at USD 2.38 billion, or 80.2% of the total global trade value (INBAR, 2022). Malaysia, in particular, reported a 66.1% increase in the export value of bamboo commodities, reaching RM14.5 million in 2022 (MTIB, 2022). This underscores the importance of bamboo as a vital raw material, especially in complementing the timber industry.

The use of bamboo in a wide range of applications, especially in engineered product manufacturing, has been extensively explored. This exploration primarily focuses on their mechanical properties, processing methods, and applications in the construction and structural engineering field (Gharavi, 2019). Cross-laminated bamboo (CLB) is one of the bamboo-engineered products that offers a versatile and resilient alternative to conventional building materials by improving structural integrity and robustness (Agustina et al., 2015). The CLB refers to a construction material made by layering bamboo strips (laminae) in a perpendicular orientation bonded with an adhesive. The advantage of CLB compared to other types of engineered bamboo products, peculiarly in parallel directional bamboo strips such as laminated bamboo lumber, glued laminated bamboo and others, lies in its orientations, which contribute to the design and the ability to be manufactured in structural applications (Chow et al., 2019) such as exceptional proportions, dimensional stability, stiffness, and adequate strength

(Mili et al., 2023). In addition, cross-laminated board promotes uniform load distribution across all surfaces (Agustina et al., 2015). Various components in buildings, such as columns and beams, walled envelopes, shear walls, and ground materials, have been identified for their exceptional strength-to-weight ratios and high tensile strength (Wang et al., 2011). With this regard, CLB has the potential to be largely utilised for structural purposes, primarily in the housing and building industries.

Gigantochloa scortechinii is one of the predominant species of bamboo found in Peninsular Malaysia and is commonly used for various applications, especially in structural (Yusof et al., 2023). The culm has good bending properties, with a modulus of rupture (MOR) and a modulus of elasticity (MOE) of 125 Nmm^{-2} and 10039 Nmm^{-2}, respectively (Siam et al., 2019). Three-layer laminated bamboo board produced from *Gigantochloa scortechinii* exhibits good strength properties of 131 Nmm^{-2} for MOR and 19661 Nmm^{-2} for MOE (Asniza et al., 2022). These values are comparable to those of some hardwood species, such as Nyatoh, with a MOR of 113 Nmm^{-2} and a MOE of 16348 Nmm^{-2}, as well as Kempas, with MOR and MOE values of 122 Nmm^{-2} and 18600 Nmm^{-2}, respectively (Wahab, 2014). These wood species are typically used for structural panels, floors as well as furniture. Given the promising strength demonstrated by *Gigantochloa scortechinii*, this study aims to explore its potential for CLB production and assess its suitability for use in structural applications by evaluating its mechanical properties.

1.2 Problem Statement and Justification

As the demand for sustainable building materials continues to rise, bamboo has emerged as a promising alternative to traditional construction materials due to its renewable nature and environmental benefits. Despite its potential, the application of laminated bamboo in structural engineering is not yet widespread. This is primarily due to a limited understanding of its strength properties when used in structural applications. Past studies suggest that while laminated bamboo exhibits favourable mechanical properties such as bending performance and shear strength, there remains significant variability in its strength parameters based on factors such as preservative types and laminate configuration. This lack of detailed, empirical data hinders the material's broader adoption in construction, where reliability and performance are paramount.

For bamboo to be transformed into CLB, it must undergo appropriate treatment to prolong its service life, mitigate deterioration, and enhance the resistance to fungi, pests and any deterioration agents (Rabbi et al., 2015; Roziela Hanim et al., 2013). Several treatment methods have been used globally by industries (Siti Rafedah et al., 2020), often in conjunction with commercial adhesive (Alipon et al., 2018) during product manufacturing. Yet, the different preservatives treatment can impact the structural stability and the mechanical properties of laminated bamboo. Scrutinising how these factors can affect properties such as mechanical properties and structural stability is crucial for optimising the material's performance. This ensures that laminated bamboo can meet the required standards for structural applications.

The strength and durability of laminated bamboo are highly dependent on the quality of the adhesive bonds between layers. The bonding properties, including adhesive and application techniques, significantly impact the mechanical performance and longevity of laminated bamboo. In spite of the potential of laminated bamboo as structural application, research has demonstrated that preservatives, due to their deposition on the material surface (Shah et al., 2018), negatively impact both wettability and bonding strength of laminated bamboo (Caldeira et al., 2010). Therefore, investigating adhesion and bonding properties essential to ensure that these bonds are strong and reliable, which is crucial for maintaining the structural integrity of laminated bamboo constructions. This understanding helps prevent potential failures and ensures safety in structural applications. Additionally, it aids in optimising the application techniques of laminated bamboo.

CLB can be fabricated with at least three layers of laminae, in which bamboo laminae can be arranged either horizontally or vertically in each layer. This lamination configuration or the arrangement of bamboo layers can significantly influence the structural performance of laminated bamboo, as it is an anisotropic material with properties in different planes. Variations in lamination configuration, such as the directionality of bamboo strips, can lead to inconsistencies in performance, affecting the reliability of laminated bamboo (Tuswan et al., 2023).

Generally, there are three possible configurations to fabricate CLB, namely horizontal-horizontal-horizontal (H-H-H), horizontal-vertical-horizontal (H-V-H) and vertical-horizontal-vertical (V-H-V) layup. The most common layup is H-H-H. However, horizontal layup is relatively more difficult to be carried out compared to vertical laying. It requires a much more precise control of pressing pressure along the strips, which is challenging when using normal clamping due to the uneven thickness of the strips. Meanwhile, vertical laying is easier to be carried out since it does not require a uniform thickness of the strips. This different layup can denote the affect towards the mechanical properties of laminated bamboo such as stiffness and flexibility. Researching various layup helps identify most effective arrangements for enhancing these properties, ensuring laminated bamboo performs well under structural loads. Therefore, it is important to investigate the CLB's layup pattern due to distinct mechanical properties along the grain and across the grain. Although behaves differently, by making CLB, it would be expected to demonstrate stable strength by cooperating between the layers to improve the behaviour. This will provide a better opportunity for CLB to be used as a structural application. Due to that, a fundamental understanding of how different bamboo strip layup patterns influence the mechanical properties of the CLB is necessary.

1.3 Aim of the Study

This study aims to determine the feasibility of using *Gigantochloa scortechinii* to fabricate cross-laminated bamboo (CLB). This study is divided into several objectives as follows:

i) To investigate the effect of the preservative treatments on the physical and mechanical properties of bamboo strips

ii) To evaluate the adhesion and bonding properties of cross-laminated bamboo (CLB) made from boron-based preservative-treated strips

iii) To examine the effect of layup patterns on the mechanical properties of cross-laminated bamboo (CLB) bonded with phenol resorcinol formaldehyde (PRF).

1.4 Scope and limitation

The scope of this study encompasses several key areas essential for evaluating the performance of CLB in structural application. This study aims to comprehensively evaluate various aspects of bamboo strips, focusing on their treatability and the impact of treatment on both physical and mechanical properties. Additionally, the study seeks to enhance the adhesion properties of bamboo strips and evaluate the bonding quality of CLB structures. Finally, it examines the impact of various layup configurations on the mechanical properties of CLB, particularly in terms of bending and compression performance, leading to optimised layup strategies for construction applications.

While this study aims to provide comprehensive insights into the strength properties of CLB, there are several limitations were encountered during the research. One significant limitation is material variability; inconsistencies in raw material quality can arise even within the same bamboo species due to variations in thickness and straightness. These factors pose challenges in achieving uniformity during the manufacturing process of laminated bamboo. Another limitation is the lack of standardized testing methods for bamboo and laminated bamboo. Currently, the available testing standards are limited. To address this, the study employed several existing standards, including those for split bamboo, wood-based panels, and wood structural standards, with appropriate adjustments made throughout the laboratory work.

1.5 Organization of the Thesis

This thesis contains six chapters. The first chapter provides an overview of bamboo and cross-laminated bamboo (CLB), introduces the problem statement, and outlines the objectives of the study. The second chapter provides a thorough assessment of the available literature review on bamboo, prior research on laminated bamboo, and the influence of preservative treatment and adhesive on the strength properties and bonding of laminated bamboo. It also reviews the concept of cross-laminated bamboo (CLB) and its prospective application as a structural application. The third chapter delves into the impact of preservative treatment on the physical and mechanical properties of bamboo strips. It discusses the evaluation of treatability, including retention, penetration, and FTIR analysis.

The fourth chapter focuses on the shear strength performance of CLB treated with boron-based preservatives. It assesses the adhesion properties of each treatment through contact angle and buffer capacity. This chapter also thoroughly analyses the relationship between treatment and glue spread rate, culminating in the identification of the optimal spread rate for the study.

Chapter 5 evaluates the mechanical properties through bending and compression tests to determine the strength properties of CLB manufactured with different layup patterns. The chapter also discusses the failure mode trends among the layup patterns and their behaviour. Finally, Chapter 6 summarises the study's findings and provides recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Bamboo Resources and Applications

Bamboo is one of the world's most significant non-timber forest commodities. In contrast to wood, bamboo can regenerate after harvesting, allowing it to be harvested annually throughout the plant's life (Li & He, 2019). Besides, it is readily available and has outstanding properties for many applications (Borowski et al., 2022); these plants are believed to alleviate timber demand pressure in natural forests, thus facilitating worldwide environmental conservation (Chung, 2002).

2.1.1 Sources of Bamboo

Bamboo is a member of monocotyledonous flowering plants known as grasses, which belong to the Poaceae family. According to Lee et al. (2023), this family was characterised into 12 subfamilies, with bamboo lying to the subfamily of bambusoideae (Figure 2.1).

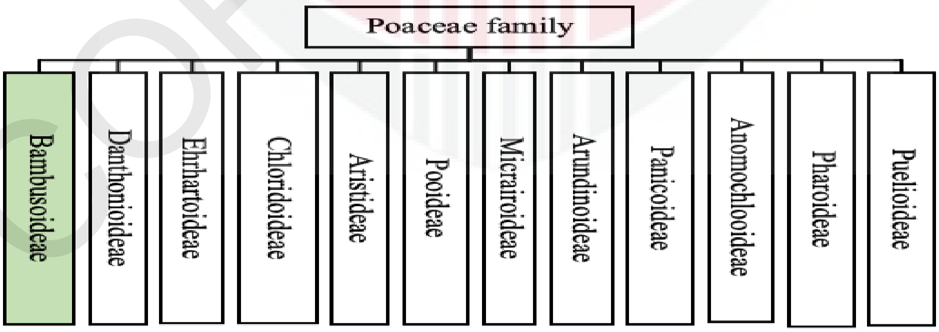


Figure 2.1: The Poaceae Family Categories
(Source: Lee et al., 2022)

Kelchner et al. (2013) stated that the Bambusoideae subfamily is divided into three groups: Olyreae, Bambuseae and Arundinarieae. Olyreae belongs to herbaceous species, whereas Bambuseae and Arundinarieae denote tropical and temperate woody bamboo.

As of 2020, 35 million hectares of bamboo are growing worldwide (Figure 2.2), either in isolated patches, mixed forests, or vast expanses of pure bamboo forest, as reported by the Food and Agriculture Organization (2021) and Global Forest Resources Assessment (2020). Based on the report, it is stated that the new development in India and China has seemingly been responsible for the over 50% rise in the total bamboo area within 30 years. Asia accounts for most bamboo resources, about 24.88 million hectares, followed by South America, with 5.39 million hectares. Africa was recorded as an area of 4.65 million hectares, and the Caribbean region (North and Central America) was noted for approximately 0.125 million hectares.

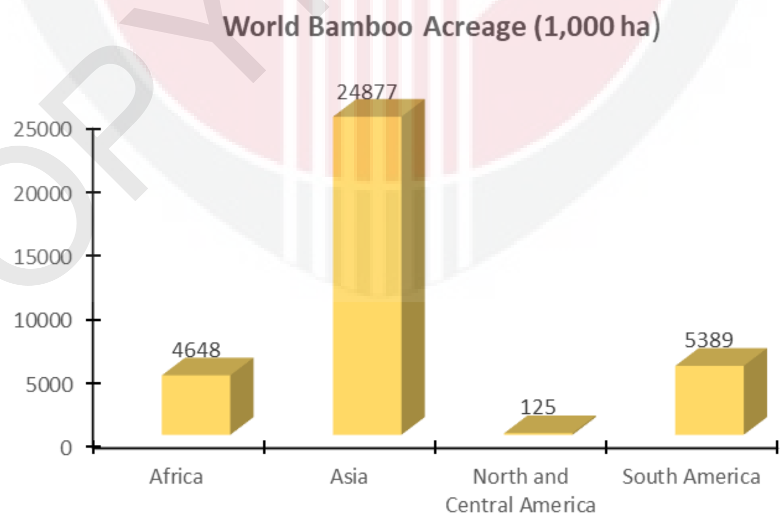


Figure 2.2: The World Bamboo Acreage
(Source: FAO, 2022; FRA, 2020)

2.1.2 Bamboo Species and Distribution

Bamboo thrives in tropical and subtropical conditions. As stated by Canavan et al. (2017), globally, there are nearly 1662 bamboo species classified into 121 genera, which were distributed into three primary bamboo regions: Asia-Pacific, American, and African. Based on the findings of Mera & Xu (2014), the Asian-Pacific region encompasses more than 80% of the global bamboo forest lands and species (Figure 2.3).

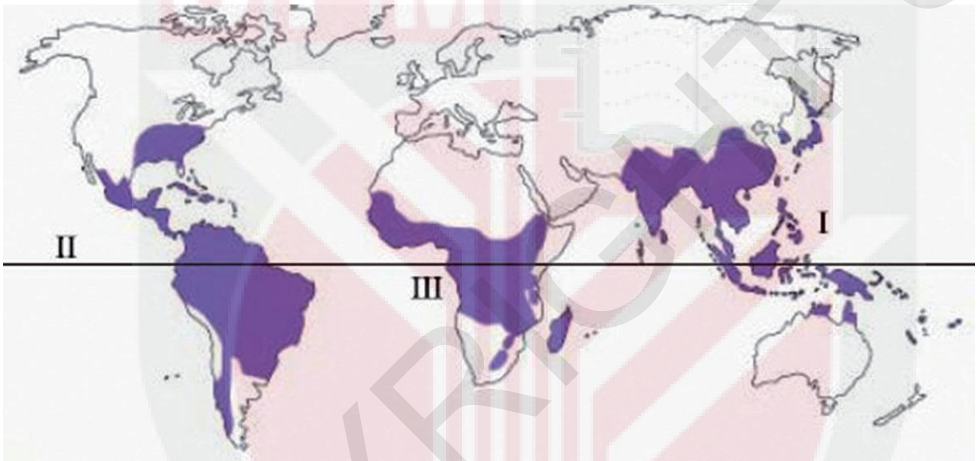


Figure 2.3: Bamboo Distribution in the Asia-Pacific Region (I), The American Region (II) and The African Region (III)
(Source: Mera & Xu, 2014)

Asia is home to the most diverse bamboo species, thriving in tropical and temperate temperatures. This region boasts around 900 species, distributed among 40 to 50 genera, representing approximately 75% of the global bamboo species. China had the highest number of bamboo species, with 600 species, followed by India, with 102 species, while Japan has 84 species (Ahmad et al., 2021). The author also observed that Asia has around 25 million hectares of bamboo plantations. Notably, India boasts the largest area of bamboo plantations, encompassing approximately 9 million hectares, while China comes second with 6.4 million hectares. The remaining 10 million hectares are distributed over many Asian countries, including Myanmar, Indonesia, Malaysia, Vietnam, Laos, Cambodia, Philippines, Thailand, Japan, Bangladesh, South Korea, Sri Lanka, Nepal, and others.

The American region is home to over 530 species of bamboo. According to Clark et al. (2015), the three areas with the most significant species diversity, namely Brazil, the Central and Northern Andes highlands, and Mexico and Central America, collectively account for almost 90% of the species distribution. According to Ruiz-Sanchez and Clark (2018), Brazil has documented the most extensive range of bamboo diversity, with 256 distinct species. Following Brazil, the Andes region boasts over 130 species of bamboo. In comparison, Mexico and Central America have identified 87 bamboo species accordingly.

According to reports, Africa has the least diverse range of bamboo species compared to the Asia-Pacific and American regions. According to the research conducted by Bahru & Ding (2021), there are presently 115 bamboo species and 35 genera that are extensively distributed over 48 countries within the African continent. The dataset encompassed around 82.8% of the African landmass, accounting for approximately 7.3% of the global bamboo species diversity. The distribution of bamboo species in Africa includes a vast geographical range, extending from the western coast of Senegal to the eastern part of Mauritius. Furthermore, these bamboo species have expanded their presence from the northern region of Morocco to the southernmost point of South Africa.

2.1.3 Characteristics of Bamboo

Bamboo is a highly versatile material that can be used for a wide range of applications. Its versatility is due to the distinct characteristics that differ among species and culm heights (Liese, 1985; Mohmod & Mustafa, 1992; Razak, 1998). To fully utilise bamboo in various fields, it is essential to have a comprehensive understanding of its fundamental attributes, including its anatomical, physical, and mechanical aspects, as well as its chemical composition.

2.1.3.1 Anatomical Properties

The anatomical characteristics of bamboo have a significant correlation with several essential qualities, including physical and mechanical attributes, absorption of preservatives, and the properties of the final product. Bamboo culm is composed of internodes and nodes. The cells at the internodes have an axial orientation, whereas the cells at the nodes serve as transverse connectors. The internodes lack radial cell components, such as rays. The culm's outer layer comprises two layers of epidermal cells, with the inner layer visibly thicker and exhibiting a high degree of lignification. The outermost cells are characterised by a cutinised layer coated with a wax polymer of hydroxyl acids (Anokye et al., 2016). According to Liese (1980b), the composition of the culm consists of approximately 50% parenchyma, 40% fibre, and 10% conducting tissues, as shown in Figure 2.4, with slight variations observed across different species.

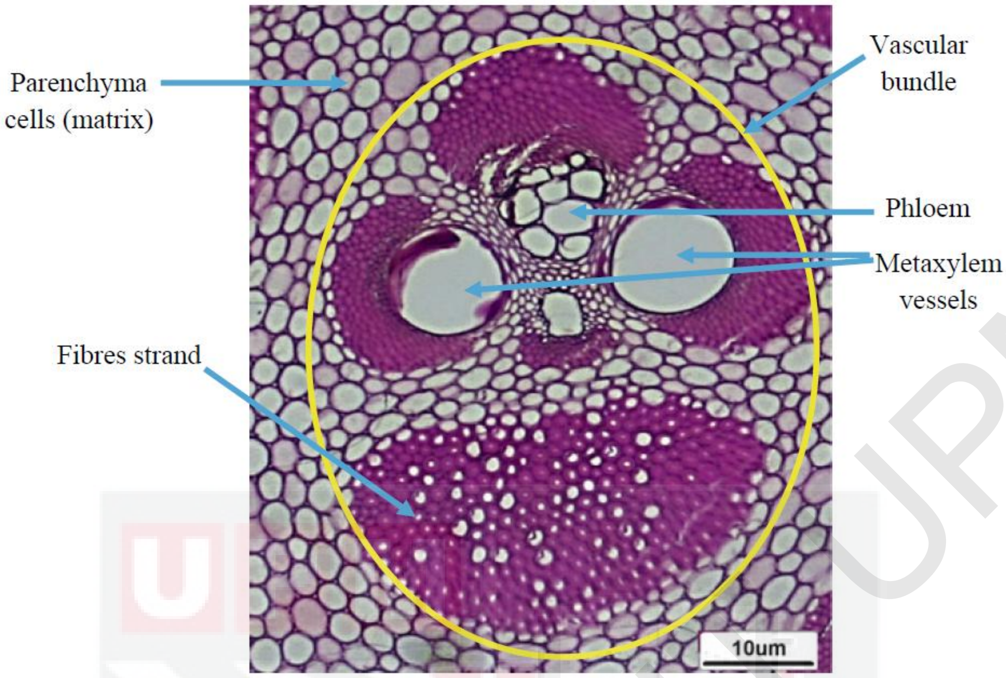


Figure 2.4: The Tissue of Bamboo Culm
(Source: Siam et al., 2023)

Vascular bundles commonly consist of vessels, sieve tubes and companion cells. The vascular bundles in bamboo serve as a structural reinforcement, providing support and strength (Liese, 1998). There are four types of vascular bundles as classified by Liese (1998), namely type I, II, III, and IV. Siam et al. (2023) reported that the presence of vascular bundles of type II, III, and IV characterises sympodial bamboo as in Malaysia.

The ground tissue of the bamboo culm consists mainly of parenchyma cells, characterised by predominantly vertical elongation, interspersed with shorter, cube-shaped cells. According to the studies conducted by Lian et al. (2020) and Chen et al. (2020), the composition and organisation of the parenchyma cell wall play a crucial role in bamboo plants' development and mechanical characteristics. This fact was explained by Elejoste et al. (2021), where the parenchyma tissue matrix undergoes lignification and hardening as the culm grows, leading to enhanced density and improved mechanical characteristics.

The fibrous tissue within the bamboo culm is of utmost significance, as it constitutes the primary source of strength within the culm (Castanet et al., 2016; Sukmawan et al., 2016). According to Liese (1998), these components comprise around 40-50% of the whole tissue and account for approximately 60-70% of the entire weight. The fibrous structures within bamboo plants are organised into clusters and protective coverings surrounding the vascular conduits. According to Liese (1998), the length of bamboo fibres surpasses that of hardwood fibres, although it falls short of the length exhibited by softwood fibres.

2.1.3.2 Physical Properties

The examination of bamboo's physical qualities is significant in comprehending its appropriateness for diverse applications, including building, furniture production, and manufactured composites. Anatomical features, such as fibre arrangement and the presence of vascular bundles, have been identified as critical elements in determining bamboo's physical qualities (Siam et al., 2019; Zakikhani et al., 2017).

Melo et al. (2014) have posited that the moisture content of bamboo has a discernible impact on its physical characteristics. The density of bamboo exhibits variation between different species, and the height of the culm also can be ascribed to its physical qualities. According to Appiah-Kubi et al. (2023), the physical characteristics of bamboo can vary based on its age and level of maturity, with mature bamboo often demonstrating superior features.

In addition to treatment, bamboo's dimensional stability and hardness may also be influenced (Xiao et al., 2022). The physical qualities of bamboo can be affected by its chemical composition, which includes the presence of hemicellulose, lignin, and cellulose (Xiao et al., 2022; Tan et al., 2019).

2.1.3.3 Mechanical Properties

Bamboo possesses unique mechanical properties compared to other materials, like wood. It has a tensile strength that is approximately two times more than of timber and its compressive strength is around 1.5 times greater than that of timber (Manik et al., 2022). In addition, bamboo exhibits a superior strength-to-weight ratio compared to both timber and mid steel (Verma and Chariar, 2012). These advantages make it desirable for various applications. Several influential elements can contribute to bamboo's mechanical properties, such as species, age, culm height, diameter and wall thickness, node structure, fibre distribution, processing, and treatment, as tabulated in Table 2.1.

Table 2.2.1: Physical and mechanical characteristics of commercial bamboo in Malaysia (Adapted from Siam et al., 2019)

Species	Culm Height (m)	Internode Length (cm)	Culm Wall Thickness (mm)	Density (Kg/m3)	MOR (N/mm^2)	MOE (N/mm^2)
Gigantochloa thoii	21	35	12	751	163	13,185
Gigantochoa scortechinii	21	42	10	641	125	10,039
Gigantochloa ligulata	18	37	12	442	180	10,800
Gigantochloa wrayi	18	38	12	628	201	10,783
Gigantochloa brang	19	40	14	536	159	11,894
Schizostachyum brachycladum	21	53	5	588	263	21,136
Schizostachyum grande	32	65	6	633	184	21,036
Schizostachyum zollingeri	22	55	4	355	143	9,717
Bambusa vulgaris	16	33	9	610	172	12,104
Bambusa blumeana	16	32	11	478	116	10,034
Bambusa heterostachya	20	41	9	531	120	10,028
Bambusa vulgaris cv vittata	30	33	11	546	176	10,294
Dendrocalamus asper	20	37	16	559	150	11,303

Variations in mechanical characteristics exist across different species of bamboo. These variations in mechanical qualities can arise from changes in factors such as culm density, fibre arrangement and chemical composition among different species (Zakikhani et al., 2017). On the other hand, the bamboo's age significantly influences its mechanical characteristics. According to D&C (2010), younger bamboo has more outstanding moisture content and poorer mechanical strength than mature bamboo.

Zakikhani et al. (2017) stated that the mechanical characteristics of bamboo exhibit variability along the culm's vertical axis, whereby the culm's bottom segment exhibits greater mechanical strength than the top segment. Besides that, bamboo's mechanical properties can also be influenced by the diameter and wall thickness, in which bamboo with greater thickness and diameter often exhibits enhanced mechanical strength (Javadian et al., 2019).

The structure of bamboo culms is defined by periodic nodes that possess an interior diaphragm and exterior ridge. As stated by Taylor et al. (2014), the culm nodes provide a biomechanical function by enhancing their rigidity and strength, mitigating structural collapse risk. Other than that, the mechanical qualities of the culm can also be influenced by the dispersion of fibres within it. The quantity and configuration of fibre strands inside the vascular bundles exhibit variability along the culm and between different species, influencing the overall mechanical characteristics (Zakikhani et al., 2017). Processing and treatment also play a crucial point as bamboo can undergo several processing and treatment techniques, including heat treatment or chemical treatment, which can substantially modify its mechanical characteristics (Javadian et al., 2019).

2.1.3.4 Chemical Composition

The primary constituents of bamboo consist of cellulose, hemicelluloses, and lignin, constituting about 90% of the overall mass (Alia Syahirah et al., 2023). The cellulose content in bamboo ranges from 40-50%, while the lignin content is typically around 25% (Mokeramin, 2020). In contrast, bamboo has been shown to possess higher alkaline extractives, ash, and silica levels than wood (Li et al., 2004).

The epidermal layer of bamboo has the most significant silica concentration, the nodes have less, and the internodes lack any silica content. According to Azeez and Orego (2018), certain bamboo species have a more outstanding ash content, potentially leading to complications in processing activities. Additionally, it is important to acknowledge that the chemical composition of bamboo varies among species and is influenced by factors such as the age of the culm, its position along the height of the culm, and its placement within the culm's wall (Sharma et al., 2018).

2.1.4 Application of Bamboo

Bamboo exhibits a high degree of versatility as a woody resource due to the multifunctionality of its various components, which can be effectively utilised for a wide range of applications. Figure 2.5 shows that a diverse range of items can be derived from every bamboo component. The bamboo culms are mainly categorised into four distinct portions: top, upper middle, lower middle, and base. According to Wu (2018), the uppermost sections of the culm account for around 5-10% of the overall volume, while the upper middle sections account for 30-40%, the lower middle sections contribute 40-50%, and the base sections account for 5-10% of the whole culm volume. Of these sections, the upper section was believed to have superior strength due to an augmented presence of vascular bundles, which serve as essential constituents that offer mechanical reinforcement and contribute significantly to the overall robustness of the plant (Siam et al., 2019).

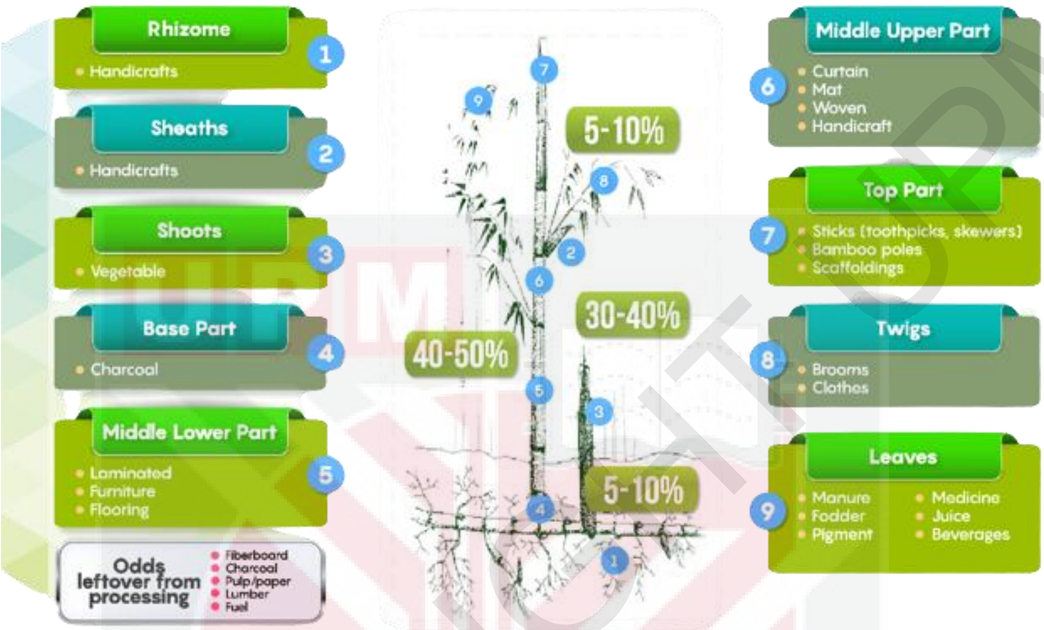


Figure 2.5: Bamboo Components
(Source: Wu, 2018)

The various features of bamboo, through its strength and durability properties, contribute to the extensive range of applications encompassing construction and craft materials and engineered bamboo products. Bamboo has been acknowledged as a viable substitute for traditional construction materials. According to Fahim et al. (2022), this material possesses essential strength characteristics and may even surpass the compressive strength of other materials like concrete. Bamboo has been employed in the architectural domain for the construction of residential structures, serving various purposes such as flooring, walls, ceilings, and roofing (Ameh et al., 2019). Fahim et al. (2022) further noted that the mechanical characteristics of bamboo, including its tensile strength, compressive strength, modulus of elasticity, and modulus of rupture, render it well-suited for implementation in structural applications.

Bamboo also finds frequent utilisation in the creation of craft products. According to Mulyana & Reorita (2022), the utilisation of yellow bamboo (Bambusa vulgaris var. striata) is persistently observed in the construction and crafting industries. Bamboo's strength and flexibility are among the reasons it is suitable for producing a wide range of products, including handicrafts and ornamental items.

In addition, engineered bamboo, or innovative bamboo products, has developed as a groundbreaking material derived from bamboo culms, exhibiting enhanced strength properties and increased durability (Sharma & Vegte, 2020). According to this researcher, novel products like parallel bamboo strands and laminated bamboo have been engineered to possess comparable strength to conventional bamboo while exhibiting enhanced uniformity in material qualities. This was proved by utilising engineered bamboo products in the global bamboo commodities in 2020, which account for 10% or USD 298 million (INBAR, 2022).

2.2 Properties of Semantan Bamboo (*Gigantochloa scortechinii*)

As stated by Mera & Xu (2014), the Asian-Pacific region comprises over 80% of the total bamboo forest areas and species worldwide. By zooming into Malaysia, The Malaysian Timber Industry Board (2021) reported that there are approximately 229,000 hectares of bamboo forests with 70 species have been recorded. According to the Forestry Department of Peninsular Malaysia (2014), there are about 13.21 million bamboo clumps, with the five most abundant bamboo species have been reported in Peninsular Malaysia, one of which is *Gigantochloa scortechinii* .

Gigantochloa scortechinii is initially can be found from Tampin, Negeri Sembilan, to the north of Peninsular Malaysia, along the Titiwangsa Range. It has now become naturalised and is found primarily in disturbed forest areas (Mohd Tamizi et al., 2019). It also can be found in Indonesia (Sumatera) and southern Thailand. This species is a widely used species for value-added product development. The Forestry Department of Peninsular Malaysia (2014) reported that this bamboo species is the most abundant in Malaysia, with a density of 0.91 clumps per hectare in Peninsular natural forest. It is also considered the most impressive tropical bamboo species for plantation (Himasree et al., 2017). The thick culm wall and uniform sizes of this species between nodes and internodes make it easy to cultivate and suitable for structural materials.

2.2.1 Physical Properties

To effectively process and utilise bamboo, understanding its physical properties is crucial. Researchers such as Liese (1985) and Hisham et al. (2006) have found that *Gigantochloa scortechinii* has longer and smaller vascular bundles in its outer zone, while the inner zone contains shorter and larger ones. Smaller vascular bundles are distributed more densely than larger ones, leading to increased density and mechanical strength in the outer zone, as determined by Liese (1985) and Zhou (2000). This indicates that fibre and ground parenchyma maturation begin on the outer edge and progresses inward, as noted by Itoh & Shimaji (1981).

In terms of moisture content, past studies (Hamdan et al., 2004; Hamdan et al., 2009; Anokye, 2015; Siam et al., 2019) reported that *Gigantochloa scortechinii* on nodes and internodes lose their moisture content along the culm from basal to middle and top of the bamboo, while the density showed an inverse trend with moisture content, indicating that the higher moisture content, the lower in density. In the view of dimensional stability, Anwar et al. (2005) and Anokye (2015) discovered that *Gigantochloa scortechinii* exhibited a limited differential radial and tangential shrinkage, which enhances the dimensional stability in comparison to wood.

2.2.2 Mechanical Properties

Gigantochloa scortechinii strips possess excellent bending properties, as evidenced by their modulus of rupture (MOR) and modulus of elasticity (MOE) values of 125 N/mm^2 and 10039 N/mm^2, as displayed in Table 2.1. These values are similar to those of some hardwood species, such as Nyatoh, which has a MOR of 113 N/mm^2 and a MOE of 16348 N/mm^2, as well as Kempas, with MOR and MOE values of 122 N/mm^2 and 18600 N/mm^2, respectively (Wahab, 2014). The superior strength properties of bamboo (*Gigantochloa scortechinii*) make it an ideal material for manufacturing structural laminated products like cross-laminated boards or laminated bamboo boards.

2.3 The Manufacturing Bamboo to Engineered Products

Round bamboo has unique properties that render it appropriate for various applications. This material is known for its strength-to-weight ratio, manipulability, visual appeal, and environmental sustainability (Su et al., 2021). Its properties make it useful in construction, interior design, and furniture making (Su et al., 2021).

However, round bamboo has various drawbacks, including inferior biological endurance and a tendency to crack (Lv et al., 2021). Using round bamboo as a structural part makes it difficult to ensure natural bamboo buildings meet industrialised mass production standards. This is owing to the lack of section homogeneity, the hollow section's bearing strength instability, and the difficulties of making trustworthy and ductile connections (Wang et al., 2017). Creating bamboo in shapes appropriate for structural uses has been of interest. This interest led to the creation of laminated bamboo, a rectangular board that can be utilised in any industrial process. The change may increase its mechanical properties (Sewar et al., 2022).

2.3.1 Types of Engineered Bamboo Products

Engineered bamboo refers to transforming bamboo culm into a board or timber based on its potential purpose. Various forms of engineered bamboo exist, including bamboo scrimber, ply bamboo and laminated bamboo lumber. Although bamboo is commonly utilised for scaffolding and supporting poles, the advent of engineered bamboo has expanded its potential usage as a material for architecture and structural purposes (Gharavi, 2019).

2.3.1.1 Bamboo Scrimber

Bamboo scrimber, known as Parallel Bamboo Strand, as described by Dixon & Gibson (2014), refers to a variant of engineered bamboo composite material produced by crushing bundles of bamboo fibres, impregnating them with resin, and subjecting them to high pressure to form a compact block (Figure 2.6). The rectangular structural part exhibits remarkable attributes, such as a higher bamboo ratio, an attractive grain pattern, and a comparable hardness and colour to hardwood (Sharma & Vegte, 2020).

Due to those characteristics, these products were viable alternatives to conventional building and furniture materials, establishing their market competitiveness (Huang et al., 2019).

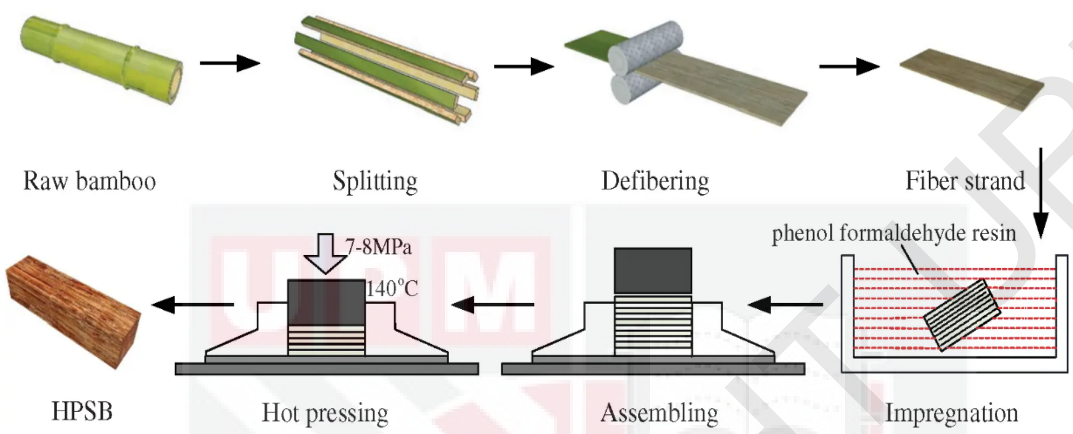


Figure 2.6: The Schematic of Manufacturing of Bamboo Scrimber
(Source: Sewar et al., 2022)

2.3.1.2 Laminated Bamboo

On the other hand, laminated bamboo products are becoming increasingly popular as a long shelf-life, cost-effective, and ecologically friendly alternative building material (Yadav et al., 2021). This product produced by laminating numerous layers of bamboo strips to establish a uniform shape and minimises the diversity of material characteristics (Sharma et al., 2015). According to past studies (Sharma et al., 2020 & Sharma et al., 2015), laminated bamboo has mechanical properties comparable to or superior to timber, showing potential in structural applications. As defined by researchers, several types of laminated bamboo lumber (LBL), glued laminated bamboo (glubam), and others can be utilised in various shapes and sizes. Figure 2.7 briefly shows the process of manufacturing laminated bamboo.

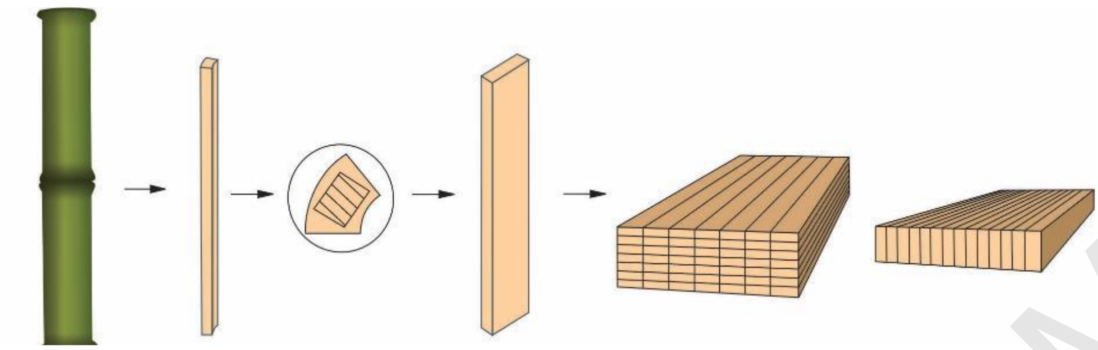


Figure 2.7: Schematic of the Manufacturing of Laminated Bamboo
(Source: Dauletbek et al., 2021)

a) Laminated Bamboo Lumber (LBL)

LBL effectively address the limitations associated with the inherent shape of bamboo by being manufactured into rectangular sections, which are better suited for utilisation in conventional structural applications. According to Mahdavi et al. (2011), LBL is a recent development that entails the adhesive bonding of bamboo material in different configurations, such as strands or mats, to create rectangular boards resembling traditional lumber. Several studies of LBL have been conducted by numerous researchers (Shen-xue et al., 2002; Nugroho & Ando, 2001; Lee et al., 1998). A study by Mahdavi et al. (2011) provided a comprehensive analysis, and the findings demonstrated the potential of bamboo as a viable alternative to wood in various structural applications.

b) Glued Laminated Bamboo (Glubam)

In addition, the other type of laminated bamboo, glubam has been developed as a novel laminated bamboo product by Xiao et al. (2008), demonstrating the cost-effective potential for utilisation as structural components. Glubam sheets, typically 20 to 40 mm thick, are fabricated using a method modified for plybamboo. They are then laminated to be manufactured into the structure of glubam components. Unlike ply bamboo, which is commonly employed in the construction industry for concrete formwork and flooring, glubam is manufactured with heightened standards, especially in the bamboo strip orientation, which aims to enhance the global sheets' mechanical qualities (Xiao, 2016).

2.3.2 Mechanical Properties of Laminated Bamboo

The utilisation of laminated bamboo in structural applications has the capacity to revolutionise the methods employed in building construction. Bamboo's fibrous microstructure can be represented as a composite material reinforced with fibres (Penellum et al., 2018). Due to this, considerable investigations have been undertaken on laminated bamboo's mechanical characteristics. According to Dauletbek et al. (2023) and Sharma et al. (2017), research has indicated that laminated bamboo possesses mechanical characteristics that are comparable to those of timber-based products, for instance, laminated veneer lumber, glulam, and cross-laminated timber (CLT) as shown in Table 2.2. Similarly, research conducted by Yang et al. (2020) has demonstrated that laminated bamboo has comparable levels of strength and rigidity to those observed in wood.

Table 2.2: Some mechanical properties of laminated bamboo and wood products

Product	Bending strength parallel to grain (MPa)	Modulus of elasticity (MOE) in bending (MPa)	Tensile strength parallel to grain (MPa)	Modulus of elasticity (MOE) in tension parallel to grain (MPa)	Compressive strength parallel to grain (MPa)	Modulus of elasticity (MOE) in compression parallel to grain (MPa)	Shear strength parallel to grain (MPa)	Reference
Laminated bamboo	63.87 – 128.4	8320 – 10912	90 – 124	10700	29.55 – 72.60	8396 – 11022	7.15 – 17.5	(Chen et al., 2020; Jorissen et al., 2007; Li et al., 2019; Li et al., 2016; Ni et al., 2016; Sharma et al., 2015)
Laminated Veneer Lumber	54.2 – 71.7	15400 – 19300	88.5	13790	36	-	7.34	(Chen et al., 2020; Forest Products Laboratory, 2021; Huang et al., 2019; Zhang et al., 2018)
Glulam	48.74	15370	16.5 – 26	9400 – 11900	24 – 31	8600	2.7 – 4.3	(Marx & Moody, 1981; Sousa et al., 2013; Zhang et al., 2018)
Wood Plastic Composite	26.1	4100	11.6	3000	28.1	3700	8.1	(Hugot & Cazaurang, 2009)
Cross-laminated timber	27 – 36	10740 - 12369	-	-	28.1 -29.0	4787.5 - 5304.2	-	Yusof et al., 2019

Rittironk and Elnieri (2008) noted that laminated bamboo has similar stiffness but greater strength when compared to several widely used wood species, including Spruce, Douglas fir, and Birch. In addition, previous studies on laminated bamboo for structural applications have examined that several properties of laminated bamboo, such as the fabrication process, equilibrium moisture content, and preservative treatment, can influence the mechanical properties (Li et al., 2016; He et al., 2015; Sharma et al., 2015).

According to Sharma et al. (2015), laminated bamboo exhibits similar behaviour to wood when subjected to tension. Through failure mode analysis, it was reported that laminated bamboo undergoes elastic deformation but is prone to brittle failure. Regarding the bamboo wall section, it was noted that the middle bamboo wall section has more robust tensile behaviour Rassiah et al. (2014) than the outer and inner layers, which suited the manufacturing of laminated bamboo.

Li et al. (2013) studied the assessment of laminated bamboo's compressive performance and observed an increase in both mean and characteristic compressive strength modulus resulting from the bamboo's height. The researchers further observed that the compressive behaviour of the laminated bamboo exhibits a tri-linear pattern, which commences with an initial elastic response followed by a combination of elastic-plastic deformation and ultimately culminates in significant plastic deformation. Nevertheless, in contrast to the behaviour shown under stress, it has been demonstrated that this material exhibits increased ductility (He et al., 2015).

2.4 Cross-laminated Bamboo (CLB)

2.4.1 Concept of CLB

Cross-laminated bamboo (CLB) is an inventive material that arranges and adheres bamboo strips in alternate orientations (Agustina et al., 2015). According to the researcher, the benefit of CLB is the material's ability to be manufactured into sizeable panels, resulting in improved structural integrity and robustness. Besides, CLB products are anticipated to exhibit dimensional stability, as the shrinkage expansion ratio in the length and width direction is expected to equal one. Furthermore, the researcher described that the alternate direction of the layers facilitates the even distribution of load across all surfaces, especially for the wall and flooring application. Therefore, to achieve the most favourable strength values in such applications, it is essential to suit the strength value of CLB according to the thickness and orientation of each single layer. Figure 2.8 shows the manufacturing process of CLB.

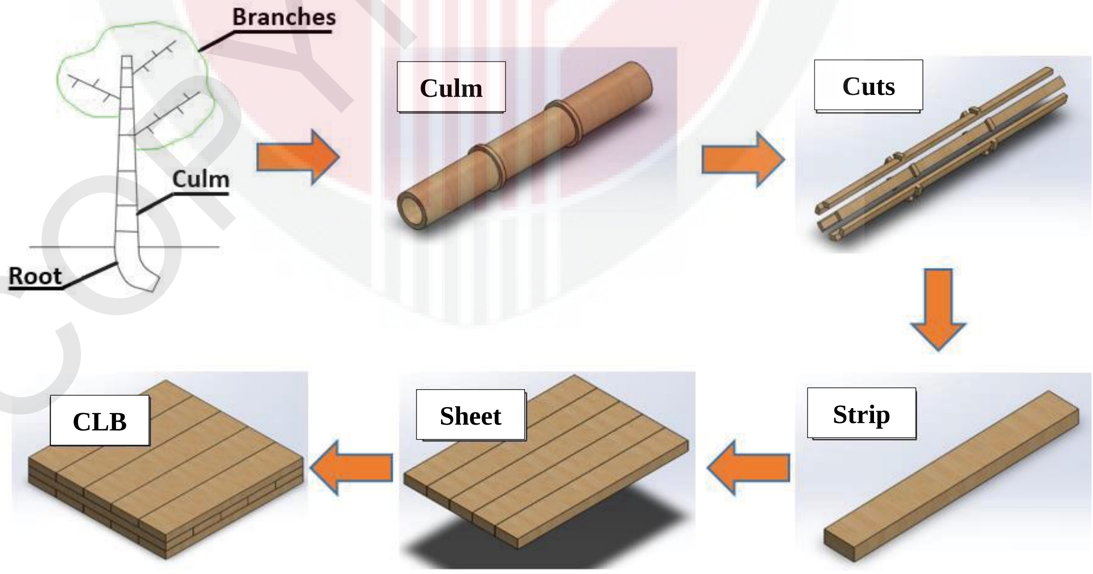


Figure 2.8: The Manufacturing Process of CLB
(Source: Castaneda & Bjarnadottir, 2016)

2.4.2 Prospective Application on CLB as a Structural Application

The prospective applications of CLB as a structural material are diverse and promising, offering numerous advantages in various construction projects. Among the prospective applications are residential construction, prefab and modular houses, interior applications and others. In those applications, bamboo holds significant promise, driven by its unique combination of strength, sustainability, and versatility. The potential use of CLB as a structural application can be categorised as structural beams and columns, girders, flooring, roof trusses, bridges and other load-bearing structural members (Gharavi, 2019).

2.4.3 Research on CLB as a Structural Application

Typically, the mechanical characteristics of natural bamboo can be likened to those of mild steel, cast iron, aluminium alloys, and wood (Ashraf et al., 2021; Su et al., 2021; Li et al., 2020; Yang et al., 2020; Jin et al., 2017; Huang et al., 2016; Mahdavi et at al., 2011) especially with regards to its tensile properties as shown in Table 2.3. These characteristics, along with laminated bamboo's exceptional mechanical qualities, as shown in Table 2.2, have led researchers to explore deeper potential of another type of laminated bamboo, such as cross-laminated bamboo, in structural applications.

Table 2.3: Several mechanical properties of bamboo and structural reinforced materials

Material	Yield strength (MPa)	Tensile strength (MPa)	Tensile modulus (GPa)	Reference
Bamboo	201	309	277	Dauletbek et al., 2022; Kewei et al., 2022
Steel	442	620	207	Chen et al., 2016; Adewuyi et al., 2015; Li et al., 2020
Glass Fibre Reinforced Plastic	680	3100 – 4150	57 – 86	Weber et al., 2022; Rosyidah et al., 2018; Zhang et al., 2008
Carbon Fibre Reinforced Plastic	-	3500 – 6000	230 – 600	Truong et al., 2019; Zhang et al., 2008
Aramid Fibre Reinforced Plastic	-	1540 – 3400	70 – 140	Truong et al., 2019; Zhang et al., 2008; Wardle et al., 2000
Basalt Fibre Reinforced Plastic	-	3000 – 4840	79 - 93	Kampmann et al., 2021; Truong et al., 2019; Zhang et al., 2008; Wardle et al., 2000;

Several studies have been conducted, and insights regarding the potential of CLB have been found. In a study by Sharma et al. (2015), a comparison was made between cross-laminated bamboo, structural timber, and laminated veneer lumber. This comparison aimed to showcase the possible applications and practical use of cross-laminated bamboo. The research emphasised that cross-laminated bamboo composites have mechanical qualities comparable to conventional structural materials, rendering them well-suited for architectural and structural purposes.

On the other hand, Agustina et al. (2015) investigated the characteristics of CLB as a structural material. Compared to cross-laminated timber (CLT), the study resulted in higher compressive strength with a value of 434 kg/m^3 compared to 245 kg/cm^3 of CLT value. The result showed a positive outcome towards utilising CLB as a structural material. Another study was conducted by Lv et al. (2021) to investigate the CLB as a wall application on seismic performance, showing that the analytical model is suitable for predicting the behaviour of the CLB rocking wall under cyclic stress. The comparative analysis demonstrated the analytical model's potential use in the engineering design context, indicating its suitability for practical implementation.

Xiao et al. (2019) explored the development of a combination of cross-laminated bamboo and timber (CLBT) panel as a complement to other wood-based products such as glulam and CLT. In their study, they found that CLBT performed well in pilot testing for manufacturability and mechanical performance as building slabs and panel. Based on those findings, with further examination, CLB has the potential to compete with established engineered wood products such as CLT as structural material, particularly in the context of load-bearing components.

2.5 Factors Influencing Laminated Bamboo Properties

Multiple factors influence the characteristics of laminated bamboo, including species utilisation, pretreatments, bamboo density, preservative treatment, adhesives, configuration layup and others.

2.5.1 Bamboo Species

The selection of bamboo species significantly impacts the process of obtaining raw materials and the subsequent performance of the product. This is mostly due to the considerable morphological variances observed across different bamboo species (Kelkar et al., 2023). Chemical and microstructural changes in various species have been related to this phenomenon (Kamruzzaman et al., 2008). The differences have an impact on both the mechanical properties of the composites as well as the determination and effect of the chemical and mechanical processing parameters (Huang et al., 2019).

Numerous research has been conducted to examine the viability of different species for the production of laminated bamboo. For instance, Sulastiningsih and Nurwati (2009) reported that species of *Gigantochloa apus* Kurz and *Gigantochloa robusta* Kurz had a notable impact on the characteristics of the laminated bamboo. Similar findings were found by Xie et al. (2013), Huang et al. (2019), Kelkar et al. (2021) and Kumar & Mandal (2022) on the diversity of the physical and mechanical properties of laminated bamboo prepared from *Phyllostachys edulis* J.Houz, *Dendrocalamus latiflorus* Munro, *Bambusa bambos* (L.) Voss, *Bambusa vulgaris* Schrad and *Guadua angustifolia* Kunth. It is believed that anatomical characteristics such as lumen diameter, length of fibre and fibre cell wall thickness play a role in determining water absorption and flexural characteristics, as discussed by Huang et al. (2019).

2.5.2 Density

Bamboo, an inherently porous material characterised by many hydroxyl groups, can absorb moisture and water via hydrogen bonding. Moreover, it has been shown that the capillaries and pores present in bamboo have sponge-like properties, facilitating the permeation of water (Khalil et al., 2012; Abdullah et al., 2012). Nevertheless, when the density was augmented, the structure exhibited enhanced uniformity and closure, accompanied by more effective bonding sites. Consequently, a decrease in water absorption was observed (Yu et al., 2017). In a study conducted by Shah et al. (2015) on the thermal conductivity of laminated bamboo, the findings revealed a significant positive relationship between thermal conductivity and density. The increasing result observed may be ascribed to a concurrent increase in the amount of solid cell wall material, which possesses a relatively higher conductivity, and a decrease in the total volume of pores (Mounika et al., 2012).

2.5.3 Preservative Treatment

Like wood, bamboo products are significantly impacted by any fungus, commonly categorised as brown-rot, white-rot and soft-rot fungi (Wang et al., 2000; Xu et al., 2013). At the same time, powder post beetles, termites and borers are among the primary organisms responsible for the biodegradation of bamboo and bamboo-based products (Rust and Su, 2012). To prevent the deterioration of these products, applying preservative treatment is advisable and has a notable impact on the characteristics and attributes of laminated bamboo. Among of the method for preservation is by using chemical preservative. According to Reynolds et al. (2019), chemical preservatives have the potential to enhance the longevity and resilience of bamboo by mitigating degradation and insect infestation, thereby prolonging its functional lifespan.

Chemical preservative is generally can be categorised as oil-borne and water-borne, with water-borne fixed type preservatives being the preferred choice for outdoor applications (Prance & Findlay, 1986). The water-borne preservatives contain fixation salts, which serve to reduce the leaching of hazardous elements like arsenic, fluorides, copper and boron from the bamboo, thus effectively binding these elements within the bamboo (James et al., 2019). This will lead to the desirable attributes of an optimal preservative that exhibit toxicity towards intended organism while demonstrating minimal impact on non-target organisms, ought to process the capability to permanently adhere within the bamboo, demonstrate high penetration ability into the bamboo tissues, possibly increase the strength of the bamboo (Liese & Kumar, 2003). Environmentally benign and water-borne preservatives possess these desired properties as they effectively infiltrate the tissue, thus providing protection (Handana et al., 2020). Among water-borne preservatives are copper chrome arsenic (CCA), copper chrome boron (CCB) and boron.

Nevertheless, the impact of such preservative treatments on the characteristics of laminated bamboo may differ based on the particular treatment method employed and the specific mechanical attributes under examination. The use of boron improves its resistance to biological durability. However, this treatment may also impact the physical and mechanical properties of bamboo. Studies have shown that mechanical strength in boron-treated bamboo was increased by 30% compared to untreated samples. Similar results also obtained by Grnanaharan et al. (1995) and Handana et al. (2020) on the increasing of mechanical strength on boron-based preservative treatment. On the contrary, wood treated with boron has lower mechanical strength compared to untreated wood (Ayrilmis et al., 2005; Colakoglu et al., 2003). Another study by Simsek & Baysal (2015) discovered that boron treatment led to an increase in surface roughness, density and modulus of elasticity (MOE) of the treated wood. In terms of bonding strength, Ayden and Colakuglu (2006) observed a decrease in the adhesive strength of alder and beech plywood panels bonded with boron-based preservatives. Similar with Özçifçi et al. (2007) discovered that boron-based preservative has a detrimental impact on the wood strength bonded with phenol formaldehyde.

Due to the toxicity of arsenic in copper chrome arsenic (CCA), the industry has transitioned towards the utilisation of CCB which is also known as waterborne preservative (Shanu et al., 2015). According to the researcher, this shift is driven by its markedly improved safety profile and the potential for reduced environmental impact. The utilisation of this preservative as reported by (Tame et al., 2007) forms chemical bonds with compounds found in the material. It is believed that copper ions liberated from preservative solutions can bind specific functional groups present in wood polymers, such as hydroxyl and methoxy groups. The reactivity of chemical elements used as preservatives, therefore can impact the qualities of materials and have a negative effect on traits like mechanical strength and adhesion (Faria et al., 2020). However, this preservative has varying effects on the strength. Amaral et al. (2023) and Luis et al. (2016) observed that CCB has decreased the density compared to untreated bamboo. Meanwhile, some studies found the increasing of the mechanical strength after CCB preservative treatment (Gauss et al., 2019; Shanu et al., 2015; Icimoto et al., 2013). In terms of bonding strength, Temiz et al. (2016) reported that copper preservative like CCB have the ability to prevent adhesion and decrease bond performance. This is evident from study by Faria et al (2020) and Temiz et al. (2015) who observed a decrease in adhesion and bonding strength in wood treated with CCB.

2.5.4 Adhesive and Spread Rate

The adhesive properties can significantly affect the bonding performance of laminated bamboo especially when it is used as structural application. Due to bamboo's unique characteristics, such as its high silica content and varying moisture levels, achieving uniform and long-lasting adhesive connections can be challenging. Several key parameters that have been identified influence adhesive bond are adhesive type and glue spread rate (Sewar et al, 2024). These factors can contribute to the impact of strength and overall quality of bonding properties of laminated bamboo (Sewar et al., 2024).

According to Xiao (2014), most engineered bamboo composites are primarily manufactured with phenol resorcinol (PF) adhesives due to their cost-effectiveness, durability and wide availability. Nevertheless, there are also widely used adhesives such as emulsion polymer isocyanate (EPI), polyurethane (PUR), melamine-urea-formaldehyde (MUF), hybrid polymer adhesive (HPA) and polyvinyl acetate (PVAc) that has been evaluated for manufacturing cross-laminated bamboo as reported by Xing et al. (2019). According to their research, the MUF adhesive performed the most effectively, whereas EPI adhesive was considered inadequate for glueing bamboo. Despite those adhesives, another adhesive commonly used in structural applications industrially is phenol resorcinol formaldehyde (PRF). Various studies using this adhesive has shown the impact on laminated bamboo's mechanical and bonding properties. A study conducted by various researchers (Yusof et al., 2023; Yusof et al., 2019; Ammann et al., 2014; Kurt, 2015; and Konnerth et al., 2007) discovered that PRF is a superior adhesive for laminated bamboo resulted to higher bonding strength and more reliable performance than other adhesives.

Besides adhesive, the spreading rate is crucial as it ensures that the adhesive is evenly dispersed and forms a thin layer when pressure is applied to the bonding surface. Several studies have investigated the spread rate of glue in laminated bamboo, with researchers such as Ogunsanwo et al. (2019), Correal et al. (2010), Nugroho et al. (2001) examining spread rates ranging from 80 g/m2 to 300 g/m2. Among these rates, the most recommended for achieving higher bonding strength is 300 g/m2. This finding also supported by Yusof (2018) who observed that higher adhesive spread rate leads to an increase in bonding strength. Therefore, it is essential to select the optimal spread rate to ensure the stability and integrity of the lamination structure under applied load.

2.5.5 Layup Pattern

Generally, there are several factors that affect the strength and stiffness of laminated bamboo, with the most discussed being bonding influences (Ariffin, 2005). However, the orientation of the bamboo strips and layup pattern also contributes to its strength. This statement can be observed in several studies, including Kariuki et al. (2014) and Akinbade et al. (2020), who discussed the impact of flexural strength due to the orientation and arrangement of bamboo strips on the structural laminated bamboo beam. A further assessment by Akinbade et al. (2020) revealed that the behaviour of the bent bamboo culm wall strips varies based on their orientation, which is determined by the structure of the wall. A deeper investigation verified that the systematic arrangement of bamboo strips according to fibre volume serves as a convenient and readily measurable indicator of the relative material qualities across different culms or species, as discussed by Harries (2023).

Research by Yang et al. (2020) and Verma and Chariar (2012) also showed a similar observation on the strength performance. Yang et al. (2020) observed that parallel orientation showed superior compression performance, exhibiting a 70% higher compared to perpendicular orientation. Verma and Chariar (2012), on the other hand, stated that the arrangement of layers had a significant impact on the mechanical properties, resulting in 20% higher in parallel orientation particularly in tensile and compressive strength. In another research, Agustina et al. (2015), found that thickness along with layup pattern can be main factor attributed to the mechanical properties with thicker board increased the strength. The study found that 13.3 mm bamboo board resulted in higher bending than 10 mm and 8 mm, respectively.

2.6 Summary

This chapter provided an insight into the advantages of bamboo as a substitute raw material for wood. With an abundance of raw materials worldwide and its unique characteristics across physical and mechanical properties, bamboo has a potential source for the development of value-added products. Despite its superior strength properties, bamboo has not been widely utilised in structural applications due to the variance in diameter across the culm and the inefficiency in forming strong connections due to its inherent hollow shape. To address this issue, laminated bamboo is preferable as it is rectangular and easy to utilise in any structural work. Nevertheless, there are various types of laminated bamboo that have been studied, with most focusing on parallel orientation. Past studies show that bamboo is stronger in the direction parallel to the grain and weak in the direction perpendicular to the grain. Therefore, manufactured bamboo in the cross-laminated direction will benefit the material integrity and demonstrate dimension stability.

However, the performance of cross-laminated bamboo (CLB) using various configuration layups should be assessed to evaluate its suitability for structural applications. Various angle studies, consisting of treatment, adhesion and bonding properties, and layup patterns, are discussed in this thesis. It is hoped that the study can provide benefits to the industries in the use of value-added bamboo in structural applications.

CHAPTER 3

THE EFFECTS OF PRESERVATIVE TREATMENT ON THE PHYSICAL AND MECHANICAL PROPERTIES OF A BAMBOO STRIPS

3.1 Introduction

Bamboo is one of the potential alternative raw materials to be used for a variety of applications, particularly as a structural material (Sharma et al., 2015). It is frequently converted into strips or thin flat laminae to produce laminated products due to its hollow cylindrical features (Edi Suhaimi et al., 2019; Zaidon et al., 2016). To ensure the long-term viability of the bamboo applications, bamboo must be preserved to protect it from harmful organisms and to extend its lifespan (Rabbi et al., 2015). Despite the availability of numerous preservatives, waterborne preservatives are frequently used in treatment due to their advantages and effectiveness (Smith, 2020). The most widely used are boron and copper chrome boron (CCB) (Siti Rafedah et al., 2020). In addition, these preservatives have also been widely utilised by the bamboo industries in Asia and other bamboo regions for a variety of product applications, including structural purposes (Jivkov et al., 2021; Kaminski et al., 2016; Liese & Tang, 2015).

Boron is an effective preservative in treating bamboo, but its use is restricted to dry and interior applications as it can leach out when exposed to rain (Liese & Tang, 2015). In contrast, CCB is better suited for exterior applications due to its better fixation and weather resistance (Gauss et al., 2020; Shanu et al., 2015). The use of appropriate preservatives with promising strength values, particularly for structural purposes, has been highly desired. There have been limited studies evaluating the treatment effectiveness of boron and CCB on *Gigantochloa scortechinii* bamboo strips, particularly for such applications. Several studies reported that boron-based preservative treatment improves the physical properties of a material by increasing density and dimensional stability (Aristri et al., 2021; Baraúna et al., 2021; Gecer et al., 2015). A similar positive trend was reported for the mechanical properties of treated materials when compared to untreated specimens (Norhasliya et al., 2018; Percin et al., 2015), and vice versa as reported by De Souza Almeida et al. (2019) and Kartal et al. (2008). In another study conducted by Gauss et al. (2019), the mechanical properties of boron-based treated moso bamboo culms were not affected by the treatment.

Therefore, the main objective of this chapter was to investigate the impact of boron and CCB treatment on the physical and mechanical properties of *Gigantochloa scortechinii* bamboo strips. The variables examined in this study and study research flowchart are depicted in Figure 3.1. The specific objectives of this study were:

i) To evaluate the treatability of bamboo strips through retention, penetration and FTIR analysis

ii) To examine the physical properties of untreated and treated bamboo strips, including moisture content, density and shrinkage/swelling

iii) To assess the mechanical properties of untreated and treated bamboo strips by evaluating the static bending and compression

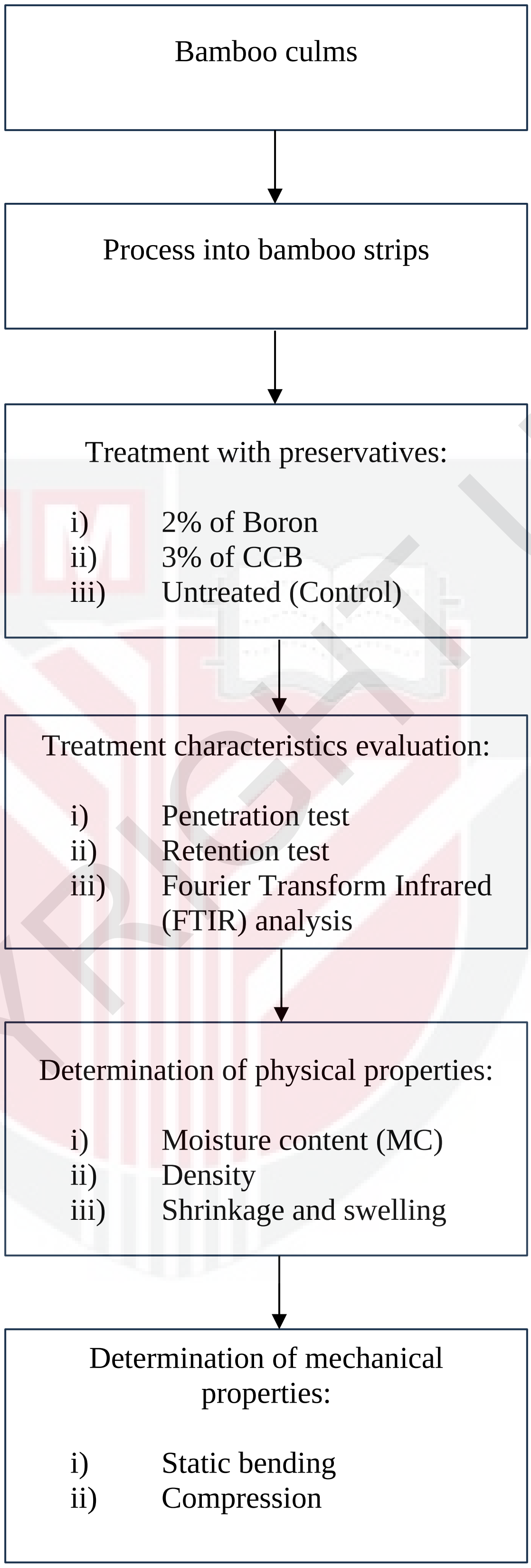
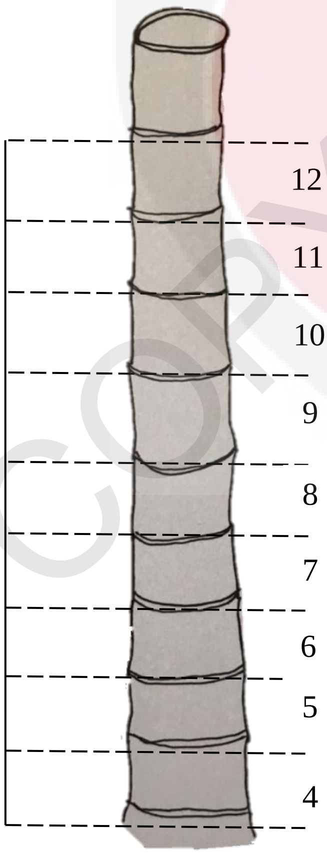


Figure 3.1: Study Research Flow Chart in Chapter 3

3.2 Materials and Methods

3.2.1 Preparation of Materials

Twenty mature bamboo culms of *Gigantochloa scortechinii* were selected from Hulu Langat, Selangor. Each culm was cut about 10 to 15 cm above the ground level, and only eight feet were taken. The culms were air-dried for two weeks to reduce their moisture content before proceeding to the processing stage. Only the basal portion of the bamboo culms was used in this study. The selection is based on the wall thickness compared to other portions, making it suitable for producing bamboo strips with the preferred thickness size. The same portion will also be used in other studies in Chapters 4 and 5. The process for segregating the internodes for this purpose is described in Figure 3.2.



Notes:

Internodes	:	Tests
4 – 7	:	Retention, penetration, and physical properties
8 – 12	:	Mechanical properties

Figure 3.2: Segregation of Bamboo Culm for Testing
(Adapted from Anwar et al., 2005)

The air-dried bamboo culms were cut into bamboo splits using a splitter machine and subsequently processed into bamboo strips using a thicknesser planner (Figure 3.3). The final size of the prepared samples was 2400 mm x 20 mm x 5 mm (Figure 3.4). The samples were then air dried until their moisture content (MC) reached <15% and then conditioned at a temperature of 20 ± 2 °C and at a relative humidity of 65 ± 5 % to reach 12%. The samples were divided into two groups: untreated (control) and treated.

(a) (b)

Figure 3.3: Bamboo Strips Process using (a) Bamboo Splitter and (b) Thicknesser Planner

(a) (b)

Figure 3.4: Images of Bamboo Strips from (a) Top View and (b) Thickness

3.2.2 Treatment of Bamboo Strips with Preservatives

The prepared bamboo strips were divided into two groups: untreated, which serves as a control, and treated samples. For the treated samples, two preservatives, boron and CCB (Figure 3.5), were used at concentrations of 2% and 3%, respectively, in accordance with the manufacturer's recommendations. Before treatment, the samples were cut based on the segregation of internodes (Figure 3.2), with reference to the testing size for each test that will be carried out.

(a) (b)

Figure 3.5: Preservatives Used (a) Boron and (b) Copper Chrome Boron (CCB)

The preservative preparation involved diluting 5 kg of Boron in 250 litres of water, while CCB was prepared by diluting 75 litres of CCB in 250 litres of water to achieve 2% and 3% solution concentrations, respectively. The bamboo strips were placed in a container for the treatment process using the vacuum chamber method (Figure 3.6). The treatment was carried out in three stages: initial vacuum, application of pressure, and final vacuum. The complete treatment cycle can be described as follows:

i) Initial vacuum : > 85kPa for 30 min (to take the air out of the bamboo)

ii) Applying Pressure : > 1300kPa for 60 min after the preservative solution was introduced into the treatment cylinder

iii) Final vacuum : > 85kPa for 20 min (to remove the access preservative from the bamboo)

Figure 3.6: Treatment Process using Vacuum Chamber

Following the treatment, the samples were removed and subjected to oven-drying at 50 °C for two days. Subsequently, they were placed in a conditioning room at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 % to attain a moisture content of 12%.

3.2.3 Treatment Characteristic Evaluation

3.2.3.1 Retention and Penetration

To evaluate the amount of preservatives absorbed by the samples, two types of treatment evaluation methods were used in this section: weight percent gain (WPG) and net dry salt retention (NDSR). For these evaluations, 20 specimens for each treatment were cut to the size of 300 mm x 20 mm x 5 mm. The weights and dimensions of all specimens were measured before treatment. After treatment, the excess solution was drained off for 30 min. Ten specimens from each treatment were placed in an oven at 103 ± 2 °C for 24 h until they reached a constant weight for WPG analysis. The remaining ten specimens from each sample treatment were conditioned at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 % until a constant weight was achieved to determine NDSR. Treatment characteristics were evaluated using WPG and NDSR by calculating the weight difference before and after treatment for the same specimens using the equations as below (Equation 3.1 and Equation 3.2):

$$\text{WPG (\%)} = \left(\frac{W_t - W'}{W'}\right) \text{x } 100 \qquad \textbf{[Equation 3.1]}$$

Where, W_t is the weight of the treated specimen and *W'* is the weight (g) of oven-dried of bamboo strips.

$$\text{NDSR (kg/m}^3\text{)} = \left(\frac{W_t - W_u}{V}\right) \text{x treating solution concentration} \qquad \textbf{[Equation 3.2]}$$

Where, W_t is the weight of the treated specimen, W_u is the weight (g) of the initial specimen, and V is the volume (m^3) of the treated specimen.

An additional evaluation of treatment characteristics was conducted by using the penetration method. This method involved two dried specimens from each treatment, cutting them into lengths of 20 mm x 20 mm and spraying them with two different chemical reagents as a qualitative test to evaluate the depth of penetration in the treated samples. The chemical reagents used included Azurol S for copper detection in CCB preservative and Curcumin for boron detection (Figure 3.7).

Figure 3.7: Chemical Reagents Used in Qualitative Test

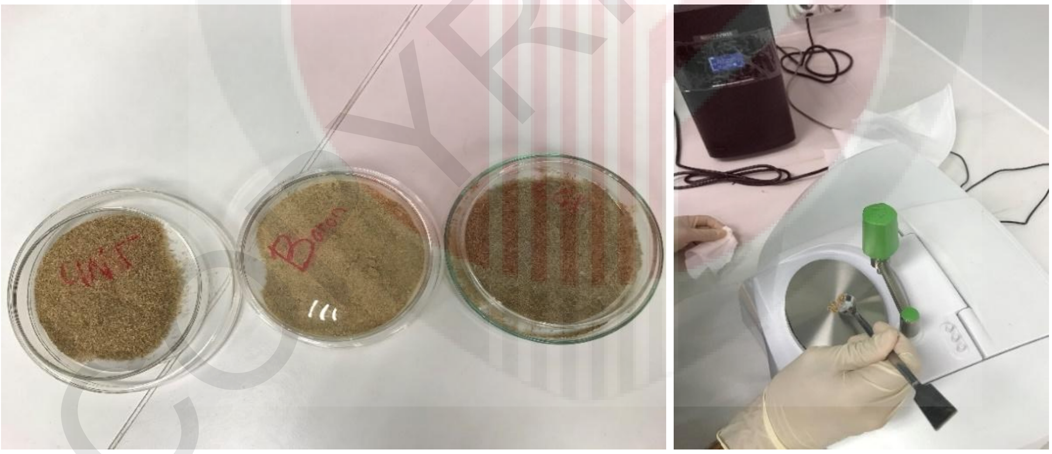
Copper was tested using a solution of Chrome Azurol S and sodium acetate mixed in water. Meanwhile, the penetration of boron was analysed using a curcumin solution composed of turmeric powder and ethyl alcohol (10% wt/vol alcohol). The presence of boron was indicated by a red colour, while a blue colour indicated the presence of copper. The penetration pattern was analysed by referring to MS 833 (1984), as detailed in Table 3.1.

Table 3.1: Visual classification of preservative penetration according to MS 833

Penetration	Grading	Condition
Nil	1	No penetration
Slight	2	Less than 25% of the cross-sectional area penetrated
Moderate	3	25% - 50% of cross-sectional area penetrated
Heavy	4	50% - 75% of cross-sectional area penetrated
Complete	5	75% - 100% of cross-sectional area penetrated

3.2.3.2 Fourier Transform Infrared (FTIR) Analysis

Three specimens from each treatment, each with dimensions of 300 mm x 20 mm x 5 mm, were ground into particles using a Wiley machine and then placed in a shaker with sieves of 40-60 mesh. The particles that remained by the sieves were reserved for FTIR testing to analyse their chemical content (Figure 3.8).



(a) (b)

Figure 3.8: (a) Bamboo Particles for Each Treatment, (b) ATR-FTIR Machine

3.2.4 Determination of Physical Properties

Three types of tests were conducted to study the physical properties of both control and treated bamboo, taken from internodes 4 – 7 (Figure 3.2). The preparation of samples and the procedures for determining density and moisture content followed the Indian Standard of Method of Tests for split bamboo IS 8242 (1976), as described by Anwar et al. (2005). The tests for shrinkage and swelling were carried out according to ISO 13061-13 (2017) and ISO 13061-15 (2017), respectively.

3.2.4.1 Density

Density is defined as mass per unit volume. In this test, ten specimens of each untreated and treated bamboo were cut into sizes of 25 mm x 25 mm x 5 mm. For each specimen, the dimensions and initial weight were measured before they were conditioned at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 % until the weight reached a constant value using a digital balance (with a precision of 0.01 g). The volume of the specimens was calculated by measuring the dimensions using a calliper to the nearest 0.01mm. The density of the specimens was then calculated using Equation 3.3 as follows:

$$\text{Density } (\text{kg}/m^3) = \left(\frac{W}{V}\right) \qquad [\textbf{Equation 3.3}]$$

Where, *W* is the initial weight (g) and *V* is the volume of the specimen (mm^3).

3.2.4.2 Moisture Content

The moisture content (MC) was determined by the differences between the weight of the green sample and the weight after oven drying. A total of ten specimens for both control and treated samples were cut into sizes of 25 mm x 25 mm x 5 mm. The specimen weights were measured, and then they were dried in an oven at a temperature of 103 ± 2 °C for 24 hours. The oven-dried weights were recorded at regular intervals until a constant weight was reached, indicated by a variation of no more than 0.002 g. The specimens were then allowed to cool in a desiccator before their final weights were measured. The MC was expressed as a percentage, and the equation was determined using the following formula:

$$\text{MC (\%)} = \left(\frac{W-W'}{W'}\right) \times 100 \qquad \textbf{[Equation 3.4]}$$

Where, W is the initial weight of bamboo strips (g) and W' is the weight of oven-dried bamboo strips (g).

3.2.4.3 Dimensional Stability

The test for the determination of radial and tangential shrinkage and swelling was conducted according to ISO 13061-13 (2017) and ISO 13061-15 (2017), respectively. A total of 20 specimens from both the control and treated sample groups, each measuring 20 mm x 20 mm x 5 mm, were used in this test. Before the test, all specimens were marked on both faces to determine the radial and tangential directions, facilitating dimensional measurement. The directions for radial (R), tangential (T) and longitudinal (L) are depicted in Figure 3.9, where the thickness of the culm's wall represents the radial direction, while the width and length denote the tangential and longitudinal directions, respectively.

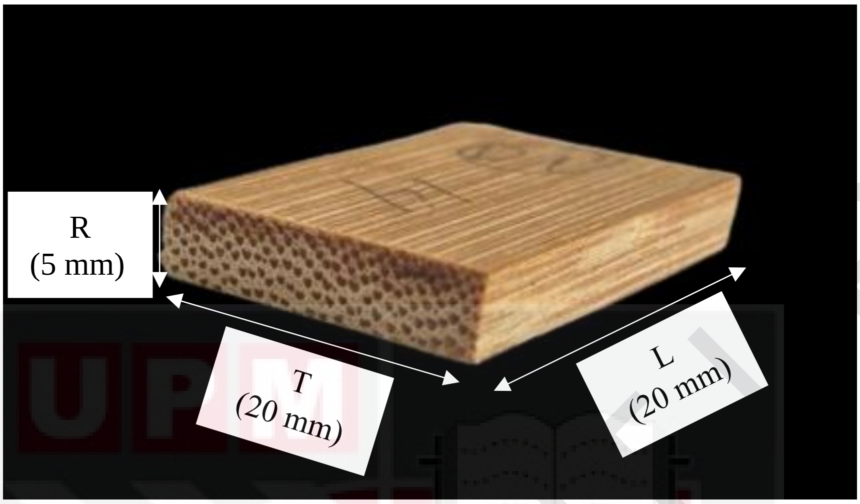


Figure 3.9: Dimensional Measurement on Radial (R), Tangential (T) and Longitudinal (L) of Bamboo Strip for Swelling and Shrinkage Evaluation

a) Swelling Test

For the swelling test, the specimens were oven-dried at a temperature of 103 ± 2 °C for 24 hours. The weight and dimensions of the specimens in radial and tangential directions were measured every eight hours, ensuring that the difference between two successive weighings did not exceed 0.2% or the difference in dimension did not exceed 0.02 mm. Subsequently, the specimens were soaked in distilled water at a temperature of 20 ± 2 °C until no further change in dimensions occurred, both in radial and tangential directions. Measurements were taken at the same point every three days, ensuring that the difference between two successive measurements did not exceed 0.02 mm. Finally, the linear swelling and volumetric swelling of each specimen were determined using Equation 3.5 – 3.7 as follows:

$$\text{Radial swelling (\%)} = \left(\frac{l_{r2} - l_{r1}}{l_{r1}}\right) x\ 100 \qquad [\textbf{Equation 3.5}]$$

$$\text{Tangential swelling (\%)} = \left(\frac{l_{t2} - l_{t1}}{l_{r1}}\right) x\ 100 \qquad [\textbf{Equation 3.6}]$$

$$\text{Total volumetric swelling (\%)} = \left(\frac{(l_{r2}\ x\ l_{t2}) - (l_{r1}\ x\ l_{t1})}{l_{r1}\ x\ l_{t1}}\right) x\ 100 \ [\textbf{Equation 3.7}]$$

Where, l_{r2} and l_{t2} are the dimensions of the fully saturated test piece measured in the radial and tangential directions, respectively, while l_{r1} and l_{t1} are the dimensions of the test piece at oven-dry condition, measured in the radial and tangential directions, respectively.

b) Shrinkage Test

Each of the untreated and treated specimens were soaked in distilled water at a temperature of 20 ± 2 °C until no further change in dimensions occurred. The dimensions of the specimens in radial and tangential directions were checked every three days until the difference between two consecutive measurements of dimension did not exceed 0.02 mm, and the final dimensions were recorded. Subsequently, the specimens were air-dried in room conditions and periodically weighed until it reached a moisture content of approximately 12%, followed by oven-dried at a temperature of 103 ± 2 °C. The specimens' weight or dimensions in radial and tangential directions were checked every eight hours until the difference between two successive weighing did not exceed 0.2% or when the measurement of the dimension did not exceed 0.02 mm. The final dimensions were recorded. The equation for linear shrinkage and volumetric shrinkage of the specimens were determined using Equation 3.8 – 3.10 as follows:

$$\text{Radial shrinkage (\%)} = \left(\frac{l_{r1} - l_{r2}}{l_{r1}}\right) x\ 100 \qquad [\textbf{Equation 3.8}]$$

$$\text{Tangential shrinkage (\%)} = \left(\frac{l_{t1} - l_{t2}}{l_{t1}}\right) x\ 100 \qquad [\textbf{Equation 3.9}]$$

$$\text{Total volumetric shrinkage (\%)} = \left(\frac{(l_{r1}\ x\ l_{t1}) - (l_{r2}\ x\ l_{t2})}{l_{r1}\ x\ l_{t1}}\right) x\ 100 \ [\textbf{Equation 3.10}]$$

Where, l_{r1} and l_{t1} are the dimensions of the green or fully saturated test piece measured in the radial and tangential directions, respectively while l_{r2} and l_{t2} are the dimensions of the test piece at oven-dry condition measured in the radial and tangential directions, respectively.

3.2.5 Determination of Mechanical Properties

3.2.5.1 Static Bending

Internodes 8 to 12 were used in this test. For the static bending test, the specimens were prepared and tested in accordance with the procedure described by Anwar et. al. (2005), with reference to IS 8242 (1976), which was affirmed as current standard method in 2020. A total of 30 specimens, each measuring 140 mm x 20 mm x 5 mm, were used for both untreated and treated sample groups. The tests were conducted using a 10 kN Shimadzu Universal Testing Machine (Figure 3.10) with constant load applied at a rate of 0.0175 mm/min. Approximately 20 mm of the length, near the rupture point, from each specimen was taken for moisture content and density calculation. The results for the modulus of rupture (MOR) and modulus of elasticity

(MOE) were calculated using Equation 3.11-3.12. The test results then need to be calculated to newton units by multiply to 0.098.

$$\text{MOR (kgf/cm}^2) = \left(\frac{3P'l}{2bh^2}\right) \qquad \textbf{[Equation 3.11]}$$

$$\text{MOE (kgf/cm}^2) = \left(\frac{Pl^3}{4bh^3d}\right) \qquad \textbf{[Equation 3.12]}$$

Where, P is the load at the proportional limit, *b* is the width of the specimen, *h* is a depth of specimen, *l* is span length, *P'* is the maximum load and *d* is the deflection at proportional limit.

Figure 3.10: Static Bending Test

3.2.5.2 Compression Parallel to the Grain

A total of 90 specimens, comprising of 30 specimens from both the untreated and treated groups were subjected to testing in accordance with the procedure described by Anwar et al. (2005), with reference to IS 8242 (1976), which was affirmed as the current standard method in 2020. The specimens were cut with an adjustment to the dimensions of 40 mm x 20 mm x 5 mm according to equipment setting and were tested using a 10 kN Shimadzu Universal Testing Machine. In this test, the width and thickness of the specimens were measured with an accuracy of 0.1 mm at the middle span of the specimen. Each specimen was positioned vertically between two parallel metal plates (Figure 3.11).

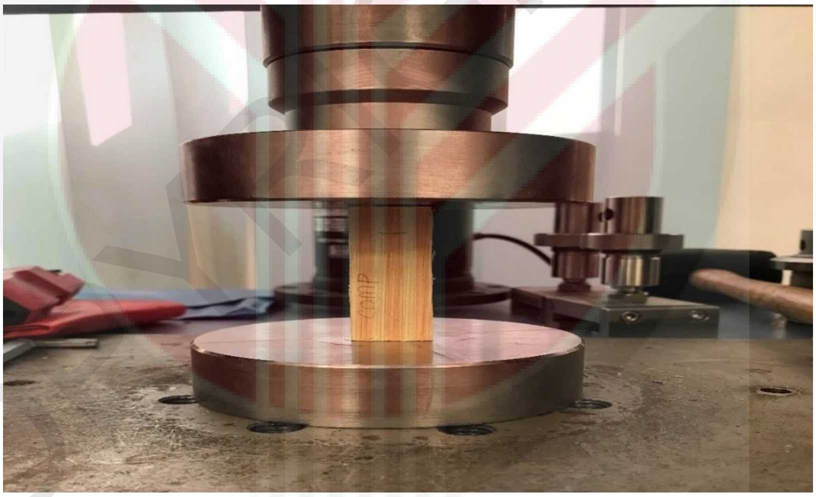


Figure 3.11: Compression Parallel to the Grain

A constant load was applied at the top of the specimens at a rate of 0.6 mm/min. The MC and density were evaluated after the test. The compressive strength was determined using Equation 3.13, and subsequent test results require conversion to newton units by multiplication with 0.098.

$$\text{Compressive strength } (\text{kgf/cm}^2) = \left(\frac{P}{bh}\right) \qquad \textbf{[Equation 3.13]}$$

Where P is the maximum crushing load, b is width of the specimen and h is the thickness of the specimen.

3.3 Result and Discussion

3.3.1 Treatment Characteristics Evaluation

3.3.1.1 Retention and Penetration of *Gigantochloa scortechinii* Strips

Both retention and penetration are important to evaluate the preservative treatment efficacy. Retention is normally expressed as the weight of chemicals absorbed in the wood, whereas penetration is performed to observe the presence of preservatives within the material (Gauss et al., 2020). On the other hand, weight gain is an indicator of the chemical load in the material (Baysal et al., 2006).

Table 3.2 displays the treatability of *Gigantochloa scortechinii* by using boron and CCB preservatives. The values obtained for WPG and NDSR of boron-treated bamboo strips were 18.43% and 2.63 kg/m^3, respectively. In the case of CCB treatment, significantly higher WPG and NDSR values of 23.12% and 4.9 kg/m^3, respectively, were recorded.

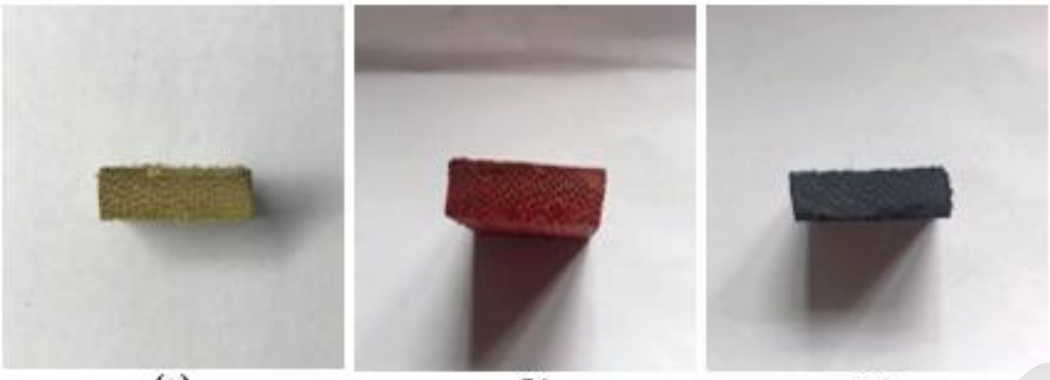
Table 3.2: Mean of weight percent gain (WPG) of treated bamboo strips

Treatment	WPG (%)	Net Dry Salt Retention (kg/m^3)
Boron	18.43^{b} (7.83)	2.63^{b} (0.81)
Copper Chrome Boron (CCB)	23.12^{a} (7.03)	4.92^{a} (1.36)

Note: Values in parenthesis are standard deviations
Means with the same letters ^{a,b} in the same column are not significantly different ($p<0.05$) according to Tukey HSD

The result showed that there is a consistent increase in WPG and NDSR with the higher treatment concentration. The NDSR value for CCB-treated strips surpassed the minimum requirement for waterborne preservatives stipulated by the America Wood Preservative Association (AWPA) which is 4 kg/m^3. While boron barely achieved 2.8 kg/m^3 of the minimum standard. Generally, the NDSR obtained in this study were comparable to those reported by other studies. Baysal et al. (2016) reported retention values of 4.63 kg/m^3 and 4.83 kg/m^3 in *Phyllostachys bambusoides,* resulting from treatment using 3% boron and CCB treatment, respectively. While Razak et al. (2005) found the mean retention in *Gigantochloa scortechinii* was between 4.41-6.30 kg/m^3 when treated with 1, 2, 4, and 8% of boron solution. In addition, Gauss et al. (2019) discovered that the retention rate for *Dendrocalamus asper* ranged from 11.82 – 17.41 kg/m^3 when using 5% and 8% boron concentration.

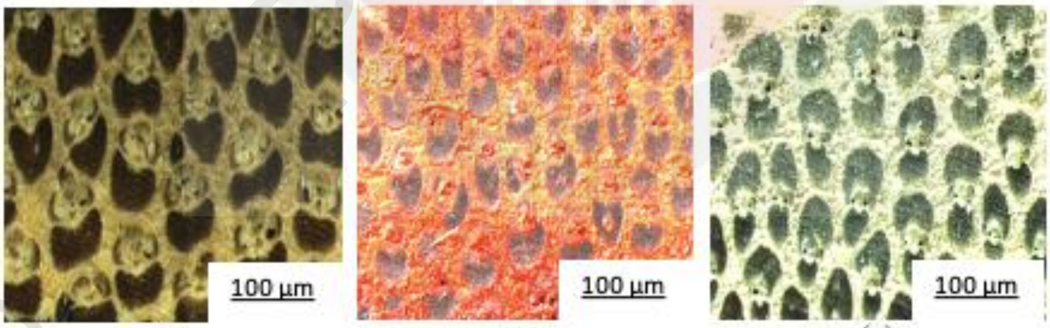
Visual assessment of the penetration revealed that the treated bamboo strips exhibited thorough penetration of the preservative. The presence of the test chemicals was determined by changes in the colour of the specimen. A blue colour indicated the presence of copper, while a red colour indicated the presence of a boron element (Figure 3.12). Previous reports have suggested that changes in colour during preservative penetration resulted from the chemical treatment and atmospheric conditions (Bons & Dhawan, 2013).



(a) (b) (c)

Figure 3.12: Analysis of Penetration in Longitudinal Direction with Curcumin and Azurol S for (a) Untreated Specimen, (b) Boron-treated Specimen and (c) CCB-treated Specimen

Figure 3.13 shows the microscope images of the boron and CCB-treated specimens subjected to the penetration test and were compared to the control specimen. The test clearly illustrates that the entire cross-section was fully impregnated with the preservative, turning red (for boron-treated specimen) and blue (for CCB-treated specimen). According to MS 833 (1984), both treated samples were classified as grade 5 (Table 3.1), signifying complete penetration with the preservative.



(a) (b) (c)

Figure 3.13: Microscope Image for (a) Untreated Specimen, (b) Boron-treated Specimen and (c) CCB-treated Specimen

3.3.1.2 FTIR Analysis

The changes in chemical function groups of the bamboo strips before and after treatment with boron and CCB are displayed in Figure 3.14.

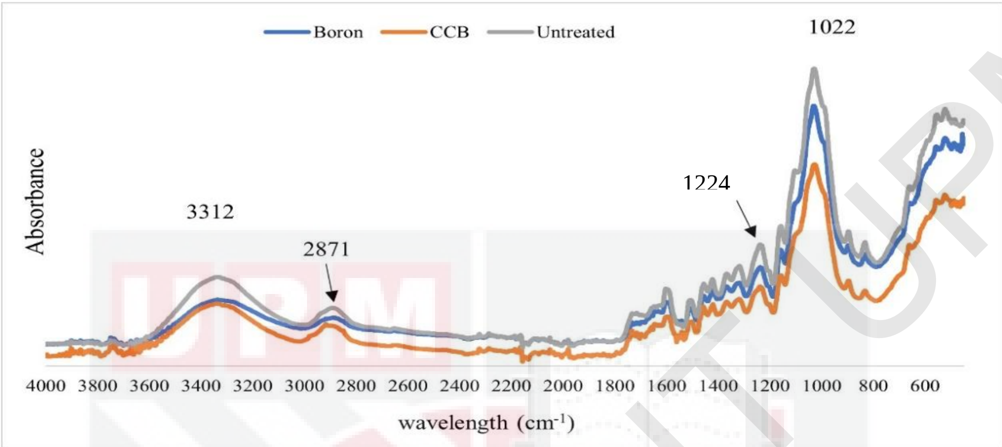


Figure 3.14: FTIR Spectra of Untreated, Boron- and CCB-treated Bamboo

The functional regions at 3312 and 2871 cm^{-1} correspond to the hydroxyl groups (-OH) and C-H stretching of cellulose, respectively. Both boron and CCB-treated bamboo exhibited lower intensity at these peaks compared to that of untreated bamboo. This observation indicates that boron and CCB treated bamboo have a reduced tendency to absorb water, as further demonstrated by the reduced swelling in the following section. Similar trends were also observed near the peaks at 1224 and 1022 cm^{-1}, corresponding to the guaiacyl ring breathing with CO-stretching (associated with lignin and hemicelluloses) and primary alcohol (Gauss et al., 2021), respectively. The reduction in the intensity of C-O stretching vibration near 1224 cm^{-1} may be attributed to the modification of lignin by chromium (Yalinkilic et al., 1999).

3.3.2 Evaluation of Physical Properties

Table 3.3 shows the effect of preservative treatment on MC, density, swelling and shrinkage for untreated and treated bamboo strips. From the table, untreated bamboo showed the highest mean values in most of the physical properties compared to treated bamboo. After treatments, the density of boron-treated specimens increased by 2.3%, from 713.32 kg/m^3 to 730.03 kg/m^3. Meanwhile, CCB-treated specimens increased by 1% from 751.18 kg/m^3 to 758.97 kg/m^3 when compared to initial density. The increment may have been attributed to the cellulose crystallisation of the fibre due to the partial removal of non-cellulosic components like hemicellulose and the dissolving of amorphous zones (Kadivar et al., 2022; Saikia et al., 2015). In addition, the active ingredient of preservative solution reacts with the cellulose structure which resulted in an increase in the weight of the specimens. The increasing trend in density was similar as reported by Yusof et al. (2023) and Augustina et al. (2020) on several bamboo species treated using boron-based preservatives with the increasing of 1 to 3% from the untreated bamboo.

Table 3.3: Physical properties of untreated and treated *Gigantochloa scortechinii* strips

Specimen	Initial density (kg/m^3)	Density after treatment (kg/m^3)	MC (%)	Swelling			Shrinkage		
				Radial (%)	Tangential (%)	Total Volumetric (%)	Radial (%)	Tangential (%)	Total Volumetric (%)
Untreated	778.74	-	9.9^{a} (0.1)	9.58^{a} (3.5)	20.00^{a} (6.2)	16.85^{a} (5.5)	11.18^{a} (3.5)	*19.53^{b} (5.6)	15.94^{a} (4.1)
Boron	713.32	730.03^{b} (22.26)	9.8^{a} (0.1)	7.69^{ab} (2.0)	19.32^{a} (6.2)	14.54^{a} (3.2)	9.84^{a} (2.9)	*22.83^{ab} (3.9)	15.76^{a} (3.1)
CCB	751.18	758.97^{a} (46.11)	9.9^{a} (0.2)	6.84^{b} (2.4)	19.56^{a} (5.1)	13.70^{a} (3.9)	9.12^{a} (2.4)	*25.62^{a} (4.8)	15.65^{a} (2.8)

Note: Values in parenthesis are standard deviations
Means with the same letters ^{a,b,c} in the same column are not significantly different ($p<0.05$) according to Tukey HSD
*Values have been revised after repeated testing

In terms of MC, there were no significant differences in the effect of preservatives on the MC of bamboo strips. However, both untreated and CCB-treated bamboo specimens had the same value of 9.9%. Whilst for boron, a slight decrease of 0.1% in MC was observed when compared to CCB.

There is no significant different was observed in total volumetric changes in swelling test as displayed in Table 3.3. However, treatment has an effect on the swelling in the radial direction by having CCB-treated bamboo strips have the lowest swelling values. Similarly, the total volumetric changes in the shrinkage test showed no effect from the treatment. In contrast to swelling test, the CCB-treated bamboo strip exhibited the highest tangential shrinkage values compared to the other specimens.

As stated by Biswas et al. (2011), higher density after treatment in bamboo strips exhibited lower swelling and higher shrinkage value, which is comparable with this study. A similar pattern was observed by Yusof et al. (2023) and Baraúna et al. (2021) who discovered that boron-treated bamboo and eucalyptus had a lower value in radial swelling and higher value in tangential shrinkage. Another factor was due to the treatment, which was believe linked to the formation of boron on the bamboo surface which create the limitation of water absorption (Priadi et al., 2021), as seen in the FTIR analysis (Figure 3.14) at the functional regions of 3312 and 2871. In result, it attributed to the chemical modifications in the lignocellulosic materials (Gauss et al., 2021) which is supported by FTIR analysis in Figure 3.14. These findings suggest that the preservative treatments had a noticeable effect on the physical properties of bamboo strips. The findings were also consistent with other studies that utilised various preservative treatments (Huang et al., 2019; Meng et al., 2016; Anwar et al., 2009). Changes in several chemical components were responsible for alterations in certain physical properties of bamboo, such as density, swelling, volume shrinkage, and equilibrium moisture content, as reported in these studies.

3.3.3 Evaluation of Mechanical Properties

The results of the mechanical properties of treated and untreated bamboo strips are presented in Table 3.4. The mean values for density were recorded at 760.27 kg/m^3, 725.71 kg/m^3 and 748.42 kg/m^3 for untreated, boron- and CCB-treated CLB, respectively. Meanwhile, the MOR for each untreated and treated bamboo strip was 183.03 N/mm^2, 180.03 N/mm^2, and 185.34 N/mm^2, respectively. The MOE of the treated specimen showed a decrease compared to the untreated specimen. While there was no significant difference in MOR, MOE displayed a contrasting trend (Table 3.4). For compression strength parallel to the grain, a significant difference was observed between untreated and treated specimens.

Table 3.4: Mechanical properties of untreated and treated *Gigantochloa scortechinii* bamboo strips

Sample	Density (kg/m^3)	Strength properties		
		MOR (Nmm^{-2})	MOE (Nmm^{-2})	Compression (Nmm^{-2})
Untreated	760.27^{a} (39.06)	183.03^{a} (16.8)	25645.54^{a} (2633.0)	74.31^{b} (7.0)
Boron	725.71^{b} (36.93)	180.03^{a} (30.3)	22223.23^{b} (2475.8)	77.92^{ab} (7.7)
CCB	748.42^{ab} (44.84)	185.34^{a} (27.8)	22417.10^{b} (2614.8)	80.97^{a} (7.3)

Note: Values are an average of 30 specimens adjusted to 12% MC
Values in parenthesis are standard deviations
Means with the same letters ^{a,b} in the same column are not significantly different ($p<0.05$) according to Tukey HSD

Density of treated bamboo strips were lower when compared to the untreated. When comparing between treatments, boron-treated bamboo had the lowest density by having 4.5% lower compared to untreated bamboo. Meanwhile, the density of CCB-treated bamboo recorded 1.6% lower density. However, it does not display significant changes in terms of strength properties (Table 3.4). As stated by Saikia et al. (2015), boron-based treatment exhibits crystallinity to the fibre due to the treatment. This statement is supported by Tang et al. (2019), who explained the increasing mechanical strength of bamboo after being treated with tung oil.

As seen in Table 3.4, the elastic modulus of treated bamboo strips lowered by 13.3% for boron treatment and 12.6% for CCB treatment when compared to the untreated sample. The reduction in stiffness values was probably due to the increased rate of hydrolysis in the bamboo. According to Fidan and Adanur (2019), the chemical structure and fixation process with woods during impregnation are linked to the reduction in stiffness. The acidic substances in boron lead to the hydrolysis of wood sugars, inducing interactions with cell wall components. During the fixation process, the oxidation of cell wall components occurs, resulting in changes in mechanical characteristics. A similar reduction in stiffness has been observed by other researchers in boron-impregnated wood and borax-treated bamboo (Handana et al., 2020; Gecer et al., 2015; Percin et al., 2015). Meanwhile, there was also a notable increase in MOR for CCB, although it is not significant.

The presence of preservatives in bamboo strips after treatment increased compression strength by 4.6% for boron and 8.2% for CCB, as shown in Table 3.4. The results demonstrated significantly higher compression strength in treated bamboo strips compared to untreated strips. The increased strength could be due to the formation of salt crystals within the bamboo microstructure, which can enhance its load-carrying capacity (Gauss et al., 2019). While it improves compression, this phenomenon would lead to brittleness, reducing flexibility and preventing its function as a load-bearing capacity (Wang et al., 2019). Several studies using boron-based treatments have yielded similar compressive strength results. Icimoto et al. (2013) discovered higher compression strength parallel to the grain in CCB-treated Paricá wood. Similarly, Shanu et al. (2015) reported an approximately 9.11% increase in compressive strength for *Albizia richardiana* treated with a boron-based treatment compared to untreated wood. Kurhekar (2014) obtained similar results with bamboo samples, noting that *Pseudoxytenanthera ritcheyi* bamboo treated with boric acid, borax, and CCB marked the highest compressive strength after being exposed to environmental conditions.

Overall, treatment with boron and CCB did not give a notable adverse effect on both the physical and mechanical properties of bamboo strips. CCB-treated bamboo strips performed slightly better in bending and compressive strength in comparison to boron. Higher WPG and NDSR observed in CCB-treated bamboo strips may have contributed to this improvement.

3.4 Conclusion

The study observed that CCB appears to perform better than boron, with a high NDSR of 4.8 kg/m^3. Additionally, this study revealed that treatment with boron and CCB did not significantly affect the dimensional stability and strength properties of bamboo strips. However, this study observed that CCB is attributed to greater mechanical properties compared to boron preservatives.

CHAPTER 4

ADHESION AND BONDING PROPERTIES OF BORON- AND CCB-TREATED CROSS-LAMINATED BAMBOO

4.1 Introduction

In any lamination process, adhesives play an essential role in determining the performance of laminated members (Alipon et al., 2018). Adhesive bonding is attributed to various mechanisms, such as mechanical interlocking through wetting of the wood surface, resin penetration and dissemination, physical attraction, and covalent chemical bonding (Skeist, 2012; Frihart & Hunt, 2010). In addition, the use of the appropriate adhesive can provide proper penetration into the material surface, creating bonding between the fibres and laminae (Antwi-Boasiako & Appiah Kyei, 2012; Anwar et al., 2005), which indirectly contributes to excellent product quality through the formation of strong adhesive bond.

Interactions between adhesive and preservatives must be carefully considered to ensure the quality of laminated product. Inappropriate wetting on the material surfaces and the preservative's blockage of moisture absorption from the glue line are linked to poor bonding (Kilmer et al., 1998). Effective wetting requires the formation of a low contact angle with the surface, while better surface coverage i.e., the amount of adhesive or spread rate, results in more robust bond growth (Ayanleye et al. 2022; Shirmohammadi & Leggate, 2021). Delamination and unexpected consequences for the overall structure capacity may occur if the internal bond strength of the laminated structural product is insufficient (Correal & Ramirez, 2010). Therefore, identifying the ideal glue spread is crucial to maintain the effectiveness of the shear within the lamination structure (Wang et al., 2020), ensuring the stability and good condition of the lamination when load is applied.

There have been several studies on the adhesive bond performance in laminated bamboo. For instance, studies on the effect of adhesives on shear strength were found to be reported widely by researchers (Yusof et al. 2023; Syaifudin et al., 2022; Xing et al, 2018), most of them using various adhesive such as Urea Formaldehyde, Polyurethane Reactive and Phenol Resorcinol Formaldehyde. However, fewer studies were reported on optimising the glue spread rate in bamboo lamination for structural purposes. According to Sikora et al. (2016), structurally used adhesives such as Phenol Resorcinol Formaldehyde (PRF) occasionally require a higher spread rate compared to adhesives recommended by the manufacturer depending on the species used. In a previous study, researchers discovered that glue spread rate significantly affected bond shear strength in various products such as glued laminated bamboo and laminated veneer lumber (Khoo et al., 2021; López et al., 2019; Correal and Ramirez, 2010).

Therefore, this chapter investigated the adhesion properties and bonding shear strength of cross-laminated bamboo that were fabricated by using boron-based treated bamboo strips. The study research flow chart and variables studied in this chapter are shown in Figure 4.1. The objectives of this study were:

i) To determine adhesion properties via contact angle wettability and buffering capacity of bamboo strips according to preservative treatments
ii) To evaluate the influence of glue spread rate on the bonding properties of cross-laminated bamboo (CLB)

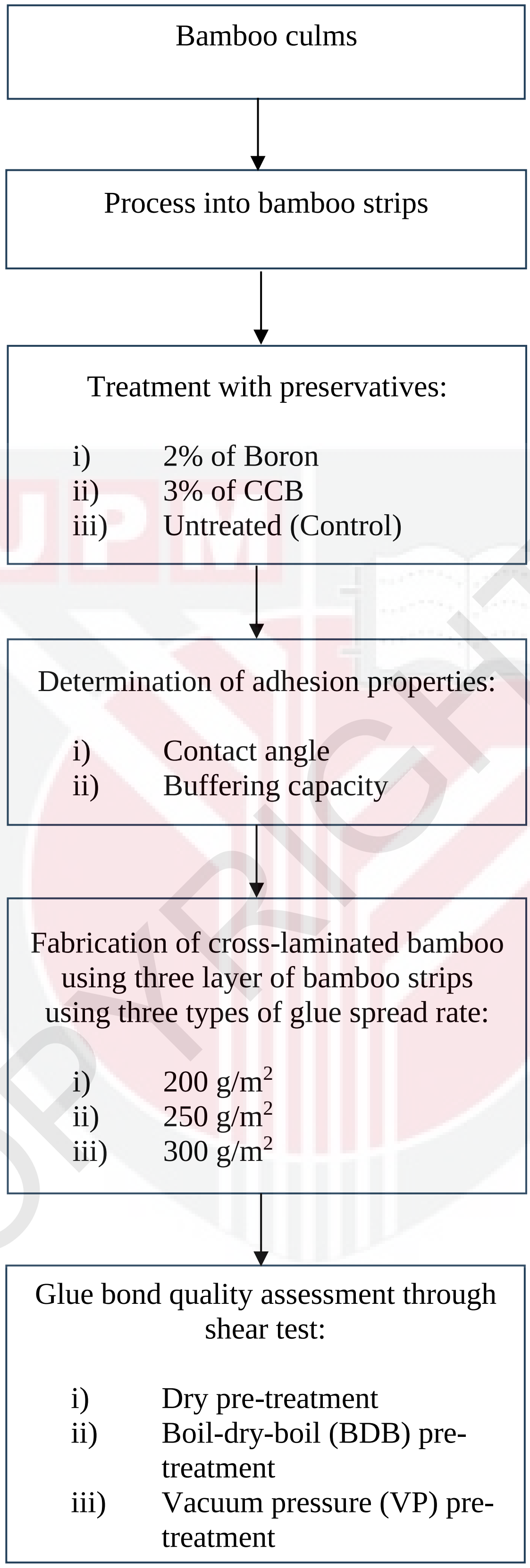


Figure 4.1: Study Research Flow Chart in Chapter 4

4.2 Materials and Methods

4.2.1 Preparation of Samples

A total of 25 bamboo culms of *Gigantochloa scortechinii*, each measuring eight feet in length, were prepared following the procedure described in Paragraph 3.2.1 of Chapter 3. These bamboo culms were then processed into strips measuring 2400 mm x 20 mm x 5 mm in size. Subsequently, they underwent treatment using two preservatives, namely, boron and copper chrome boron (CCB), at a 2% and 3% concentration, respectively. The treatment was carried out using the vacuum chamber method, which includes an initial vacuum of more than 85 kPa for 30 min, followed by a pressure of over 1300 kPa for 60 min, and finally, a final vacuum of more than 85 kPa for 20 min. The untreated (control) and boron-based treated strips were then dried in an oven at 50°C for 48 hours.

4.2.2 Adhesion Properties

Adhesion properties were evaluated using 15 bamboo strips taken from the seventh internode of the bamboo culm, as illustrated in Figure 3.1 in Chapter 3. This chapter investigated two factors affecting the adhesion properties, such as contact angle and buffer capacity.

4.2.2.1 Contact Angle

The test to determine wettability was carried out following ASTM D7334-08 (2022). A total of 30 specimens, each measuring 40 mm x 20 mm x 5 mm, were tested for contact angle using a KRUSS drop shape analyser. These specimens represented each treatment and surface. They were conditioned at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 % for one week and subsequently sanded with 100-grid sandpaper before the test. A 5 μL droplet of distilled water was applied to both bamboo surfaces; inner and outer, using a syringe tube with the sessile drop method. The image of the droplet was captured, and measurements were recorded after two seconds for each reading until no water remained on the bamboo surface (Figure 4.2).

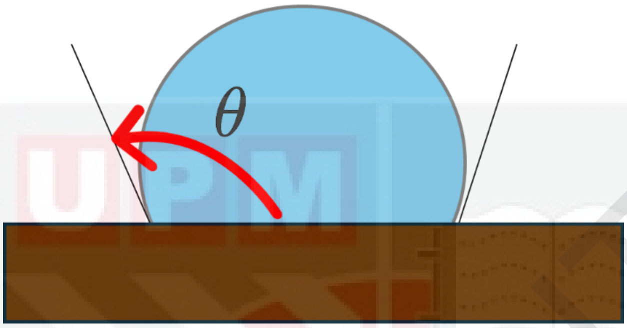


Figure 4.2: Schematic Diagram of Contact Angle Tested using KRUSS Drop Shape Analyser

4.2.2.2 Buffering Capacity

Ten bamboo strips from both control and treated samples were chipped and ground into particles using a Wiley machine. These specimens were then placed in a shaker with sieves measuring 40-mesh (0.425 mm diameter) and kept on a 60-mesh screen (0.250 mm diameter). The pH value and buffer capacity were evaluated using particles which remained on the 60-mesh screen.

Before the test, the initial pH of the particles was determined using the measurement of hydrogen ion concentration in paper extracts, following the cold extraction method as described by Malanit et al. (2011), with reference to TAPPI 509 om-06. In this procedure, 1 g of bamboo particles was placed into a 100 ml beaker and subsequently added 70 mL of distilled water (pH 6.7). The mixture was stirred and left to soak for an hour at room temperature 20 ± 2 °C. The measurement was taken using a pH meter, and readings were recorded after the measurement remained stable for 30 sec.

The buffering capacity was evaluated using the procedure outlined by Nayeri et al. (2013). Fifteen grams of particles were weighed and then placed in a beaker containing 200 mL of distilled water. The mixture was stirred using a magnetic stirrer and gradually heated on a hot plate for an hour at 60 to 70 °C. After heating, the mixture was filtered using a buchner funnel and filter paper. The resulting solution was left to cool until it reached a temperature of 20 ± 2 °C.

The solution was titrated using 0.01 N of hydrochloric acid (HCl) until the pH changed to 3.5 (Figure 4.3). The same titration procedure was then repeated using 0.01 N of sodium hydroxide (NaOH) until the pH turned 11. This process was repeated three times, and the amount of solution used in both titration processes was recorded.

4.2.3 Fabrication of Cross-Laminated Bamboo

The preparation of cross-laminated bamboo (CLB) board fabrication involved several steps. Initially, the bamboo strips, each measuring 2400 mm x 20 mm x 5 mm, were cut into two different lengths: 200 mm and 260 mm. These bamboo strips were conditioned at temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 % to maintain the EMC at 12% prior fabrication process. These varying lengths were later used to assemble the CLB for the surface and middle laminae, respectively.

For each length, the strips were arranged side by side and bonded with PRF at a glue spread rate of 200 g/m^2 to produce a continuous single-layered panel, called laminae.

The laminae were stored at ambient for three days. Following this, three-layered bamboo boards were produced by arranging the laminae perpendicularly to each other by using PRF adhesive obtained from Akzo-Nobel. The PRF was mix with hardener at 4:1 ratio. Three different adhesive spread rates, 200 g/m^2, 250 g/m^2 and 300 g/m^2, were applied onto a single face of the laminae (single glue line). The CLB was pressed at 14 kg/m^2 for 3.5 hours at ambient temperature. A total of 27 (3 replications x 3 treatments x 3 spread rates) three-layer CLB with final dimensions of 200 mm x 260 mm x 15 mm were produced. The fabrication process of the CLB is summarised in Figure 4.3.

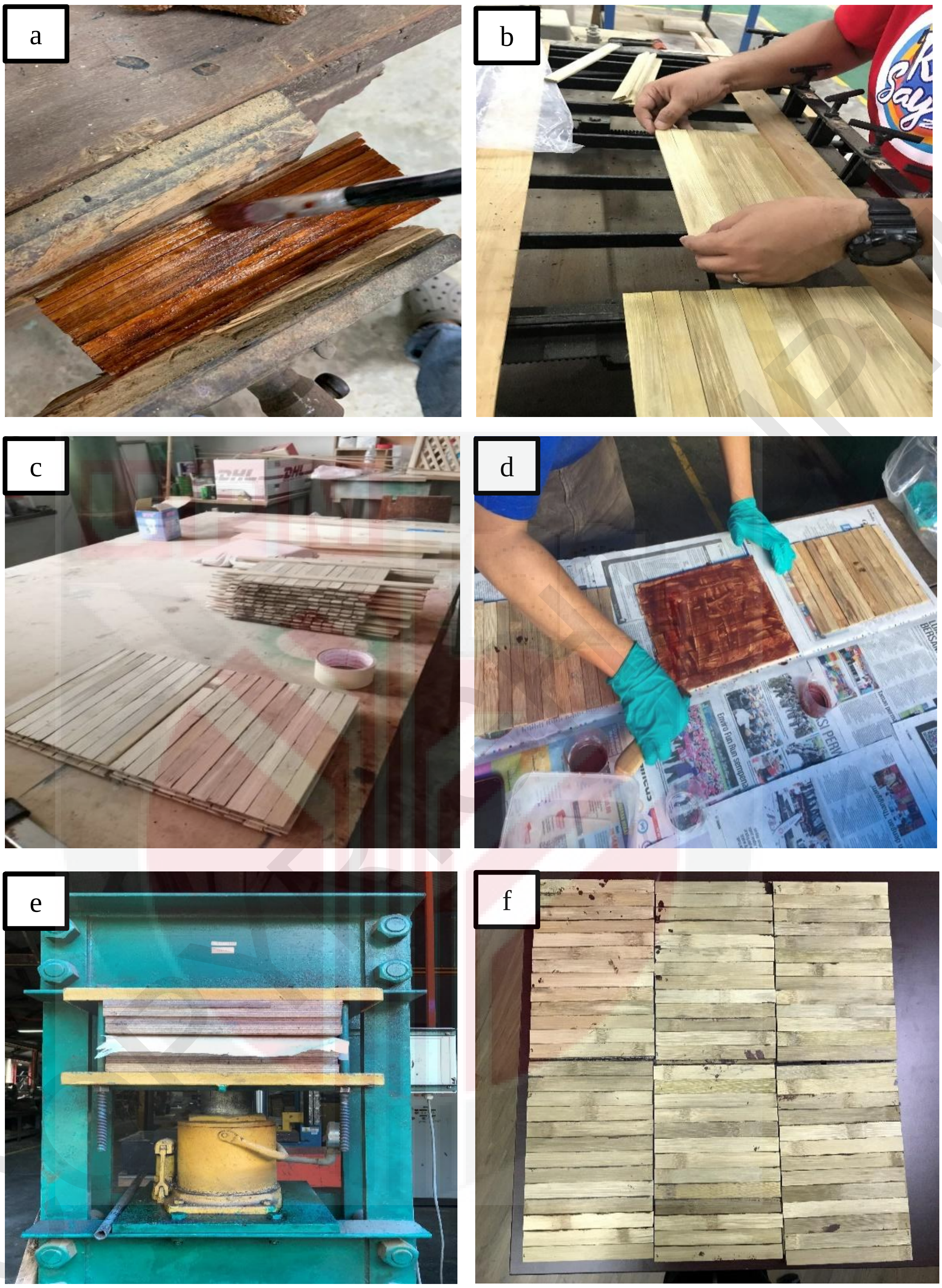


Figure 4.3: CLB Fabrication Process Involved (a-c) Laminae Manufacturing, (d) Glue Spreading, (e) Pressing, and (f) Untreated and Treated CLB

4.2.4 Glue Bond Quality Assessment Through Shear Test

Specimens for shear testing of adhesive bonds were cut and tested according to ISO 12466-1 (2007) (Figure 4.4). Based on this standard, specimens are required to be tested in a pre-treatment condition, according to bonding classes as stated in ISO 12466-2 (2007). The mean shear strength and the average apparent cohesive bamboo failure for each bonding quality class were calculated in line with this standard.

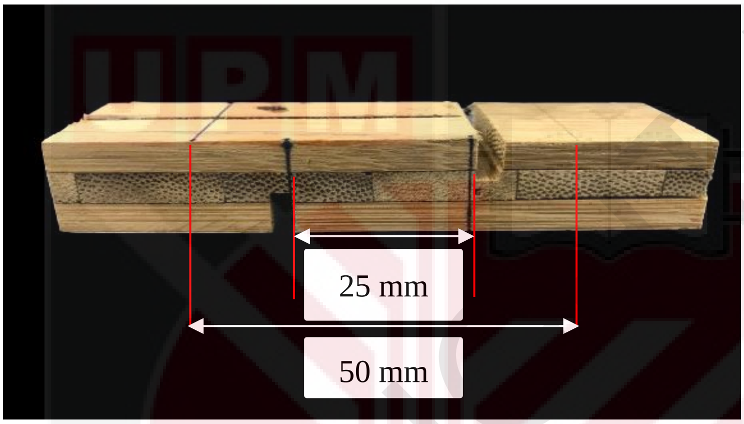


Figure 4.4: CLB Specimens for Bonding Shear Test According to ISO 12466-1

A total of 270 specimen (10 specimens x 3 replications x 3 treatments x 3 spread rates) were tested in each pre-treatment condition such follows:

a) Dry - The test specimens were conditioned at a temperature of 20 ±2 °C and a relative humidity of 65 ± 5 % until the weight reached a constant value before test were executed.

b) Boil-Dry-Boil (BDB) - The test specimens were submerged in boiling water for a duration of 4 hours, followed by drying in a ventilated drying oven for 16-20 hours at 60 ± 3 °C. Subsequently, they were immersed in boiling water for another 4 hours, and finally, allow it to cool in a water at a temperature below 30°C for a minimum of 1 hour.

c) Vacuum pressure (VP) - The test specimens were submerged in water at ambient temperature and subjected to a vacuum of 85 kPa for a duration of 30 min. This is followed by the immediate application of a pressure ranging from 450 to 480 kPa for a further 30 min (Figure 4.5).

Figure 4.5: Vacuum Pressure Method

All test specimens were then tested for bonding shear test using a UTM Shimadzu machine equipped with a 10 kN load cell (Figure 4.6) at a rate of 3 mm/min. The maximum loads at the break, which indicated the failure or firmness of bonding, were recorded, and the shear strength at the glue lines was determined using the equation 4.1. In addition, the apparent cohesive bamboo failure was determined.

Shear strength (N/mm^2) = F/lb **[Equation 4.1]**

Where, F is the force or load (N) at the failure of the test piece, l is the length (mm) of the shear area, and b is the width (mm) of the shear area

Figure 4.6: Specimen Tested using UTM Shimadzu Machine

4.3 Result and Discussion

4.3.1 Determination of Adhesion Characteristics

4.3.1.1 Contact Angle

The contact angle values for each treatment of the inner and outer layers of bamboo strips are shown in Figure 4.7. The initial contact angle values for the inner layer of untreated, boron-treated, and CCB-treated bamboo strips were 50.6°, 83.2° and 118.1°, respectively. Meanwhile, the contact angle values for the outer layer of untreated, boron-treated, and CCB-treated bamboo strips were recorded at 56.1°, 78° and 116.8°, respectively.

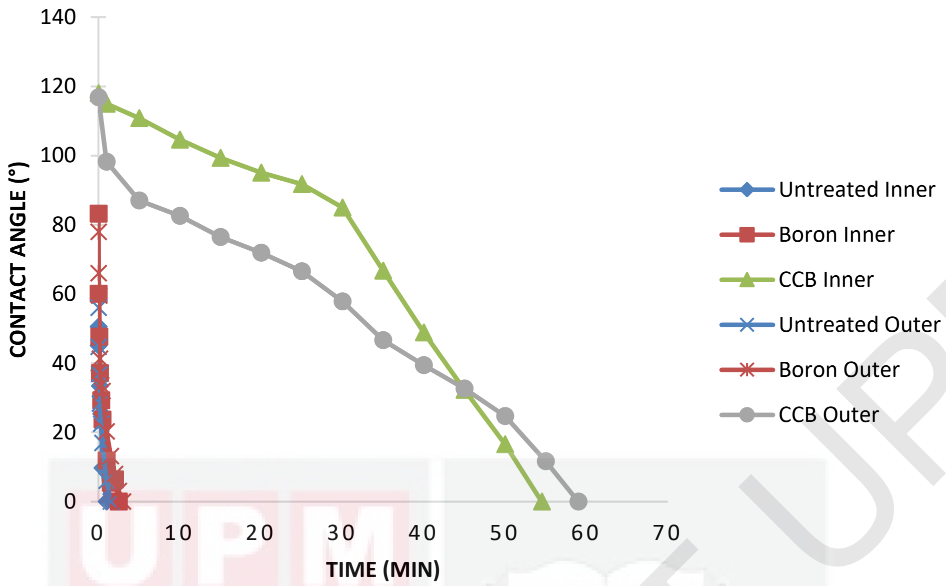


Figure 4.7: Contact Angle vs Time of Untreated and Boron-treated Bamboo Strips

The duration for contact angle of the outer layer for untreated bamboo strips to become fully absorbed was 50% longer than that of the inner layer. In comparison, the duration of boron-treated bamboo strips for the outer layer was 20% longer than the inner layer to be fully absorbed. Similarly, the outer layer of CCB-treated bamboo strips took 59 minutes, approximately 8.3% longer, to fully absorbed.

The results from the contact angle measurements were analysed using analysis of variance (ANOVA), as shown in Table 4.1. The analysis revealed that there was a significant difference in contact angles observed among the treatments, by having CCB treatment exhibited the highest contact angle, followed by boron and untreated specimen (Table 4.2). However, there was no significant difference in contact angle between surfaces, and no relationship was observed between treatment and the bamboo strip surfaces. This result led to the decision to use any surface for the lamination process.

Table 4.4.1: Analysis of variance of contact angle (ANOVA)

Source of variation	df	p-value
Treatment	2	0.000*
Surface (Inner and Outer)	1	0.341
Treatment x surface	2	0.200

Note: *Significant at $p < 0.05$

Table 4.4.2: Mean values of contact angle of untreated and treated bamboo strips

Treatment	Contact angle (°)
Untreated	27.58^{b} (18.17)
Boron	31.42^{b} (26.06)
CCB	65.94^{a} (33.87)

Note: Values in parentheses are standard deviations
Means with the same letters ^{a,b} in the same column are not significantly different ($p<0.05$) according to Tukey HSD

Table 4.2 shows the mean values of contact angle of untreated and treated bamboo strips. The CCB-treated bamboo strips resulted in the highest contact angle value compared to boron and untreated bamboo strips on both surfaces. According to Alade et al. (2022), chemical components inhabiting the treated bamboo cells might cause poor wettability, rendering the bamboo surface hydrophobic. This assumption was concurred by Mbhamali (2021), who stated that the chemical contamination and the surface treatment of wood can lead to difficulty in wetting. In addition, using preservatives can cause the wood surface to deteriorate, resulting in surface unevenness and blockages that can prevent adhesives from thoroughly wetting the surface (Frihart & Hunt, 2010). A similar result was found by Maldas & Kamdem (1998) when working with red maple treated using CCA preservative. Kinata et al. (2013) also discovered that CCB modified the behaviour of pine wood after being treated, resulting in poor wettability, as observed in the analysis through Scanning Electron Microscopy (SEM).

Although boron treatment had higher contact values than that of untreated specimens, it demonstrated a tendency for contact angle to decrease over time (Figure 4.7). The higher contact angle in this treatment might be due to the presence of boron salt, which is known to have hygroscopic properties and is believed to adversely affect the hydrophobicity properties. Tomak (2022) reported higher contact angle in boron-treated specimens to control specimens in pine and beech wood. Meanwhile, Yusof et al. (2023) discovered that *Dendrocalamus asper* and *Gigantochloa scortechinii* yielded higher contact angles after being treated with 5% boric acid. Aydin & Colakoglu (2007) also obtained the same result with alder and beech plywood treated with 5% borax dan boric acid.

Untreated specimens exhibited the smallest contact angle. According to Anwar et al. (2005) and Roziela Hanim et al. (2010), bamboo strips typically exhibit significantly smaller contact angle over a shorter period due to their outstanding wettability. It has been demonstrated that both surfaces of untreated bamboo strips form contact angles below 20° in less than 1 minute, indicating their wettability or hydrophilicity (Koski & Ahonen, 2008). After treatment, the contact angle of the bamboo strips increased, with more pronounced in the CCB treatment, exceeding 100%.

4.3.1.2 pH and Buffering Capacity

A buffering capacity test can determine the acidity or alkalinity of raw materials (Kamal et al., 2010). Depending on the resin employed, it is believed that the alkalinity or acidity of the raw materials may affect the bond line, thus influencing the adhesive curing time (Wang et al., 2010; Paridah et al., 2001). Table 4.3 shows the average initial pH of untreated, boron-treated, and CCB-treated bamboo strips.

Table 4.3: Average initial pH in untreated, boron-treated and CCB-treated bamboo strips

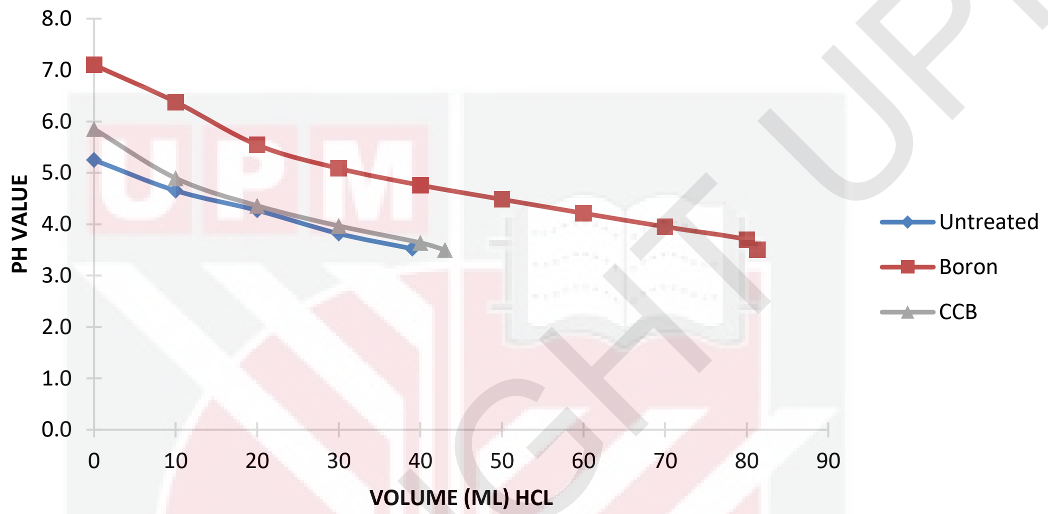
Treatment	Initial pH
Untreated	5.5
Boron	7.0
CCB	5.7

This study discovered that the initial pH values for each treatment were recorded at 5.5, 7.0 and 5.7, respectively. The results show that the initial pH values of treated bamboo strips are higher than that of untreated bamboo strips. However, no significant difference was observed between untreated and treated samples. Bamboo generally has an acidic pH value (Maulana et al., 2020; Junior et al., 2009). It is noteworthy that after treatment, the pH value increased. This is consistent with the study conducted by Can (2017), which found that the pH of wood treated with boron compounds increased after treatment.

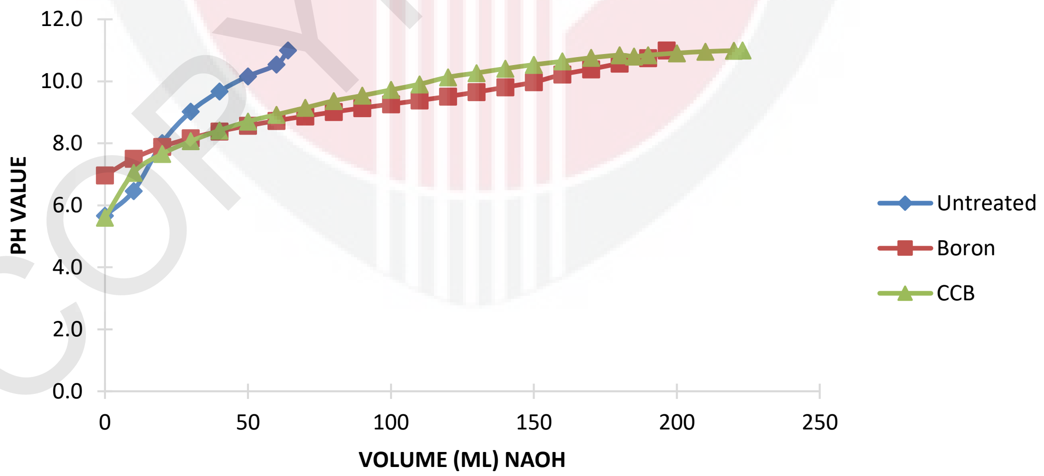
The result for the mean buffer capacity in each treatment are summarised in Table 4.4, while Figures 4.8(a) and 4.8(b) show the buffering capacity of untreated and treated bamboo strips in acidic and alkaline conditions. According to the results, the untreated, boron-treated, and CCB-treated bamboo strips required approximately 39 mL, 81.3 mL and 43 mL of HCl titration solution, respectively to change the pH to 3.5. Similarly, the same specimens needed about 94 mL, 217 mL, and 223 mL of NaOH solution to change their initial pH to 11.

Table 4.4: Mean values of buffer capacity for untreated, boron-treated and CCB-treated bamboo strips

Treatment	Buffer capacity	
	HCL solution	NaOH solution
Untreated	39 mL	94 mL
Boron	81.3 mL	217 mL
CCB	43 mL	223 mL



(a)



(b)

Figure 4.8: The Buffering Capacity of Untreated and Treated Bamboo Strips in (a) Acidic Conditions and (b) Alkaline Conditions

The results indicate that the untreated bamboo strips and each treatment appeared to be more stable in alkaline conditions, as shown in Table 4.4, Figure 4.8(a) and 4.8(b). This condition is known as high buffering capacity, when high amount of NaOH needed to increase the pH (Maloney, 1977). Similar results were reported by Yusof et al. (2023) for four bamboo species treated with boric acid.

4.3.2 Glue Bond Quality

The effect of treatment and adhesive glue spread rate on the bonding performance of cross-laminated bamboo were conducted using shear tests by selecting three pre-treatments according to bonding classes, namely dry, BDB and VP. The results of shear strength are summarised in Table 4.5. Subsequently, the analysis of variance (ANOVA) for the shear strength of each pre-treatment was conducted and tabulated in Table 4.6. The analysis shows that the significant difference occurred in all sources of variation in the dry pre-treatment. Meanwhile, only glue spread rate shows significant difference on the shear strength in all pre-treatment conditions.

Table 4.5: Mean values for shear strength and bamboo failure of CLB according to treatment and glue spread rate in three pre-treatment conditions

Treatment	Spread rate (g/m^2)	Pre-treatment					
		Dry (N/mm^2)	Bamboo failure (%)	BDB (N/mm^2)	Bamboo failure (%)	VP (N/mm^2)	Bamboo failure (%)
Untreated	200	1.83 (0.5)	50 (12.9)	0.88 (0.1)	60 (16.3)	1.18 (0.2)	50 (21.6)
	250	1.93 (0.4)	50 (14.0)	1.37 (0.5)	60 (24.4)	1.39 (0.5)	50 (9.8)
	300	1.95 (0.8)	60 (20.4)	1.62 (0.4)	70 (15.1)	1.98 (0.4)	60 (14.6)
Boron	200	2.01 (0.4)	50 (21.5)	1.39 (0.4)	50 (20.7)	1.54 (0.3)	50 (10.0)
	250	1.86 (0.5)	50 (23.7)	1.55 (0.7)	70 (21.9)	1.52 (0.6)	60 (16.4)
	300	2.05 (0.7)	70 (23.6)	1.65 (0.4)	70 (17.0)	1.88 (0.2)	70 (6.9)
CCB	200	1.60 (0.2)	50 (13.8)	1.10 (0.4)	50 (11.0)	1.12 (0.2)	50 (4.5)
	250	2.76 (0.3)	70 (31.0)	1.40 (0.4)	70 (13.8)	1.77 (0.4)	70 (4.1)
	300	2.62 (0.3)	90 (12.5)	1.80 (0.3)	70 (29.1)	2.20 (0.3)	50 (12.9)

Note: Values in parentheses are standard deviations

Table 4.6: Analysis of variance (ANOVA) of pre-treatment shear strength of CLB in pre-treatment conditions

Source of variation	df	p-value		
		Dry	BDB	VP
Treatment	2	0.000*	0.203	0.401
Spread rate	2	0.014*	0.000*	0.000*
Treatment x glue spread	4	0.006*	0.531	0.143

Note: Significant at $p < 0.05$

Figure 4.9 presents the mean values of shear strength of CLB in dry condition according to their respective treatments and glue spread rate. The mean value for CLB in untreated condition by using 200 g/m^2, 250 g/m^2 and 300 g/m^2 glue spread rate were recorded at 1.83 N/mm^2, 1.93 N/mm^2 and 1.95 N/mm^2, respectively. Meanwhile shear strength for boron-treated CLB recorded at 2.01 N/mm^2, 1.86 N/mm^2 and 2.05 N/mm^2, respectively. Additionally, the result for CCB-treated CLB were 1.60 N/mm^2, 2.76 N/mm^2 and 2.62 N/mm^2, accordingly. In general, the shear strength of CLB was higher when it was fabricated with treated strips and had higher glue spread rate. For instance, CLB treated with CCB treatment using 250 g/m^2 glue spread rate exhibited the highest shear strength. Meanwhile, the lowest shear strength was observed for untreated with 200 g/m^2, using the same treatment solution.

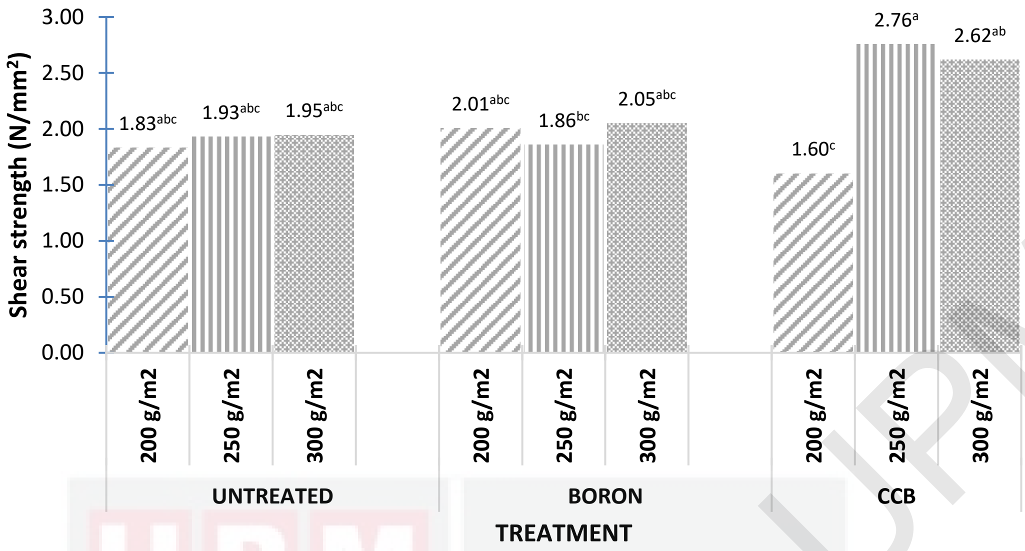


Figure 4.9: Mean Value of Dry Shear Strength of Different Glue Spread in Each Treatment

Note: Means with the same letters [a,b,c] are not significantly different ($p<0.05$) according to Tukey HSD

Higher shear strength values for treated specimens in dry pre-treatment could be related to several factors, such as the adhesive type, buffering capacity and bond line pH stability (Ayanleye et al., 2022; Nkeuwa et al., 2022; Sikora et al., 2016; Taşçıoğlu et al., 2004; Xing et al., 2004). According to Paridah et al. (2001), theoretically, a good bonding occurs when both the shear strength and wood failure percentage levels are higher. This theory aligns with the results presented in Table 4.5, where shear strength and bamboo failure increased with treatment and at higher glue spread rate. Furthermore, the relationship between the pH of the adhesive and buffer capacity also contributes to bonding performance (Paridah et al., 2001). Paridah et al. (2009) reported that acid-resistance rubberwood produces excellent glue bond strength when bonded with acid-curing resin. This explains the high shear strength in boron and CCB treatments, as they exhibit a remarkable buffering ability towards alkaline conditions, which is compatible with an alkaline-curing resin such as PRF.

Table 4.6 revealed that the glue spread rate is also statistically impacted the shear strength of CLB in BDB and VP conditions, with a more pronounced effect at higher glue spread rates. Table 4.7 displayed the mean values of shear strength of CLB in BDB and VP conditions, according to the glue spread rate. The mean values of shear strength of CLB in BDB condition with glue spread rate of 200 g/m^2, 250 g/m^2 and 300 g/m^2 were measured at 1.13 N/mm^2, 1.44 N/mm^2 and 1.69 N/mm^2, respectively. Meanwhile, the shear strength in the VP condition was recorded with the value of 1.97 N/mm^2, 1.55 N/mm^2 and 1.29 N/mm^2.

Table 4.7: Shear strength of CLB in BDB and VP conditions according to glue spread

Sample	**Shear strength (N/mm^2)**	
Glues spread	**BDB**	**VP**
200 g/m^2	1.13^b (0.4)	1.29^b (0.3)
250 g/m^2	1.44^{ab} (0.5)	1.55^b (0.5)
300 g/m^2	1.69^a (0.3)	1.97^a (0.3)

Note: Values in parentheses are standard deviations
Means with the same letters ^{a,b} in the same column are not significantly different ($p<0.05$)according to Tukey HSD

In general, regardless of the pre-treatment conditions, CLB with 300 g/m^2 had the highest shear strength followed by 250 g/m^2 and the lowest was at 200 g/m^2 glue spread rate (Table 4.7). The increasing strength value corresponds to the glue spread rate in this study was probably due to the penetration of an adequate adhesive into the surface, creating a continuous and solid glue line, thus improving shear strength (Nur Amira et al., 2021; Khoo et al., 2021). While insufficient glue spread rate will significantly decline bonding quality (Singha & Thakur, 2008). Figure 4.10 shows the bamboo failure of CCB-treated CLB with a glue spread of 300g/m^2 in BDB pre-treatment.

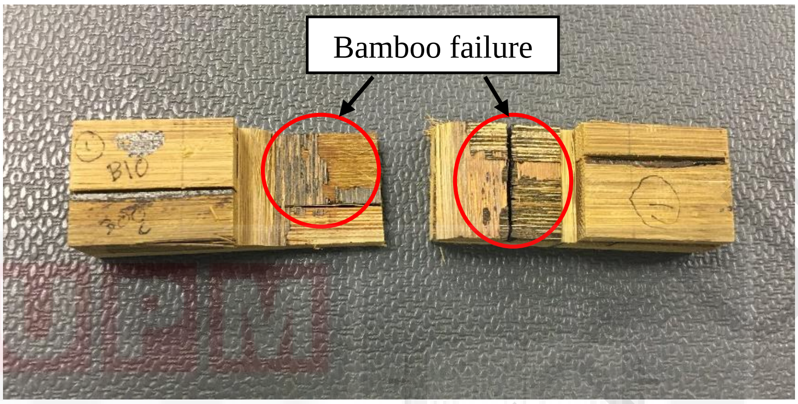


Figure 4.10: Bamboo Failure of CCB-treated CLB Observed in BDB Pre-treatment

Several studies have shown similar results, indicating superior bonding performance at higher glue spread rates. Correal & Ramirez (2010) discovered that the ideal adhesive spread rate for the structural application of glued laminated bamboo on wide faces was 300 g/m^2, in contrast to the adhesive spread rate recommended by the manufacturer which was at 400 g/m^2. Nur Amira et al. (2021) observed that the shear strength of cross-laminated timber (CLT) of mixed wood species was unaffected by preservatives and found that the optimum glue spread rate used in manufacturing CLT, at 300 g/m^2, had a positive effect on shear strength. Meanwhile, Bekhta & Marutzky (2007) discovered that the bonding quality in plywood degraded as adhesive application decreased due to insufficient resin, leading to reduced adhesion.

4.4 Conclusion

This chapter investigated the adhesion properties via contact angle analysis and buffering capacity of bamboo strips provides valuable insights from the effect of preservative treatment. The findings revealed a significant outcome in the adhesion properties according to the treatment. The evaluation of the pH and buffering capacity revealed that CCB-treated bamboo strips were more stable in alkaline environments than in acidic ones, resulted a positive effect on bonding with PRF adhesive, although the contact angle was recorded higher after the treatment. Additionally, this study showed evidence that bonding properties was higher with treatment and at a higher spread rate, with CCB preservative treatment and 300 g/m^2 resulted in the most optimum shear strength.

CHAPTER 5

THE EFFECT OF LAYUP PATTERN ON MECHANICAL PROPERTIES OF PHENOL RESORCINOL FORMALDEHYDE (PRF) BONDED CROSS-LAMINATED BAMBOO (CLB)

5.1 Introduction

Bamboo has frequently been suggested in structural applications due to it is readily available in many tropical and sub-tropical locations (Archila-Santos et al., 2012). However, due to technological advancements, engineered bamboo material is being extensively explored. The utilization of round and engineered bamboo products demonstrates promising mechanical properties, making them a compelling alternative to wood (Gharavi, 2019). When compared to natural bamboo culm, the advantages of using engineered bamboo products become evident in manufacturing and application. Engineered bamboo products address issues related to section homogeneity, unstable bearing strength stemming from hollow sections, and the challenges associated with constructing dependable and ductile connections (Wang et al., 2017).

The exploration of existing laminated bamboo has led to various products development, such as bamboo mat plywood, bamboo curtain plywood, bamboo particleboard, laminated bamboo lumber, laminated bamboo composite timber and more (Guan et al., 2018), which can be used in structural applications. Among these products, laminated bamboo, which is constructed using several layers of bamboo pressed in various orientations depending on the structural and architectural specifications, has been studied to be the most promising material (Xiao et al., 2014).

Orientations of the bamboo strips and the fabrication configuration in the laminated panel influence its properties. Yang et al. (2020) studied the effect of parallel and perpendicular orientation of bamboo strips in laminated panels on their mechanical properties. The results exhibited that parallel orientation is better than perpendicular both in elasticity and compression. This is due to the unidirectional fibre in the parallel direction. Likewise, on the layup configuration, studies have reported that vertical arrangement performed better than horizontal (Yusof et al., 2023; Kariuki et al., 2014) due to the stiffer properties of carrying the load (Panellum et al., 2018) as compared to horizontal arrangement. The diversity of fabrication patterns, hence subject to be studied to develop a robust and appropriate material that can be utilised in structural application.

Therefore, this study aims to manufacture cross-laminated bamboo (CLB) from *Gigantochloa scortechinii* treated with copper chrome boron (CCB) bonded with phenol resorcinol formaldehyde (PRF). The CLB is fabricated in three different layup configurations: Type 1, which is horizontal-horizontal-horizontal (H-H-H); Type 2, horizontal-vertical-horizontal (H-V-H); and Type 3, vertical-horizontal-vertical (V-H-V). Figure 5.1 provides a summary of the research flow chart and variables investigated in this chapter. The objectives of the study were:

i) To examine the effect of different layups on the bending and compression properties of CLB;

ii) To observe the failure modes and understand the failure trends between the various layup configurations and their behaviour under loading stresses.

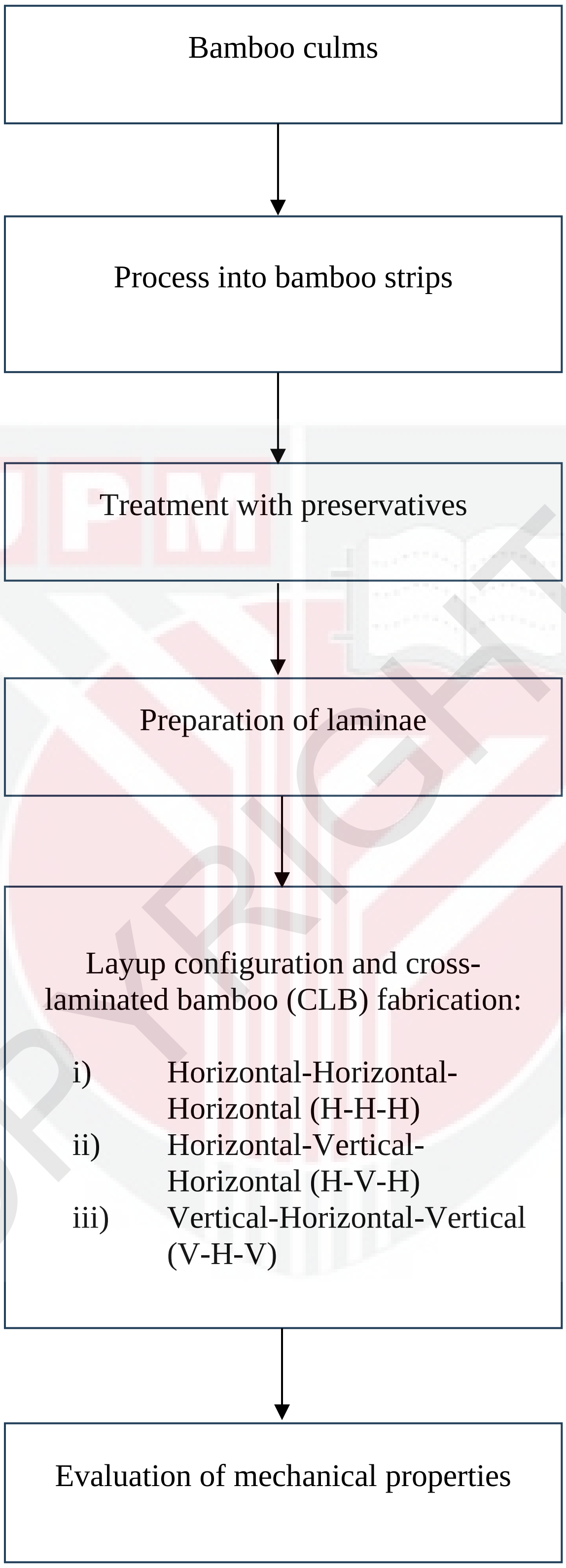


Figure 5.1: Study Research Flow Chart in Chapter 5

5.2 Materials and Methods

5.2.1 Preparation of Samples

A total of 140 bamboo poles of *Gigantochloa scortechinii*, each measuring 8 feet in length, were prepared following the procedure described in Section 3.2.1 of Chapter 3. This process produced 840 strips, each measuring 2400 mm x 20 mm x 5 mm. For this study, bamboo strips treated with 3% copper chrome boron (CCB) were used based on the results obtained from Chapter 4.

5.2.2 Preparation of Laminae

Figure 5.1 shows the manufacturing process of the three-layered CLB in this study that involved three distinct layup patterns. Bamboo strips were conditioned at a temperature of 20 ± 3 °C and a relative humidity of 65 ± 5 %, maintaining the EMC at ±12% prior to the fabrication process. Subsequently, the bamboo strips were categorised into two groups, and they were then assembled either edge-to-edge or face-to-face using PRF adhesive (Figure 5.2). This assembly process resulted in the formation of single-layered panels, termed as bamboo laminae (Figure 5.3). The terminologies employed to denote the orientation of the manufactured panels are "flatwise" and "edgewise," corresponding to the two orientations, respectively.

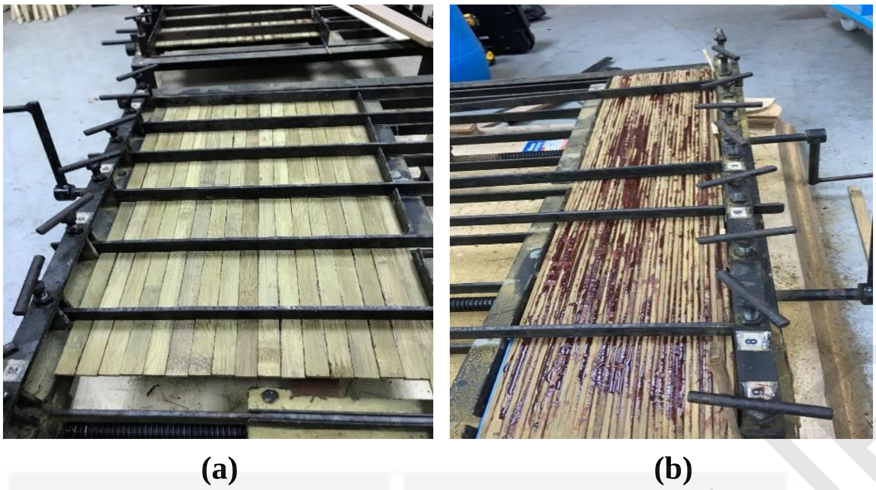


Figure 5.2: Bamboo Strips Assembled (a) Edge to Edge (Flatwise) and (b) Face to Face (Edgewise)

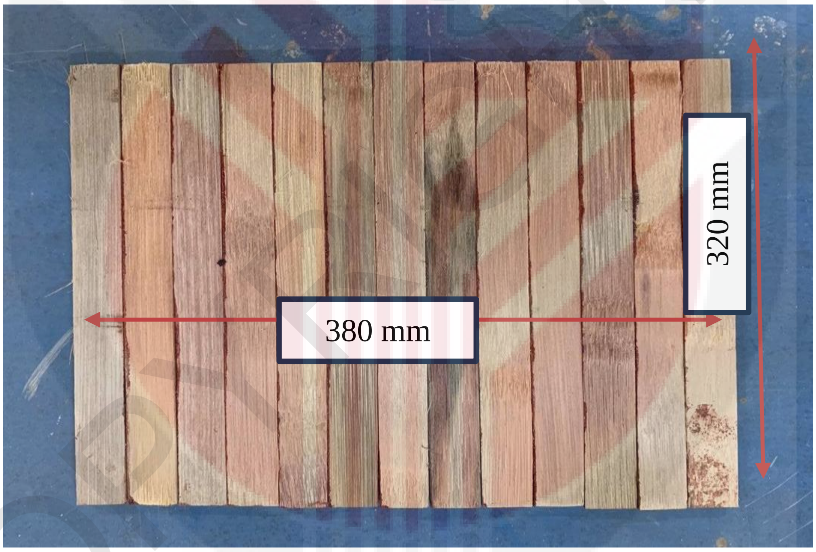


Figure 5.3: Example of a Close-up View of a Bamboo Laminae in Flatwise Orientation (Edge-to-Edge Bonded)

5.2.3 Layup Configurations and Cross-Laminated Bamboo (CLB) Fabrication

The laminae were conditioned at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 % for three days before being manufactured into three distinct types of board layups, incorporating combinations of flatwise and edgewise orientations as depicted in Figure 5.4.

Figure 5.4: Side View of the Layup Patterns: (a) Type 1 (H-H-H), (b) Type 2 (H-V-H) and (c) Type 3 (V-H-V)

In Type 1, the boards were manufactured with a flatwise orientation, denoted as H-H-H. For Type 2, the boards were fabricated with two laminae oriented flatwise and one laminae oriented edgewise (H-V-H). In Type 3, the boards were manufactured using two laminae-oriented edgewise and one lamina-oriented flatwise (V-H-V), as schematically illustrated in Figure 5.5.

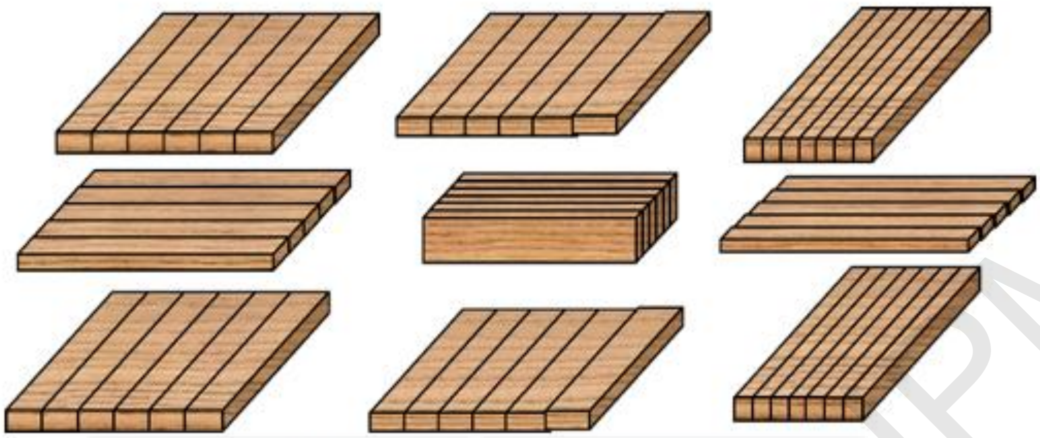


Figure 5.5: The Schematic Image from Front View (Cross Section) of Three Types of CLB

The dimensions of each layup differed due to the distinct combinations of flatwise and edgewise orientations. The dimensions for Type 1 were 380 mm (length) x 320 mm (width) x 15 mm (thickness). Type 2 boards have dimensions of 600 mm (length) x 300 mm (width) x 30 mm (thickness), while Type 3 boards measured at 880 mm (length) x 340 mm (width) x 45 mm (thickness). These orientations were designed in conjunction with the objectives of this study, which aim to determine the most suitable CLB orientation that resulted in better mechanical performances for structural purposes.

The three-layer boards were bonded with PRF with a 4:1 ratio (Adhesive: Hardener) at a spread rate of 300 g/m^2 and were then cold pressed at a pressure of 14 kg/m^2 for 3.5 h. Four replicates were prepared for each layup pattern, resulting in a total of 12 boards. Subsequently, the boards were conditioned for two weeks before subjected to testing.

5.2.4 Evaluation of Mechanical Properties

The mechanical tests conducted on CLB in this study were carried out following the European Standard BS EN 408:2010+A1 (2012) (Timber structures - structural timber and glued laminated timber). This standard is authorised for accessing the stiffness and strength properties of laminated wood, following the prEN 16351 standards. The selection of this standard is appropriate for the purpose of this study, as it aims to evaluate the suitability of CLB for structural applications.

5.2.4.1 Determination of bending strength and global modulus of elasticity in bending

Each type of CLB layup pattern was cut to match the test specimen's dimension specified in Table 5.1. Prior to testing, specimens were conditioned at a temperature of 20 ± 2 °C and a relative humidity of 65 ± 5 % until a constant mass was achieved. A total of 30 test specimens were subjected to bending tests using a 450 kN Universal Testing Machine. The load was applied in a flatwise direction, with a loading rate ranging from 0.02 to 0.04 mm/s, depending on the layup pattern. The four-point bending setup included loading points placed over a span equal to 18 times the depth of the specimen, as shown in Figure 5.6. The linear variable differential transformer (LVDT) was installed at the retrieved from the LVDT (Figure 5.7) and was recorded for analysis. Additionally, the failure modes were examined and documented after the test.

Table 5.1: The dimension of CLB test specimens for static bending

Layup pattern (side view)	Dimension of test specimens	Specimens quantity
Type 1: H-H-H 	310 mm (L) x 20 mm (W) x 15 mm (T)	10
Type 2: H-V-H 	600 mm (L) x 30 mm (W) x 30 mm (T)	10
Type 3: V-H-V 	880 mm (L) x 45 mm (W) x 45 mm (T)	10

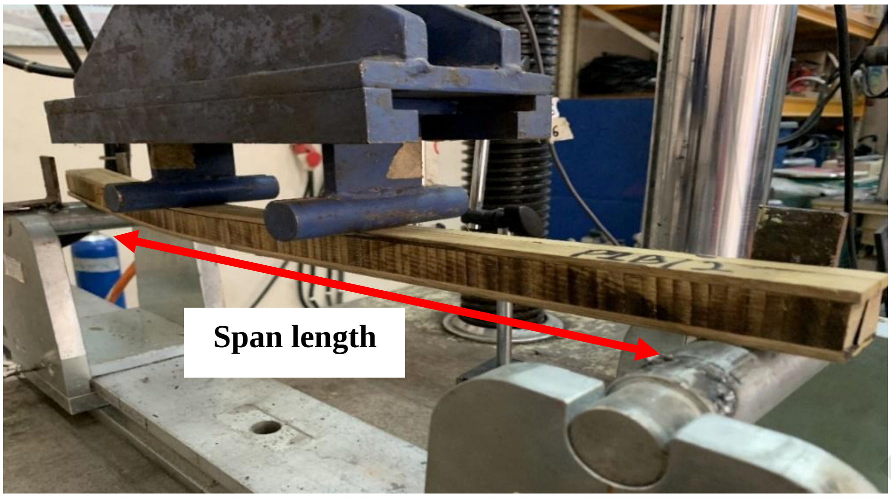


Figure 5.6: Static Bending Test Set-up

Figure 5.7: Installation of LVDT

The Modulus of Rupture (MOR) and Global Modulus of Elasticity (MOE) were determined using Equations 5.1 to 5.2 as follows:

$$\text{MOR (N/mm}^2\text{)} = \frac{3Fa}{bh^2} \qquad \textbf{[Equation 5.1]}$$

$$\text{Global MOE in bending (N//mm}^2) = \frac{3al^2 - 4al^3}{2bh^3\left(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh}\right)}$$ **[Equation 5.2]**

Where, F is the applied load, a is the distance between a loading position and the nearest support, b is the width of the specimen, h is the depth of the specimen, l is the span length, F_2-F_1 is an increment of load, G is the shear modulus and the shear modulus G shall be taken as infinite, and w_2-w_1 is the increment of the deformation corresponding to F_2-F_1.

MOE resulted from the test was adjusted at 12% moisture content according to BS EN 384 (2016) as below:

$$\text{MOE adjusted (N/mm}^2) = E_0(u)\,(1+0.01\,(u - u_{ref})$$ **[Equation 5.3]**

Where E_0 is the modulus of elasticity parallel to the grain, u is the moisture content at testing where $8\% \leq u \leq 18\%$ and u_{ref} is the reference moisture content, which normally at 12%.

In accordance with BS EN 384 (2016), the larger dimension of the board is typically referred to as "h", representing its depth. However, in this context, it is more suitable to refer to the larger dimension as the width. To address bending samples with a width of less than 150 mm, it is necessary to adjust the bending strength by dividing it by the factor k_h, as described in BS EN 384 (2016), as shown in Equation 5.4:

$$K_h = \text{Min}\begin{cases}\left(\frac{150}{h}\right)^{0.2} \\ 1.3\end{cases}$$ **[Equation 5.4]**

From Equation 5.4 above, explicitly, one can write and calculate the bending formula as Equation 5.5 and 5.6 below:

$f_{m,0,\ 150}$ (N/mm^2) = $\frac{f_{m,0}}{1.3}$, if h < 40 mm **[Equation 5.5]**

$f_{m,0,\ 150}$ (N/mm^2) = $f_{m,0}\left(\frac{150}{h}\right)^{-0.2}$, if 40 mm ≤ h < 150 mm **[Equation 5.6]**

Where $f_{m,0}$ is bending strength and h is width.

5.2.4.2 Determination of Compressive Strength and Compressive Modulus

A total of 30 test specimens were used to examine the compressive strength using a 450 kN Universal Testing Machine, following the standard of EN 408:2010+A1 (2012). The samples were cut into dimensions, as shown in Table 5.2.

Table 5.2: The dimension of CLB test specimens for compressive strength test

Layup pattern (side view)	Dimension	Specimens quantity
Type 1: H-H-H 	90 mm (L) x 20 mm (W) x 15 mm (T)	10
Type 2: H-V-H 	180 mm (L) x 30 mm (W) x 30 mm (T)	10
Type 3: V-H-V 	270 mm (L) x 45 mm (W) x 45 mm (T)	10

The test specimens were placed centrally with spherically seated loading heads, enabling a compressive load to be applied without inducing bending. The load was applied parallel to the grain of the material, with the loading rate ranging between 0.007 to 0.009 mm/s to ensure failure occurred within a specified time frame of (300 ± 120) s. The LVDT was installed on the samples to assess the deformation using a central gauge length equal to four times the sample thickness (Figure 5.8). All data were recorded, and failure modes were examined at the end of the test.

Figure 5.8: Compression Parallel to the Grain Test Set-up

The result for the determination of compressive strength and the compressive modulus (MOE) were calculated using Equation 5.7 – 5.8, as below:

Compressive strength (N/mm^2) = $\frac{F_{max}}{bh}$ **[Equation 5.7]**

Compressive modulus (N//mm^2) = $\frac{l_1(F_2 - F_1)}{A(w_2 - w_1)}$ **[Equation 5.8]**

Where, F_{max} is the maximum load, b is the width of the specimen, h is the depth of the specimen, l_1 is the gauge length, F_2-F_1 is an increment of load, and w_2-w_1 is the increment of the deformation corresponding to F_2-F_1.

The compressive strength obtained from the test was adjusted to account for a moisture content of 12% according to BS EN 384 (2016), as below:

Adjusted compressive strength (N/mm^2) = $f_{c,0}$ (u)(1+0.03(u-u_{ref})) **[Equation 5.9]**

Where, $f_{c,0}$ is the compressive strength, u is the moisture content at testing (8% ≤ u ≤18%) and u_{ref} is the reference moisture content normally at 12%.

5.2.5 Evaluation of Failure Mode in Bending and Compressive Strength

The failure behaviour of both bending and compressive strength was observed to anticipate their respective behaviour under applied load. These observations were then compared to the failure modes recommended by Bodig and Jayne (1993), as illustrated in Figure 5.9 and 5.10. The percentage of the failure mode for both tests was calculated according to their respective layups.

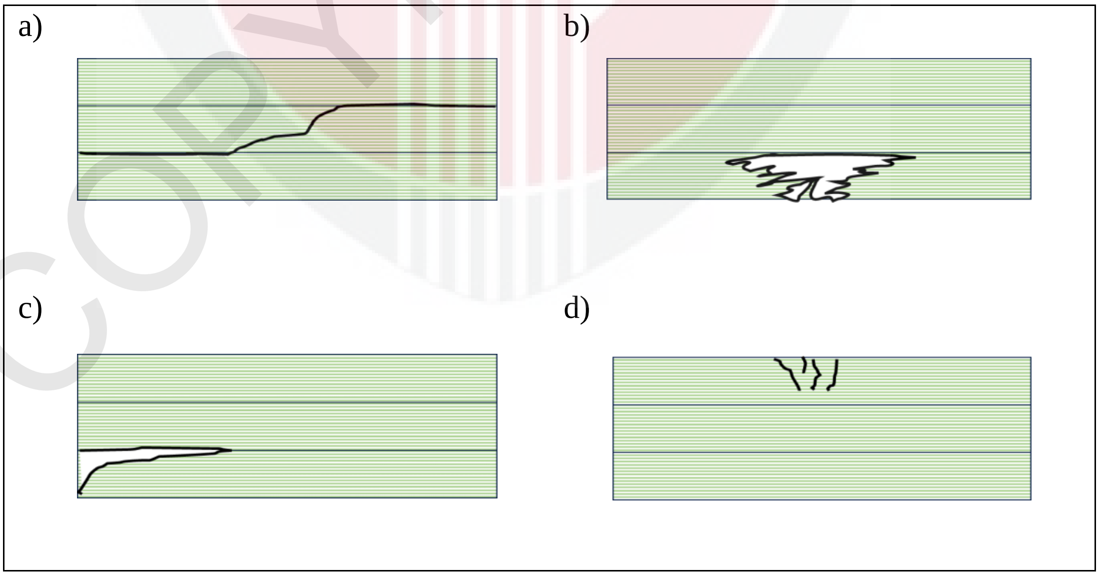


Figure 5.9: Figure 5.9: Illustration of Failure Mode for Bending Test
(a) Rolling shear, (b) Tension, (c) Glue line, and (d) Compression
(Source: Bodig & Jayne, 1993)

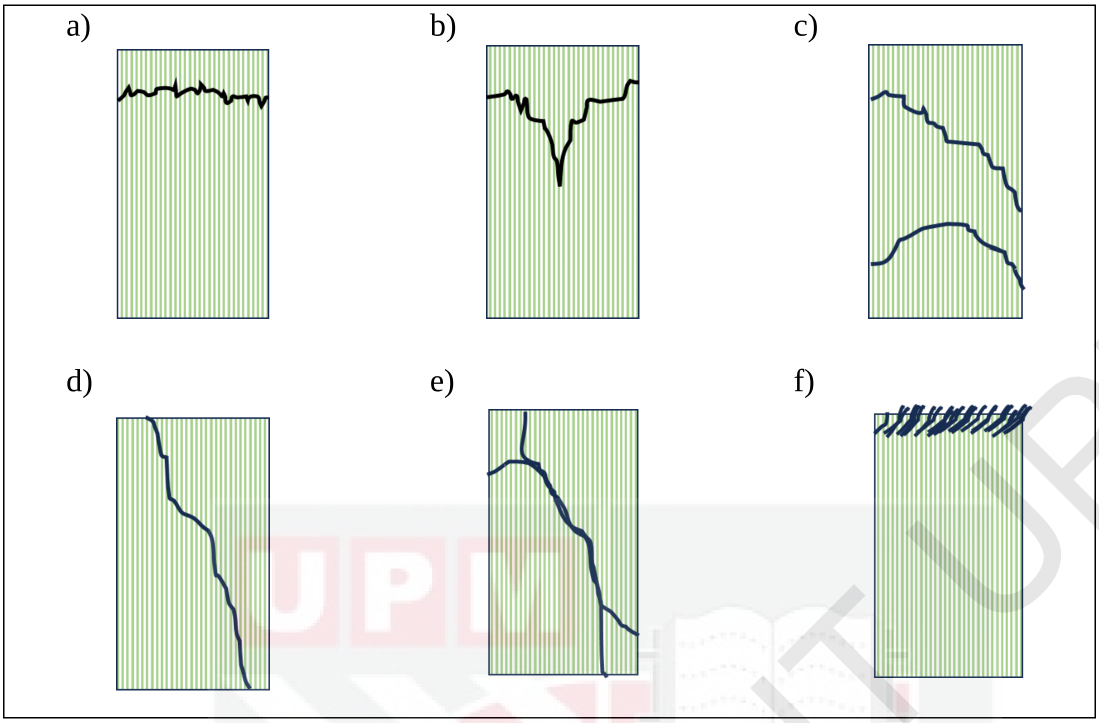


Figure 5.10: Illustration of Failure Mode for Compression Parallel to the Grain Test
(a) Crushing, (b) Wedge Splitting, (c) Shearing (d) Splitting, (e) Compression and Shearing, and (f) Brooming or End Rolling
(Source: Bodig & Jayne, 1993)

5.3 Results & Discussion

5.3.1 Bending Strength and Global Modulus of Elasticity in Bending

Table 5.3 presents the Analysis of Variance (ANOVA) of bending properties of CLB according to the layup. Based on the analysis, there was a significant difference in both MOR and Global MOE for CLB. Further analysis of the mean of the bending properties in each layup was carried out (Table 5.4), and the result emphasised the substantial impact of bamboo strip orientation and arrangement within CLB on its mechanical properties. Type 1 and Type 3 panels demonstrate comparable MOR values, with Type 3 showing notably higher values, while Type 2 exhibits the lowest strength. On the contrary, in MOE, Type 2 and Type 3 were recorded to have equal

MOE values, with Type 3 demonstrating higher values. Type 1, on the other hand, displayed the lowest value.

Table 5.3: Analysis of variance (ANOVA) on bending strength of different layups of CLB

Source	df	p-value	
		MOR	Global MOE
Layup	2	0.000*	0.000*

Note: *Significant at $p < 0.05$

Table 5.4: Mean values of MOR and Global MOE in CLB

Layup pattern	Strength properties	
	MOR (N/mm^2)	Global MOE (N/mm^2)
Type 1 (H-H-H)	46.57^a (5.95)	8526.30^c (1427.39)
Type 2 (H-V-H)	25.25^b (8.96)	12670.81^b (1829.53)
Type 3 (V-H-V)	55.25^a (15.11)	17432.29^a (1518.13)

Note: Values are an average of 30 specimens adjusted to 150 mm depth for MOR and 12% MC for MOE
Values in parenthesis are standard deviations
Means with the same letters ^{a,b} in the same column are not significantly different ($p<0.05$) according to Tukey HSD

In general, Type 3 exhibits the best performance for both MOR and MOE, which aligns with a study conducted by Wang et al. (2023). According to the study, vertical layup (Type 3) of Moso laminated bamboo obtained the highest MOR and MOE compared to horizontal layup due to the variations in the fibre arrangement along the vertical axis. This study explains that the neutral layer of vertical direction consistently remained at the centre of the sample height, whereas for horizontal layup, the neutral layer was displaced towards the top or bottom area. The statement aligns with the result for Type 3 panels that feature vertical layups on their faces (Figure 5.11). Upon observation, this layup includes both outer and inner sections, enabling them to contribute equally to resist the applied load.

Figure 5.11: Cross Section of Type 3 of Test Specimen

Similar to Type 3, Type 1 displayed higher MOR compared to Type 2 due to the homogeneity effects arising from the horizontal layup in all layers of CLB. This phenomenon is analogous to observations made in cross-laminated timber (CLT) by Flaig & Blaß (2014), where the presence of a perpendicular direction of horizontal layup in the transversal layer contributes positively to the overall bending strength by preventing the propagation of cracks within the longitudinal structure.

Type 1 and Type 2 had horizontal layups at the surfaces of the panel (Figure 5.12). However, the MOR of Type 2 was observed to be the lowest. This is possibly due to the effect of vertical layup orientation in the transversal layer. Upon observation, the top layer experienced compression from the applied load. As mentioned by Wang et al. (2023), the neutral axis of the horizontal layup (top layer) can be displaced depending on the load received. However, the neutral axis on the vertical layup may remain unchanged. These distinctions may result in a variation of load distribution in the test specimen that causes a lower load to initiate the failure.

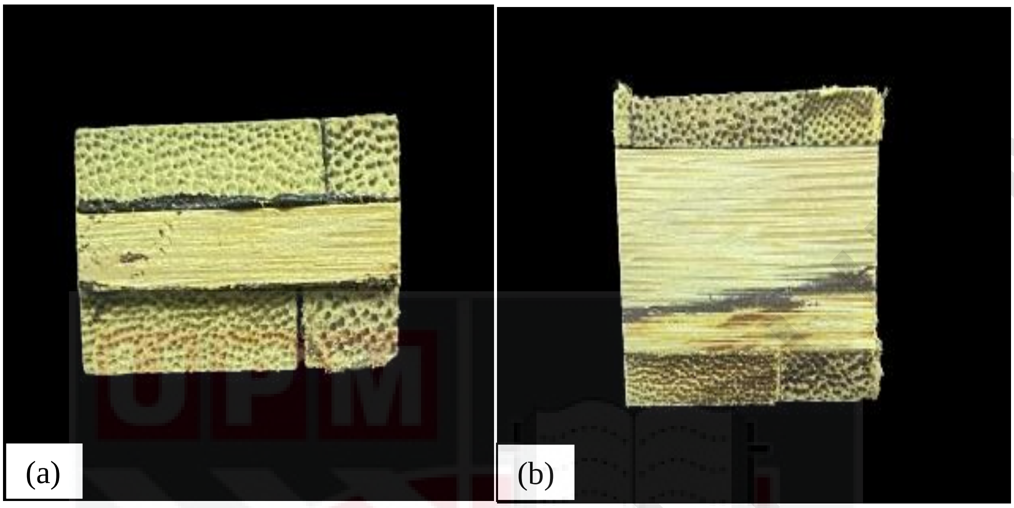


Figure 5.12: Cross Section of (a) Type 1 and (b) Type 2 of Test Specimen

There is a significant difference in Global MOE between all types of layups (Table 5.3), showing that Type 3 panels demonstrate the highest values, followed by Type 2 and Type 1, as shown in Table 5.4. This disparity most probably due to the bamboo volume fraction. A study conducted by Yusof (2023) observed that the vertical arrangement laminated bamboo composed of higher face-glued laminae, resulting in higher bamboo volume fraction. This observation can be seen in this study which Type 3 had higher face-glued laminae compared to Type 2 and Type 1. The similar finding has found by Penellum et al. (2018) who indicate a significant correlation between the volume fraction of bamboo and the bending stiffness of the boards.

5.3.2 Compressive Strength and Compressive Modulus (MOE)

Compressive strength represents the maximum stress a specimen can withstand during a test (Putri et al., 2022). A total of 30 test specimens from all layups were prepared, as shown in Table 5.2, and were tested for compressive strength. The data obtained were then analysed using ANOVA to determine the statistical significance of the mean values for each layup, as presented in Table 5.5. Based on the ANOVA, there is a significant difference in the mean values of compressive strength and compressive elasticity of CLB. Therefore, Table 5.6 presents the mean values of the compressive properties for each layup.

Table 5.5: Analysis of variance (ANOVA) on compression strength of different layups of CLB

Source	df	p-value	
		MOR	Compressive modulus (MOE)
Layup	2	0.000*	0.000*

Note: Significant at $p < 0.05$

Table 5.6: The mean value of compressive strength and MOE in CLB

Layup pattern	Compressive strength (N/mm^2)	Compressive modulus (MOE) (N/mm^2)
Type 1 (H-H-H)	23.72^{b} (1.44)	7124.13^{b} (2755.40)
Type 2 (H-V-H)	20.71^{c} (1.11)	6467.38^{b} (1018.24)
Type 3 (V-H-V)	55.69^{a} (3.52)	17650.88^{a} (5499.32)

Note: Values are an average of 30 specimens adjusted to 12% MC for compressive strength
Values in parenthesis are standard deviations
Means with the same letters ^{a,b} in the same column are not significantly different ($p<0.05$) according to Tukey HSD

Table 5.6 shows that Type 3 panels exhibited the highest strength, followed by Type 1 and Type 2, with compressive values of 55.69 N/mm^2, 23.72 N/mm^2 and 20.71 N/mm^2, respectively. In the respective order, the compressive modulus was also recorded as 17650.88 N/mm^2, 7124.13 N/mm^2, and 6467.38 N/mm^2. There were notably higher results in both compressive strength and modulus in Type 3, with an increase of approximately 169 % in compressive strength and about 173 % in modulus as compared to the lowest value panel, Type 2.

These findings suggest that the compressive properties are influenced by fibre orientation and thickness. A positive relationship between thickness and compressive strength in laminated bamboo lumber was reported by several studies (Kelkar et al., 2023; Manik et al., 2022; Zhang et al., 2021; Huang et al., 2015), which aligns with the result of this study. According to Osorio et al. (2018), the parallel arrangement of bamboo strips can enhance the load-bearing capacity of microfibrils, thereby resulting in higher compressive properties. In addition, Archila et al. (2019) concluded that higher elasticity is attributed to a greater proportion of longitudinally oriented material along the loading direction. Several researchers have reported similar findings (Deng et al., 2019; Sharma et al., 2017; Agustina et al., 2015) in their study on laminated bamboo of *Dendrocalamus asper* and Moso species.

Conversely, Type 2 panels had the lowest compressive properties due to the effect of vertical layup in the radial direction of bamboo strips (Figure 5.12) at the transverse layer. Leitner (2015) conducted a compression study, varying the applied load in transverse and longitudinal directions on the laminated bamboo lumber. The study reported that the transverse compressive strength was lower by 16.3% compared to the longitudinal compression. This is due to the collapse of vessel structure inside the vascular bundles, with a particular emphasis on the strained parenchyma, which is corroborated by Dixon and Gibson (2014).

In general, both the bending and compressive strength of CLB are comparable to engineered wood like CLT. CLT has become a demand due to their configurations and mechanical properties, making them ideal for building materials (Wang & Yin, 2021). However, when comparing the bending and compressive properties of CLB to CLT manufactured from fast-growing species (Bhkari et al., 2022), it was found that the properties were profoundly higher than those of CLT. The bending strength of those study CLT was reported to have values of 15.78 N/mm^2 and 16.66 N/mm^2 for Laran and Batai, respectively. Additionally, the compressive strength for the same species was reported at 14.33 N/mm^2 and 10.35 N/mm^2, respectively. Likewise, Yusof et al. (2019) observed that PRF-bonded *Acacia mangium* CLT exhibited bending and compressive strength values of 36.55 N/mm^2 and 28.99 N/mm^2. From these comparisons, it is highlighted that CLB has higher strength and is suitable for structural purposes. Comparison with commercial board for structural wall application like plywood and oriented strand board demonstrated that mechanical properties were lower than CLB with 46.6 N/mm^2 and 34.7 N/mm^2 for bending strength and 34.5 N/mm^2 and 17.2 N/mm^2 for compression strength, respectively (Zhiyong et al., 2021; Verma et al., 2014).

5.3.3 Failure Mode of CLB

In section 5.2.4, various types of bending failure have been presented in Figure 5.9 and 5.10. Bending failure typically occurs when the outer surface experiences compression and stress while the underlying surface is subjected to tension (Bodig & Jayne, 1993), as illustrated in Figure 5.11.

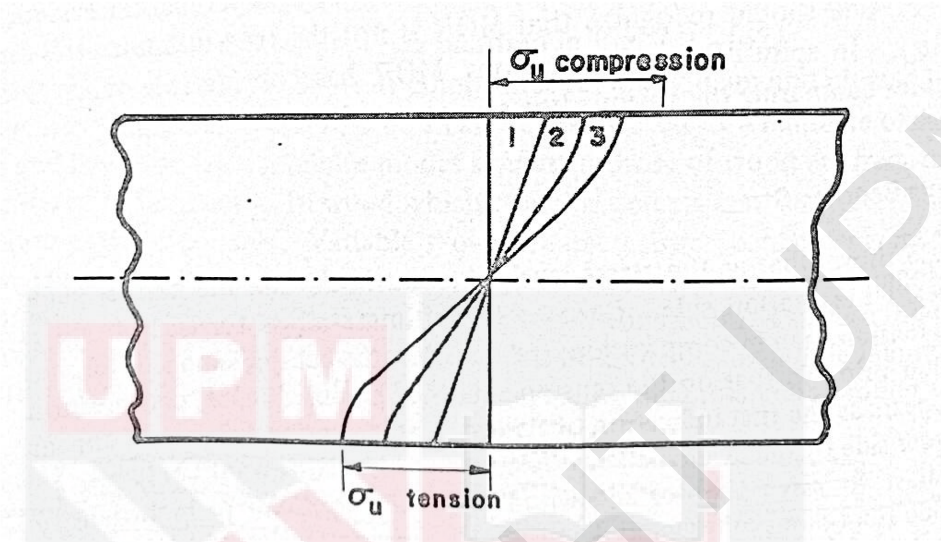


Figure 5.13: Stress Distribution in Wood Composite According to Bending Moment
(Source: Bodig & Jayne, 1982)

5.3.3.1 Bending Failure Mode

This study observed several types of failure throughout the four-point bending test (Figure 5.13). The failure was divided into four types, which are: (1) rolling shear, which occurred when the force was perpendicular to the direction of the grain; (2) compression failure, which occurred due to compression buckling at the top and tension at the bottom layer; (3) tension failure, happened when the tension occurred causing the bamboo to splinter slightly as the load force increased; and (4) glue line failure which occurred due to the weakened bond between the bamboo and adhesive, resulting to delamination. The percentage of bending failure modes varies according to their layups, as presented in Table 5.7.

Table 5.7: Percentage of failure mode in bending of CLB according to layups

Types of failure mode	Percentage (%)			Overall percentage (%)
	Type 1 (H-H-H)	Type 2 (H-V-H)	Type 3 (V-H-V)	
Rolling Shear	42	67	50	53.0
Compression	33	8	-	13.7
Tension	17	-	25	14.0
Glue line	8	25	25	19.3

Based on the overall failure mode percentage, shear failure emerged as the predominant failure mode across all layups for the bending test, with an average of 53%. This observation concurs with past studies (Lima et al., 2023; Lima et al., 2014), which reported that longitudinal shear failure in glued laminated bamboo frequently occurs at the adhesive surface. The second highest failure mode was recorded as glue line failure, with 19.3%. Comparing the layups, both Type 2 and Type 3 had more occurrences of glue line failure mode than Type 1. This high occurrence might be due to the weak point between two bonding surfaces: flatwise and edgewise of bamboo laminae. Dauletbek et al. (2022) and Verma & Chariar (2012) observed that glue line failure in bamboo laminates was also one of the predominant failure modes in bending tests, and it is believed to result from resin breakage during loading. The following failure mode is recorded as tension failure with 14%. Bodig & Jayne (1982) asserted that wood-composites exhibit high tension failure rates compared to compression failure, as obtained in this study. Numerous studies have reported tension failure in the bending strength of laminated bamboo, as evidenced by Li et al. (2018) and Rahman et al. (2015).

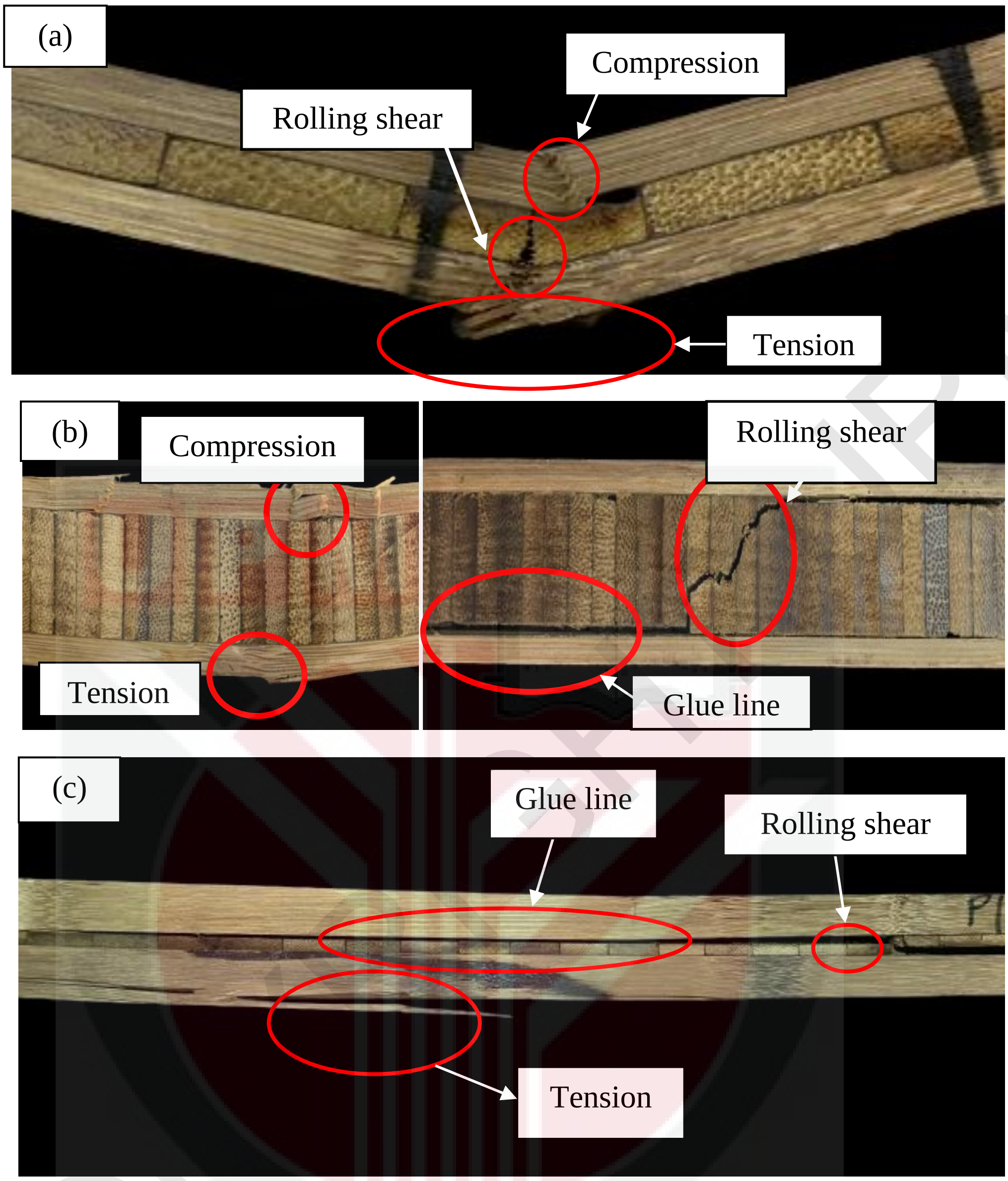


Figure 5.14: The Failure Mode of (a) Type 1, (b) Type 2, and (c) Type 3 After Bending Test

5.3.3.2 Compressive failure

Table 5.8 presents the percentage failure mode of the compression test according to the layups. Based on the observation, the failure modes of the compression test can be categorised into three distinct types: 1) crushing failure, which primarily occurs at the supports, predominantly due to the clamp exerting excessive pressure and causing the samples to be crushed; 2) shear failure, attributed to shearing occurring at the location with weak bonding and 3) splitting failure, which occurs to the sample divided longitudinally. The table indicates that crushing failure is the primary failure observed in all layups, accounting for 63% of the average. Meanwhile, 20% of the test specimens demonstrated splitting failure, and 17% showed shearing failure (Figure 5.15).

Table 5.8: Percentage of failure mode in compressive strength of CLB

Types of failure mode	Percentage (%)			Overall percentage (%)
	Type 1 (H-H-H)	Type 2 (H-V-H)	Type 3 (V-H-V)	
Crushing	30	70	90	63.3
Shear	30	10	10	16.7
Splitting	40	20	-	20.0

Figure 5.15: The Failure Mode of (a) Type 1, (b) Type 2, and (c) Type 3 After Compressive Test

A similar trend of failure has been observed in various studies, not limited to bamboo. Gharavi (2019) observed both shear and crushing failures in the compressive strength of two specimens: laminated bamboo lumber and spruce species. Wei et al. (2020) concluded that shear failure was the primary mode of failure in glulam bamboo subjected to axial loading. Bhkari et al. (2022) noted that crushing failure in cross-laminated timber manufactured from Laran and Batai was due to the weakness in compression and failure along the maximum compression line. Meanwhile, Alia Syahirah (2022) also observed shear and crushing failures in almost 80% and 12.5% of mono and mix species of cross-laminated timber, respectively.

Additionally, some specimens exhibited shearing failures associated with plane weaknesses. According to Muhammad Bazli Faliq and Zakiah (2017), the compression strength parallel to the grain is influenced by various variables, including material homogeneity, sample straightness, and even load distribution. Bodig & Jaynne (1982) explained that axially loaded samples tend to exhibit higher compression strength and a crushing failure mode. Conversely, eccentrically loaded samples are often reported to experience buckling and shearing. However, as further stated by Muhammad Bazli Faliq & Zakiah, (2017), the presence of defects within the same species used in the study can also influence the occurrence of crushing and shearing failures.

Furthermore, in splitting failure, a similar observation was also discovered by Zhang et al. (2021) in laminated bamboo lumber. Their study found that the increase in splitting was observed under higher pressure conditions, leading to fractures attributed to glue line failures. The same inability was also observed in a bamboo-plywood composite column studied by Zhao et al. (2016), which showed significant horizontal deformations. This observation aligns with the findings by Sharma et al. (2015), who reviewed various studies related to splitting failure in glued laminated bamboo.

5.4 Conclusion

In this study, CLB were manufactured into three types of layup configurations that were assessed for their mechanical properties, including bending and compression. The results revealed variations in MOR and MOE among the different layups, with Type 3 panels exhibiting the highest values in bending properties. A similar trend was observed in compression properties. The results conclude that the mechanical strength of CLB is primarily influenced by the orientation of the horizontal and vertical directions of laminae layups, owing due variations in the distribution of the fibres that differ according to the orientation. Additionally, the thickness within the board also influences the mechanical properties of CLB. During testing, several failure modes were also observed in bending, with rolling shear as the predominant failure, followed by glue line, compression and tension failure. Whereas in compression, three failure modes have been observed: crushing, splitting and shear failure.

CHAPTER 6

SUMMARY, CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

In order to understand the capabilities and versatility of bamboo as a structural application, several experimental studies have been conducted in this thesis. The primary objective of this study is to assess the viability of employing *Gigantochloa scortechinii* to produce cross-laminated bamboo (CLB) and investigate its mechanical properties for structural application.

To achieve the main objective of this study, the research has explicitly concentrated on three key areas: (1) investigating the effect of preservative treatment on the treatability, physical, and mechanical properties of bamboo strips, (2) evaluating the adhesion and bonding properties of boron-based preservatives treatment on CLB, and (3) assessing the effect of layup patterns on the mechanical properties of phenol resorcinol formaldehyde (PRF) bonded CLB.

The study findings have demonstrated a positive correlation between the concentration of preservative treatment and the resulting WPG and NDSR values. It was observed that a 3% concentration of CCB yielded values of 23.12% and 4.92 kg/m3 for WPG and NDSR, respectively. Further investigation revealed that the application of boron and CCB did not have a significant impact on the dimensional stability and strength characteristics of bamboo strips. Nevertheless, the investigation found that CCB exhibits superior mechanical qualities in comparison to boron preservatives.

The investigation of adhesion qualities through the analysis of contact angle wettability and buffering capacity of bamboo strips was found significant in regard to the treatment used in this study. The results showed a notable change in the adhesion characteristics after the treatments. The assessment of the pH and buffering capacity demonstrated that bamboo strips treated with CCB exhibited greater stability in alkaline conditions, which is compatible with PRF adhesive. This, in turn, had a positive effect on the bonding qualities of CLB under all pre-treatment conditions tested, particularly when a higher glue spread rate was applied.

The assessment of the mechanical properties of CLB revealed disparities in modulus of rupture (MOR) and global modulus of elasticity (MOE) among the various layups. The findings indicate that the mechanical strength of CLB is predominantly influenced by the arrangement of laminated bamboo (horizontal and vertical direction) and the composition of bamboo volume fraction as well as the fibre orientation. Type 3 boards, having vertical-horizontal-vertical (V-H-V) layup, display the optimum bending and compressive properties. Various failure modes were observed in both the bending and compression tests according to the layup. The most common failure modes in bending tests were rolling shear, glue line, compression, and tension failures. In compression tests, the failure modes observed were crushing, splitting, and shear failure.

The obtained result suggests that *Gigantochloa scortechinii* is a promising material for CLB boards used for structural applications. However, a study on leaching tests is recommended to assess the chemicals released from the specimens when they come into contact with water or other liquids to provide valuable insights into how leaching may affect the strength of the materials. This is due to that the treatments used in this study do not influence the shear strength in extreme conditions, that is, BDB and VP conditions. This lack of significant improvement could potentially be attributed to the leaching behaviour during the pre-treatment process. Finally, the development of a structural prototype is strongly recommended. Collaborations with the numerous wood industries in Malaysia can facilitate the manufacturing of such prototypes. This collaboration not only helps assess the suitability of CLB for structural applications but also encourages wood industries to explore new sources of raw materials in the construction sector, potentially leading to innovations and advancements in sustainable building materials.

REFERENCES

Abdullah, C. K., Jawaid, M., Khalil, H. A., Zaidon, A., & Hadiyane, A. (2012). Oil palm trunk polymer composite: morphology, water absorption, and thickness swelling behaviours. *BioResources*, *7*(3), 2948-2959.https://doi.org/10.15376/biores.7.3.2948-2959

Adewuyi, A. P., Otukoya, A., Olaniyi, O., Olafusi, O. (2015). Comparative studies of steel, bamboo and rattan as reinforcing bars in concrete: Tensile and flexural characteristics. Open Journal of Civil Engineering, 5(2), 228–238. DOI 10.4236/ojce.2015.52023.

Agustina, A., Nugroho, N., Bahtiar, E. T., & Hermawan, D. (2015). Karakteristik cross laminated bamboo sebagai bahan komposit struktural. *Journal of Agroindustrial Technology*, *25*(2). https://journal.ipb.ac.id/index.php/jurnaltin/article/view/10862

Ahmad, Z., Upadhyay, A., Ding, Y., Emamverdian, A., & Shahzad, A. (2021). Bamboo: Origin, Habitat, Distributions and Global Prospective. In *Biotechnological Advances in Bamboo*. Springer. https://doi.org/10.1007/978-981-16-1310-4

Akinbade, Y., Harries, K. A., Sharma, B., & Ramage, M. (2020). Variation of through-culm wall morphology in P. edulis bamboo strips used in glue-laminated bamboo beams. *Construction and Building Materials*, *232*, 117248. https://doi.org/10.1016/j.conbuildmat.2019.117248

Alade, A. A., Naghizadeh, Z., Wessels, C. B., & Tyhoda, L. (2022). A review of the effects of wood preservative impregnation on adhesive bonding and joint performance. *Journal of Adhesion Science and Technology*, *36*(15), 1593–1617. https://doi.org/10.1080/01694243.2021.1981651

Alia Syahirah, Y. (2022). *Adhesion characteristics and strength properties of cross laminated timber (CLT) manufactured from tropical hardwood species*. Universiti Putra Malaysia

Alia Syahirah, Y., Asniza, M., Mohd Nazrul, R., Ishak, M. R., & Anwar, U. M. K. (2023). Bonding and Finishing Properties of Bamboo Composite. In *Multifaceted Bamboo: Engineered Products and Other Applications* (pp. 131-144). Singapore: Springer Nature Singapore.

Alipon, M. A., Garcia, C. M., & Bondad, E. O. (2018). Glue and preservative effects on the properties and durability of engineered bamboo boards. *Philippine Journal of Science*, *147*(4), 601–616.

Amaral, L. M. D., Kadivar, M., Paes, J. B., Batista, D. C., Reis, M. C., Tarverdi, A., Godoy, A. S., & Savastano, H. (2023). Physical, mechanical, chemical, and durability assessment of water leaching treatment of bamboo. *Advances in Bamboo Science*, *5*, 100040. https://doi.org/10.1016/j.bamboo.2023.100040

Ameh, J., Soyingbe, A., & Oyediran, O. (2019). Acceptability and use of innovative bamboo products for the construction of residential buildings in Nigeria. International Journal of Technology, 10(4), 648. https://doi.org/10.14716/ijtech.v10i4.2574

Ammann, S., & Niemz, P. (2014). Mixed-mode fracture toughness of bond lines of PRF and PUR adhesives in European beech wood. *Holzforschung*, *69*(4), 415–420. https://doi.org/10.1515/hf-2014-0096

Anokye, R., Bakar, E. S., Ratnasingam, J., & Awang, B. K. (2016). Bamboo Properties and Suitability as a Replacement for Wood. *PJSRR Pertanika Journal of Scholarly Research Reviews*, *2*(1), 63–79. https://doi.org/10.13140/RG.2.1.1939.3048

Anokye, Rogerson (2015) *Effects of nodes and finger-jointed bamboo strips on properties of laminated bamboo timber from Gigantochloa scortechinii gamble*. [Doctoral thesis, Universiti Putra Malaysia]. http://psasir.upm.edu.my/id/eprint/57893/

Antwi-Boasiako, C., & Appiah Kyei, M. (2012). Effects of preservative-chemicals on the bonding strength of urea-formaldehyde adhesive in Bambusa vulgaris Schrad. ex J. C. Wendl. var. vulgaris hort. laminates. *Journal of the Indian Academy of Wood Science*, *9*(1), 72–78. https://doi.org/10.1007/s13196-012-0067-2

Anwar, U. M. K., Paridah, M. T., Hamdan, H., Abdul Latif, M., & Zaidon, A. (2005). Adhesion and bonding properties of plybamboo manufactured from Gigantochloa scortechinii. *American Journal of Applied Sciences*, *January*, 53–58.

Anwar, U. M. K., Paridah, M. T., Hamdan, H., Sapuan, S. M., & Bakar, E. S. (2009). Effect of curing time on physical and mechanical properties of phenolic-treated bamboo strips. *Industrial Crops and Products*, *29*(1), 214–219. https://doi.org/10.1016/j.indcrop.2008.05.003

Anwar, U. M. K., Zaidon, A., Hamdan, H., & Tamizi, M. M. (2005). Physical and mechanical properties of Gigantochloa scortechinii bamboo splits and strips. *Journal of Tropical Forest Science*, 1-12.

Appiah-Kubi, E., Awotwe-Mensah, M., & Mitchual, S. J. (2023). Assessment of physical and mechanical properties of juvenile and matured bambusa vulgaris glue-laminated bamboo for structural applications in Ghana. Sustainable Structures, 3(2). https://doi.org/10.54113/j.sust.2023.000026

Archila, H. F., Rhead, A., Ansell, M. P., Walker, P., & Lizarazo-Marriaga, J. (2019). Elastic response of cross-laminated engineered bamboo panels subjected to in-plane loading. *Proceedings of Institution of Civil Engineers: Construction Materials*, *172*(6), 284–295. https://doi.org/10.1680/jcoma.16.00080

Archila-Santos, H. F., Ansell, M. P., & Walker, P. (2012). Low carbon construction using Guadua Bamboo in Colombia. *Key Engineering Materials*, *517*(June), 127–134. https://doi.org/10.4028/www.scientific.net/KEM.517.127

Ariffin, W. T. W. (2005). *Numerical analysis of laminated bamboo strip lumber (LBSL)* (Doctoral dissertation, University of Birmingham).

Aristri, M. A., Lubis, M. A. R., Iswanto, A. H., Fatriasari, W., Sari, R. K., Antov, P., Gajtanska, M., Papadopoulos, A. N., & Pizzi, A. (2021). Bio-based polyurethane resins derived from tannin: Source, synthesis, characterisation, and application. *Forests*, *12*(11). https://doi.org/10.3390/f12111516

Ashraf, M., Hasan, M. J., Al-Deen, S. (2021). Semi-rigid behaviour of stainless steel beam-to-column bolted connections. Sustainable Structures, 1(1), 000002. DOI 10.54113/j.sust.2021.000002.

Asniza, M., Y, A. S., A, M. F., Sh, L., & Uyup, M. K. A. (2022). Properties of plybamboo manufactured from two Malaysian bamboo species—. *Physical Sciences Reviews*, *0*(0). https://doi.org/10.1515/psr-2022-0049

ASTM D7334-08. (2022). Standard practice for surface wettability of coatings, substrates and pigments by advancing contact angle measurement. ASTM International, West Conshohocken, Pennsylvania:

Augustina, S., Wahyudi, I., Darmawan, W., Malik, J., Basri, E., & Kojima, Y. (2020). Specific Gravity and Dimensional Stability of Boron-Densified Wood on Three Lesser-Used Species from Indonesia. *Journal of the Korean Wood Science and Technology*, *48*(4), 458–471. https://doi.org/10.5658/wood.2020.48.4.458

Ayanleye, S., Udele, K., Nasir, V., Zhang, X., & Militz, H. (2022). Durability and protection of mass timber structures: a review. *Journal of Building Engineering. Elsevier Ltd.*, 1–57. https://doi.org/10.1016/j.jobe.2021.103731

Aydin, I., & Colakoglu, G. (2006). Variation in surface roughness, wettability and some plywood properties after preservative treatment with boron compounds. *Building and Environment*, *42*(11), 3837–3840. https://doi.org/10.1016/j.buildenv.2006.11.009

Aydin, I., & Colakoglu, G. (2007). Variation in surface roughness, wettability and some plywood properties after preservative treatment with boron compounds. *Building and Environment*, *42*(11), 3837–3840. https://doi.org/10.1016/j.buildenv.2006.11.009

Ayrilmis, N., Kartal, S. N., Laufenberg, T. L., Winandy, J. E., & White, R. H. (2005). Physical and mechanical properties and fire, decay, and termite resistance of treated oriented strandboard. *Forest Products Journal*, *55*(5), 74–81. https://apps.dtic.mil/dtic/tr/fulltext/u2/a439379.pdf

Azeez, M. A., & Orege, J. I. (2018). Bamboo, its chemical modification and products. *Bamboo-current and future prospects*. IntechOpen. https://doi.org/10.5772/intechopen.76359

Bahru, T., & Ding, Y. (2021). A Review on Bamboo Resource in the African Region: A Call for Special Focus and Action. *International Journal of Forestry Research*, *2021*, 10–12. https://doi.org/10.1155/2021/8835673

Baraúna, E. E. P., Paes, J. B., Monteiro, T. C., Moulin, J. C., Ferreira, G. L., da Silveira, A. G., Baldin, T., Junior, C. R. S., & Arantes, M. D. C. (2021). Influence of the impregnation with boron compounds on the physical properties of Eucalyptus wood. *Scientia Forestalis/Forest Sciences*, *48*(128), 1–9. https://doi.org/10.18671/SCIFOR.V48N128.09

Baysal, E., Tomak, E. D., Topaloglu, E., & Pesman, E. (2016). Surface properties of bamboo and scots pine impreg with boron & copper-based. *Maderas: Ciencia y Tecnologia*, *18*(2), 253–264. https://doi.org/10.4067/S0718-221X2016005000023

Baysal, E., Yalinkilic, M. K., & Altinok, M. (2006). Determination of Boron Given To Wood Calculated by Some Expression Types. *Wood Research*, *51*(3), 77–84.

Bekhta, P., & Marutzky, R. (2007). Reduction of glue consumption in the plywood production by using previously compressed veneer. *Holz Als Roh - Und Werkstoff*, *65*(1), 87–88. https://doi.org/10.1007/s00107-006-0142-8

Bhkari, N. M., Chen, L. W., Azmi, A., Nordin, M. S., Yam, N. W. S., Ahmad, Z., & Hua, L. S. (2022). Bending, Compression and Bonding Performance of Cross-Laminated Timber (CLT) Made from Malaysian Fast-Growing Timbers. *Journal of Renewable Materials*, *10*(11), 2851–2869. https://doi.org/10.32604/jrm.2022.022326

Biswas, D., Bose, S. K., & Hossain, M. M. (2011). Physical and mechanical properties of urea formaldehyde-bonded particleboard made from bamboo waste. *International Journal of Adhesion and Adhesives*, *31*(2), 84–87. https://doi.org/10.1016/j.ijadhadh.2010.11.006

Bodig J and Jayne BA. (1993). Mechanics of wood and wood composites. Melbourne, FL: Krieger Pub Co. 712p.

Bodig, J., & Jayne, B. A. (1982). *Mechanics of wood and wood composites*. http://ci.nii.ac.jp/ncid/BA03256139

Bons, H. K., & Dhawan, S. (2013). Studies on preservation of guava pulp. *Indian Journal of Horticulture*, *70*(3), 452–454. https://www.cabdirect.org/cabdirect/abstract/20143045748

Borowski, P. F., Patuk, I., & Bandala, E. R. (2022). Innovative industrial use of bamboo as key “Green” material. *Sustainability*, *14*(4), 1955. https://doi.org/10.3390/su14041955.

BS EN 408: 2010 + A1: 2012. (2012). Timber structures - Structural timber and glued laminated timber - Determination of some physical and mechanical properties. British Standards Institution, London, United Kingdom.

Caldeira, F. (2010). Boron in wood preservation: a review in its physico-chemical aspects. *Silva Lusitana*, *18*(2), 179–196. https://www.cabdirect.org/cabdirect/abstract/20113299833

Can, A. (2017). The effects of industrial-scale heat treatment and impregnation with boron compounds on some physical, mechanical and biological properties of wood. *August*. https://doi.org/10.13140/RG.2.2.27938.94400

Canavan, S., Richardson, D. M., Visser, V., Le Roux, J. J., Vorontsova, M. S., & Wilson, J. R. U. (2017). The global distribution of bamboos: Assessing correlates of introduction and invasion. *AoB PLANTS*, *9*(1), 1–18. https://doi.org/10.1093/aobpla/plw078

Castaneda, H., & Bjarnadottir, S. (2016). Analysis of the Bolted Connection of a Bamboo Composite I-Shaped Beam Subjected to Bending. *Procedia Engineering*, *145*(December), 796–803. https://doi.org/10.1016/j.proeng.2016.04.104

Castanet E., Li Q., Dumée L.F., Garvey C., Rajkhowa R., Zhang J., Rolfe, B., Magniez, K. (2016) Structure-property relationships of elementary bamboo fibers. Cellulose 23(6):3521–3534. https://doi.org/10.1007/s10570-016-1078-8

Chen, G., Yu, Y., Li, X., & He, B. (2020). Mechanical behavior of laminated bamboo lumber for structural application: an experimental investigation. *European Journal of Wood and Wood Products*, *78*(1), 53–63. https://doi.org/10.1007/s00107-019-01486-9

Chen, M., Ye, L., Li, H., Wang, G., Chen, Q., Fang, C., Dai, C., & Fei, B. (2020). Flexural strength and ductility of moso bamboo. *Construction and Building Materials*, *246*, 118418. https://doi.org/10.1016/j.conbuildmat.2020.118418

Chen, Z., Wagoner, R., Gandhi, U., Lee, J. (2016). Variation and consistency of young’s modulus in steel. Journal of Materials Processing Technology, 227, 227–243. DOI 10.1016/j.jmatprotec.2015.08.024

Chow, A. W., Ramage, M., & Shah, D. U. (2019). Optimising ply orientation in structural laminated bamboo. *Construction and Building Materials*, *212*, 541–548. https://doi.org/10.1016/j.conbuildmat.2019.04.025

Chung, K., & Yu, W. (2002). Mechanical properties of structural bamboo for bamboo scaffoldings. Engineering Structures, 24, 429-442. https://doi.org/10.1016/S0141-0296(01)00110-9

Clark, L. G., Londoño, X., & Ruiz-Sanchez, E. (2015). Bamboo taxonomy and habitat. *Bamboo: The plant and its uses*, 1-30. In *Bamboo The Plant and its Uses*. Springer. https://doi.org/10.1007/978-3-319-14133-6_1

Colakoglu, G., Colak, S., Aydin, I., Yildiz, U., & Yildiz, S. (2003). Effect of boric acid treatment on mechanical properties of laminated beech veneer lumber. *Silva Fennica*, *37*(4). https://doi.org/10.14214/sf.488

Correal, J. F., & Ramírez, F. (2010). Adhesive bond performance in glue line shear and bending for glued laminated guadua bamboo. *Journal of Tropical Forest Science*, *22*(4), 433–439. https://www.cabdirect.org/cabdirect/abstract/20113018595

D, J. C. R. and C, J. M. O. (2010). Influence of age and height position on colombian guadua angustifolia bamboo mechanical properties. Maderas. Ciencia Y Tecnología, 12(2). https://doi.org/10.4067/s0718-221x2010000200005

Dauletbek, A., Li, H., & Lorenzo, R. (2023). A review on mechanical behavior of laminated bamboo lumber connections. *Composite Structures*, *313*(March), 116898. https://doi.org/10.1016/j.compstruct.2023.116898

Dauletbek, A., Li, H., Lorenzo, R., Corbi, I., Corbi, O., & Ashraf, M. (2022). A review of basic mechanical behavior of laminated bamboo lumber. *Journal of Renewable Materials*, *10*(2), 273–300. https://doi.org/10.32604/jrm.2022.017805

Dauletbek, A., Li, H., Xiong, Z., & Lorenzo, R. (2021). A review of mechanical behavior of structural laminated bamboo lumber. *Sustainable Structures*, *1*(1), 1–18. https://doi.org/10.54113/j.sust.2021.000004

De Souza Almeida, A., Criscuolo, G., De Almeida, T. H., Christoforo, A. L., & Lahr, F. A. R. (2019). Influence of treatment with water-soluble CCB preservative on the physical-mechanical properties of brazilian tropical timber. *Materials Research*, *22*(6). https://doi.org/10.1590/1980-5373-MR-2018-0688

Deng, J., He, L., & Zhu, A. (2019). Effect of laminated structure design on physical and mechanical properties of laminated bamboo sliver lumber. *BioResources*, *14*(1), 421–430. https://doi.org/10.15376/biores.14.1.421-430

Dixon, P., & Gibson, L. (2014). The structure and mechanics of Moso bamboo material. *Journal of the Royal Society Interface*, *11*(99), 20140321. https://doi.org/10.1098/rsif.2014.0321

Edi Suhaimi, B., Mohd Nazip, M. N., Anokye, R., & Lee, S. H. (2019). Comparison of three processing methods for laminated bamboo timber production. *Journal of Forestry Research*, *30*(1), 363–369. https://doi.org/10.1007/s11676-018-0629-2

Elejoste, A., Arevalillo, A., Gabilondo, N., Butron, A., & Peña-Rodríguez, C. (2021). Morphological Analysis of Several Bamboo Species with Potential Structural Applications. *Polymers*, *13*(13), 2126. https://doi.org/10.3390/polym13132126

EN 384:2016. (2016). Structural timber- Determination of characteristics value of mechanical properties and density. British Standards Institution, London, United Kingdom.

Fahim, M., Haris, M., Khan, W., & Zaman, S. (2022). Bamboo as a construction material: prospects and challenges. Advances in Science and Technology – Research Journal, 16(3), 165-175. https://doi.org/10.12913/22998624/149737

Faria, D. L., Cruz, T. M., Dias, M. C., Duarte, P. J., Mendes, L. M., & Guimarães, J. B., Junior. (2020). Physical and mechanical behavior of glulam beams produced with rubberwood treated with preservatives. *Ciência E Agrotecnologia*, *44*.

Fidan, M. S., & Adanur, H. (2019). Physical and mechanical properties of wood impregnated with quebracho and boron compounds. *Forestist*, *69*(1), 68–80. https://doi.org/10.26650/forestist.2019.041645

Flaig M and Blaß HJ. (2014). Bending strength of cross laminated timber beams loaded in plane. In Proceedings of the World Conference on Timber Engineering: proceedings: 2014 August 10-14; Salenikovich A (Ed.): Quebec City, Canada. p. 39-48.

Food and Agriculture Organization of the United Nations (FAO) (2021) Putting bamboo on the map. Available from https://www.fao.org/forestry/nwfp/98924/en/

Forest Products Laboratory. (2021). *Wood handbook wood as an engineering material*.

Forestry Department Peninsular Malaysia. (2014). *Laporan Inventori Hutan Nasional Kelima (IHN-5)*. Jabatan Perhutanan Semenanjung Malaysia (FDPM).

Frihart, C. R., & Hunt, C. G. (2010). Adhesives with wood materials: bond formation and performance. *Wood handbook: wood as an engineering material*, 10-1

Gauss, C., Harries, K. A., Kadivar, M., Akinbade, Y., & Savastano Jr., H. (2020). Quality assessment and mechanical characterization of preservative-treated Moso bamboo (P. edulis). *European Journal of Wood and Wood Products*, *78*(2), 257–270. https://doi.org/10.1007/s00107-020-01508-x

Gauss, C., Kadivar, M., & Savastano Jr., H. (2019). Effect of disodium octaborate tetrahydrate on the mechanical properties of Dendrocalamus asper bamboo treated by vacuum/pressure method. *Journal of Wood Science*, *65*(1). https://doi.org/10.1186/s10086-019-1804-6

Gauss, C., Kadivar, M., Harries, K. A., & Savastano Jr., H. (2021). Chemical modification of Dendrocalamus asper bamboo with citric acid and boron compounds: Effects on the physical-chemical, mechanical and thermal properties. *Journal of Cleaner Production*, *279*, 123871. https://doi.org/10.1016/j.jclepro.2020.123871

Gecer, M., Baysal, E., Toker, H., Turkoglu, T., Vargun, E., & Yuksel, M. (2015). The effect of boron compounds impregnation on physical and mechanical properties of wood polymer composites. *Wood Research*, *60*(5), 723–738

Gharavi, N. (2019). *Investigations into the Application of Engineered Bamboo for Future Hybrid Beams* (Issue August). https://doi.org/10.1016/j.ijadhadh.2018.05.009

Global Forest Resources Assessment (FRA) 2020: Main report (2020) Food and Agriculture Organization of the United Nations (FAO), Rome, Italy

Gnanaharan, R., Janssen, J. J. A, & Arce, O. A. (1995). *Bending strength of guadua bamboo : comparison of different testing procedures*. International Network for Bamboo and Rattan. https://pure.tue.nl/ws/files/4234110/776469.pdf

Guan, X., Yin, H., Liu, X., Wu, Q., & Gong, M. (2018). Development of lightweight overlaid laminated bamboo lumber for structural uses. *Construction and Building Materials*, *188*, 722–728. https://doi.org/10.1016/j.conbuildmat.2018.08.107

Hamdan, H. (2004). *Characterization of mechanical properties and behaviour of Giganthochloa scortechinii for structural application* (Doctoral dissertation, PhD Thesis. University of Wales, Bangor).

Hamdan, H., Uyup, M. K. A., Ashaari, Z., & Mustafa, M. T. (2009). Mechanical properties and failure behaviour of Gigantochloa scortechinii. *Journal of Tropical Forest Science*, *21*(4), 336–344. https://www.frim.gov.my/v1/jtfsonline/jtfs/V21n4/336-344.pdf

Handana, M., Surbakti, B., & Karolina, R. (2020). The effect of borax solution as preservative to the mechanical properties of bamboo. *International Journal of Sustainable Construction Engineering and Technology*, *11*(2), 79–88. https://doi.org/10.30880/ijscet.2020.11.02.009

Harries, K. A. (2023). Material characterisation of bamboo for glued-laminated products. *Advances in Bamboo Science*, *3*, 100023

He, M., Li, Z., Sun, Y., & Ma, R. (2015). Experimental investigations on mechanical properties and column buckling behavior of structural bamboo. *The Structural Design of Tall and Special Buildings*, *24*(7), 491–503. https://doi.org/10.1002/tal.1176

Himasree, P. R., Ganesan, N., & Indira, P. V. (2017). Bamboo as a substitute for steel in reinforced concrete wall panels. *IOP Conference Series: Earth and Environmental Science*, *80*(1). https://doi.org/10.1088/1755-1315/80/1/012041

Hisham, H. N., Othman, S., Rokiah, H., Latif, M. A., Ani, S., & Tamizi, M. M. (2006). Characterization of bamboo Gigantochloa scortechinii at different ages. *Journal of Tropical Forest Science*, 236-242

Huang, D., Bian, Y., Zhou, A., & Sheng, B. (2015). Experimental study on stress–strain relationships and failure mechanisms of parallel strand bamboo made from phyllostachys. *Construction and Building Materials*, *77*, 130–138. https://doi.org/10.1016/j.conbuildmat.2014.12.012

Huang, Y., Ji, Y., & Yu, W. (2019). Development of bamboo scrimber: a literature review. Journal of Wood Science, 65(1). https://doi.org/10.1186/s10086-019-1806-4

Huang, Y., Qi, Y., Zhang, Y., & Yu, W. (2019). Progress of bamboo recombination technology in china. *Advances in Polymer Technology*. https://doi.org/10.1155/2019/2723191

Huang, Z. R., Chen, Z. F., Huang, D. S., Zhou, A. P. (2016). The ultimate load-carrying capacity and deformation of laminated bamboo hollow decks: Experimental investigation and inelastic analysis. Construction and Building Materials, 117, 190–197. DOI 10.1016/j.conbuildmat.2016.04.115.

Hugot, F., & Cazaurang, G. (2009). Mechanical properties of an extruded Wood Plastic Composite. *Mecanique et Industries*, *10*(6), 519–524. https://doi.org/10.1051/meca/2010010

Icimoto, F. H., Ferro, F. S., Varanda, L. D., Souza, A. M., de Almeida, D. H., Christoforo, A. L., & Lahr, F. A. R. (2013). Physical and Mechanical Properties of Paricá Wood Species Treated with CCB Preservative. *International Journal of Materials Engineering*, *3*(4), 82–86. https://doi.org/10.5923/j.ijme.20130304.03

INBAR (2022) Trade Overview 2020: *Bamboo and Rattan Commodities in the International Market*. INBAR: Beijing, China

IS 8242. (1976). Methods of tests for split bamboos. Bureau of Indian Standards, Old Delhi, India.

ISO 12466-1. (2007). Plywood-Bonding Quality – Part 1. International Organisation for Standardisation, Geneva, Switzerland.

ISO 12466-2 (2007). Plywood – Bonding quality – Part 2. International Organisation for Standardisation, Geneva, Switzerland.

ISO 13061-13 (2017). “Physical and mechanical properties of wood -- Test methods for small clear wood specimens,” International Organization for Standardization, Geneva, Switzerland

ISO 13061-15 (2017). “Physical and mechanical properties of wood — Test methods for small clear wood specimens — Part 15: Determination of radial and tangential swelling,” International Organization for Standardization, Geneva, Switzerland.

Itoh, T., & Shimaji, K. (1981). Lignification of bamboo culm (phyllostachys pubescens) during its growth and maturation Bamboo Production and Utilization Proc. In *XVII IUFRO Congress Group 5.3. Ed. T. Higuchi Kyoto Japan* (Vol. 10, pp. 101-4).

James, J.P., Edwin, L., & Pulikottil, J.J. (2019). Effectiveness of Copper –Chrome-Boron as a Wood Preservative-A Short Review.

Javadian, A., Smith, I., Saeidi, N., & Hebel, D. (2019). Mechanical properties of bamboo through measurement of culm physical properties for composite fabrication of structural concrete reinforcement. Frontiers in Materials, 6. https://doi.org/10.3389/fmats.2019.00015

Jin, X. B., Jiang, Z. H., Wen, X. W., Zhang, R., Qin, D. C. (2017). Flame retardant properties of laminated bamboo lumber treated with monoammonium phosphate (MAP) and boric acid/Borax (SBX) compounds. Bioresources, 12(3), 5071–5085. DOI 10.15376/biores.12.3.5071-5085.

Jivkov, V., Simeonova, R., Antov, P., Marinova, A., Petrova, B., & Kristak, L. (2021). Structural application of lightweight panels made of waste cardboard and beech veneer. *Materials*, *14*(17). https://doi.org/10.3390/ma14175064

Jorissen, A. J. M., Voermans, J., & Jansen, M. H. (2007). Glued-laminated bamboo: Node and joint failure in bamboo laminations loaded in tension. *Journal of Bamboo and Rattan*, *6*(3–4), 137–144.

Junior, A. S. S., Junior, J. L. A., Torres, S. M., Barros, S., Ortiz, S. R., & Barbosa, N. P. (2009). Bamboo pH and absorption in different liquids. *11th International Conference on Non-Conventional Materials and Technologies (NOCMAT 2009), September 6-9, September*, 6–9.

Kadivar, M., Gauss, C., Tomazello-Filho, M., Ahrar, A. J., Ghavami, K., & Savastano, H. (2021). Optimization of thermo-mechanical densification of bamboo. *Construction and Building Materials*, *298*, 123860. https://doi.org/10.1016/j.conbuildmat.2021.123860

Kamal, I., Poh, K. M., Eng, T. Y., Ren, X. J., Zaidon, A., Abood, F., Beyer, G., & Masseat, K. (2010). Buffering capacity of Fast-Growing species and curing time of UF resin modified with zinc borate and monoammonium phosphate. *American Journal of Applied Sciences*, *7*(8), 1079–1082. https://doi.org/10.3844/ajassp.2010.1079.1082

Kaminski, S., Lawrence, A., Trujillo, D. J. A., & King, C. (2016). *Structural use of bamboo: Part 2: Durability and preservation Development of grading methods for bamboo View project*. *October*. www.thestructuralengineer.org

Kampmann, R., Telikapalli, S., Ruiz Emparanza, A., Schmidt, A. E., Dulebenets, M. (2021). Tensile properties of basalt fiber-reinforced polymer reinforcing bars for reinforcement of concrete. ACI Materials Journal, 118(1), 111–126. DOI 10.14359/51729288.

Kamruzzaman, M., Saha, S. K., Bose, A. K., & Islam, M. N. (2008). Effects of age and height on physical and mechanical properties of bamboo. *Journal of Tropical Forest Science*, 211-217

Kariuki, J., Nyomboi, T., & Mumenya, S. (2014). Effect of orientation and arrangement of bamboo strips on structural strength of laminated bamboo beam. *International Journal of Engineering Sciences & Emerging Technologies*, *7*(2), 555-567

Kartal, S. N., Hwang, W. J., & Imamura, Y. (2008). Combined effect of boron compounds and heat treatments on wood properties: Chemical and strength properties of wood. *Journal of Materials Processing Technology*, *198*(1–3), 234–240. https://doi.org/10.1016/j.jmatprotec.2007.07.001

Kelchner, S. A. (2013). Higher level phylogenetic relationships within the bamboos (Poaceae: Bambusoideae) based on five plastid markers. *Molecular Phylogenetics and Evolution*, *67*(2), 404–413. https://doi.org/10.1016/j.ympev.2013.02.005

Kelkar, B. U., Shukla, S. R., Nagraik, P., & Paul, B. N. (2023). Structural bamboo composites: A review of processing, factors affecting properties and recent advances. *Advances in Bamboo Science*, *3*(January), 100026. https://doi.org/10.1016/j.bamboo.2023.100026

Kelkar, B.U., Sharma, S.K., Shukla, S.R., 2021. Comparative performance of phenol formaldehyde- bonded laminated bamboo lumber and bamboo strand lumber prepared from four different bamboo species. J. Trop. For. Sci 33 (4), 482–493. https://doi.org/10.26525/jtfs2021.33.4.482

Kewei, L., Jayaraman, D., Yongjiu, S., Harries, K., Yang Jun, J. W. et al. (2022). Bamboo: A very sustainable construction material-2021 international online seminar summary report. Sustainable Structures, 2(1), 00015. https://doi.org/10.54113/j.sust.2022.000015

Khalil, H. A., Bhat, I. U. H., Jawaid, M., Zaidon, A., Hermawan, D., & Hadi, Y. S. (2012). Bamboo fibre reinforced biocomposites: A review. *Materials & Design*, *42*, 353-368.https://doi.org/10.1016/j.matdes.2012.06.015

Khoo, P. S., Chin, K. L., Lee, C. L., H'ng, P. S., & Hafizuddin, M. S. (2021). Effect of glue spreads on the structural properties of laminated veneer lumber from spindleless rotary veneers recovered from short rotation hevea plantation logs. *Polymers*, *13*(21). https://doi.org/10.3390/polym13213799

Kilmer, R. W., Blankenhorn, P. R., Labosky, P., Janowiak, J. J. (1998). Wood Fiber Sci. 30,175

Kinata, S. E., Loubar, K., Paraschiv, M., Bouslamti, A., Belloncle, C., & Tazerout, M. (2013). Slow pyrolysis of CCB-treated wood for energy recovery: Influence of chromium, copper and boron on pyrolysis process and optimization. *Journal of Analytical and Applied Pyrolysis*, *104*, 210–217. https://doi.org/10.1016/j.jaap.2013.08.002

Konnerth, J., Harper, D., Lee, S., Rials, T. G., & Gindl, W. (2007). Adhesive penetration of wood cell walls investigated by scanning thermal microscopy (SThM). *Holzforschung*, *62*(1), 91–98. https://doi.org/10.1515/hf.2008.014

Koski, A., & Ahonen, R. (2008). *Applicability of crude tall oil for wood protection*

Kumar, D., Mandal, A., 2022. Review on manufacturing and fundamental aspects of laminated bamboo products for structural applications. Constr. Build. Mater. 348, 128691. https://doi.org/10.1016/j.conbuildmat.2022.128691

Kurhekar, S. P. (2014). Studies of mechanical properties of treated bamboo. *Engineering and Technology in India*, *5*(1&2), 44–48. https://doi.org/10.15740/has/eti/5.1and2/44-48

Kurt, R. (2003). The strength of press-glued and screw-glued wood-plywood joints. *European Journal of Wood and Wood Products*, *61*(4), 269–272. https://doi.org/10.1007/s00107-003-0397-2

Lee, A. W. C., Bai, X., & Bangi, A. P. (1998). Selected properties of laboratory-made laminated-bamboo lumber. *Holzforschung*, *52*(2), 207–210. https://doi.org/10.1515/hfsg.1998.52.2.207

Lee, S. H., Md Tahir, P., Osman Al-Edrus, S. S., & Uyup, M. K. A. (2023). Bamboo Resources, Trade, and Utilisation. In *Multifaceted Bamboo: Engineered Products and Other Applications* (pp. 1-14). Singapore: Springer Nature Singapore

Leitner, P. (2015). Structural Bamboo-Mechanical Properties and Potential Fields of Application. *Graz University of Technology*

Li, D., Thomas, J., Leroux, P. (2020). Yield and tensile strength of steel and aluminum. https://www.researchgate.net/publication/340003398_Yield_and_Tensile_Strength_of_Steel_and_Aluminum

Li, H. T., Deeks, A. J., Zhang, Q. S., & Wu, G. (2016). Flexural performance of laminated bamboo lumber beams. *BioResources*, *11*(1), 929–943. https://doi.org/10.15376/biores.11.1.929-943

Li, H. T., Wu, G., Xiong, Z., Corbi, I., Corbi, O., Xiong, X., Zhang, H., & Qiu, Z. (2019). Length and orientation direction effect on static bending properties of laminated Moso bamboo. *European Journal of Wood and Wood Products*, *77*(4), 547–557. https://doi.org/10.1007/s00107-019-01419-6

Li, H. T., Zhang, Q., Huang, D., & Deeks, A. (2013). Compressive performance of laminated bamboo. *Composites Part B: Engineering*, *54*, 319–328. https://doi.org/10.1016/j.compositesb.2013.05.035

Li, W., & He, S. (2019). Research on the Utilisation and Development of Bamboo Resources through Problem Analysis and Assessment. *IOP Conference Series: Earth and Environmental Science*, *300*(5). https://doi.org/10.1088/1755-1315/300/5/052028

Li, X. B., Shube, T., & Hse, C. (2004). Wettability of three Honduran bamboo species. *Journal of Bamboo and Rattan*, *3*(2), 159–167. https://doi.org/10.1163/156915904774195151

Li, Z., Chen, C., Mi, R., Gan, W., Dai, J. (2020). A strong, tough, and scalable structural material from fastgrowing bamboo. Advanced Materials, 32(10), 1906308. https://doi.org/ 10.1002/adma.201906308.

Li, Z., Gao, Y., Zhou, Q., Shan, B., & Xiao, Y. (2018). Bending performance of glubam beams made with different processes. *Advances in Structural Engineering*, *22*(2), 535–546. https://doi.org/10.1177/1369433218794327

Lian, C., Liu, R., Zhang, S., Yuan, J., Luo, J., Yang, F., & Fei, B. (2020). Ultrastructure of parenchyma cell wall in bamboo (Phyllostachys edulis) culms. *Cellulose*, *27*(13), 7321–7329. https://doi.org/10.1007/s10570-020-03265-9

Liese, W. (1980b). Anatomy of bamboo. In Bamboo research in Asia. In *Proceedings of a workshop held in Singapore* (pp. 161–164). Singapore: Ottawa: International Development Research Centre

Líese, W. (1998). *The anatomy of bamboo culms*. https://doi.org/10.1163/9789004502468

Liese, W., & Tang, T. K. H. (2015). *Preservation and drying of bamboo*. 257–297. https://doi.org/10.1007/978-3-319-14133-6_9

Liese, W., and Kumar, S. (2003). *Bamboo Preservation Compendium*, INBAR Publication, Beijing, China

Liese., W. (1985). Anatomy and properties of bamboo. Recent research on bamboos. Proceedings of the International Bamboo Workshop. October 6-14, Hangzhou, China

Lima, D. de., M., Lima Júnior, H. C., & Medeiros, I. da S. (2023). Physical and Mechanical Properties of Glued Laminated Bamboo. In *BioResources* (Vol. 18, Issue 2, pp. 3522–3539). https://doi.org/10.15376/biores.18.2.3522-3539

Lima, D. M. de, Amorim, M. M., Lima Júnior, H. C., Barbosa, N. P., & Wilrich, F. L. (2014). Avaliação do comportamento de vigas de bambu laminado colado submetidas à flexão. *Ambiente Construído*, *14*(1), 15–27. https://doi.org/10.1590/s1678-86212014000100003

Lima, D., Júnior, H., & Medeiros, I. (2023). Physical and mechanical properties of glued laminated bamboo. BioResources, 18(2), 3522–3539. https://doi.org/10.15376/biores.18.2.3522-3539

Lv, Q., Han, T., Liu, Y., Ding, Y., & Lu, Y. (2021). An experimental and analytical study on cross-laminated bamboo rocking walls with friction dampers. *Journal of Renewable Materials*, *9*(10), 1757–1779. https://doi.org/10.32604/jrm.2021.015536

Mahdavi, M., Clouston, P. L., & Arwade, S. R. (2011). Development of Laminated Bamboo Lumber: Review of Processing, Performance, and Economical Considerations. *Journal of Materials in Civil Engineering*, *23*(7), 1036–1042. https://doi.org/10.1061/(asce)mt.1943-5533.0000253

Malanit, P., Barbu, M. C., & Frühwald, A. (2011). Physical and mechanical properties of oriented strand lumber made from an Asian bamboo (Dendrocalamus asper Backer). *European Journal of Wood and Wood Products*, *69*(1), 27–36. https://doi.org/10.1007/s00107-009-0394-1

Malaysian Timber Industry Board. (2022). *Malaysian Timber Statistic*. Malaysian Timber Industry Board

Maldas, D. C., & Kamdem, D. P. (1998). Surface Tension and Wettability of Cca-treated Red Maple. *Wood and Fiber Science*, *30*(4), 368–373

Maloney, T. M. (1977). Modern Particleboard and Dry-Process Fiberboard Manufacturing. In *Miller Freeman Publications Inc., San Francisco*

Manik, P., Samuel, S., Tuswan, T., Jokosisworo, S., & Nadapdap, R. K. (2022). Mechanical properties of laminated bamboo composite as a sustainable green material for fishing vessel: Correlation of layer configuration in various mechanical tests. *Journal of the Mechanical Behavior of Materials*, *31*(1), 673–690. https://doi.org/10.1515/jmbm-2022-0075

Marx, C. N., & Moody, R. C. (1981). Bending Strength of Shallow Glued-Laminated Beams of a Uniform Grade. *USDA Forest Service Research Paper FPL (Forest Products Laboratory)*, *380*

Maulana, M. I., Marwanto, M., Nawawi, D. S., Nikmatin, S., Febrianto, F., & Kim, N. H. (2020). Chemical components content of seven Indonesian bamboo species. *IOP Conference Series: Materials Science and Engineering*, *935*(1). https://doi.org/10.1088/1757-899X/935/1/012028

Mbhamali, N. Q. (2021). Evaluating the influence of CCA and DOT wood preservative treatments on one component laminated P. patula polyurethane bond performance. https://scholar.sun.ac.za:443/handle/10019.1/110096

Melo, R., Stangerlin, D., Sant'Ana, R., & Pedrosa, T. (2014). Physical and mechanical properties of particleboard manufactured from wood, bamboo and rice husk. Materials Research, 17(3), 682-686. https://doi.org/10.1590/s1516-14392014005000052

Meng, F., Yu, Y., Zhang, Y., Yu, W., & Gao, J. (2016). Surface chemical composition analysis of heat-treated bamboo. *Applied Surface Science*, *371*, 383–390. https://doi.org/10.1016/j.apsusc.2016.03.015

Mera, F. A. T., & Xu, C. (2014). Plantation Management and Bamboo Resource Economics in China. *Ciencia y Tecnología*, *7*(1), 1. https://doi.org/10.18779/cyt.v7i1.181

Mili, M., Singhwane, A., Hada, V., Naik, A., Nair, P. B., Srivastava, A. K., & Verma, S. (2023). Advances in Bamboo Composites for Structural Applications: a review. In *IntechOpen eBooks*. https://doi.org/10.5772/intechopen.110489

Mohd Tamizi, M., Hamdan, H., Abdul Latif, M., & Amir Saaiffudin, K. (2019). *Commercial Bamboos of Malaysia*. Forest Research Institute Malaysia

Mohmod, A. L., & Mustafa, M. T. (1992). Variation in anatomical properties of three Malaysian bamboos from natural stands. *Journal of Tropical Forest Science*, 90-96

Mokeramin, M. (2020). Chemical effect on the mechanical properties of bamboo fiber for textile: a review. International Journal of Advanced Trends in Computer Science and Engineering, 9(1.4), 353-359. https://doi.org/10.30534/ijatcse/2020/5191.42020

Mounika, M., Ramaniah, K., Prasad, A.V.R., Rao, K.M., Reddy, K.H.C. (2012). Thermal conductivity characterisation of bamboo fiber reinforced polyester composite. J. Mater. Environ. Sci. 3 (6), 1109–1116

MS 833 (1984). “Qualitative analysis of wood preservatives and treated timbers - Test methods,” Department of Standards Malaysia, Cyberjaya, Malaysia

Muhammad Bazli Faliq, M. P., & Zakiah, A. (2017). *Comparing the Compressive Strength Properties of Structural Size and Small Clear Specimens for Malaysian Tropical Timber*. *29*(1), 25–29

Mulyana, N. and Reorita, N. (2022). Culm characteristics of yellow bamboo (bambusa vulgaris var. striata) from private forest in sleman regency, yogyakarta. Journal of Sylva Indonesiana, 5(02), 103-112. https://doi.org/10.32734/jsi.v5i02.7536

Nayeri, M. D., Tahir, P. M., Harun, J., Abdullah, L. C., Bakar, E. S., Jawaid, M., & Namvar, F. (2013). Effects of temperature and time on the morphology, pH, and buffering capacity of bast and core kenaf fibres. *BioResources*, *8*(2), 1801–1812. https://doi.org/10.15376/biores.8.2.1801-1812

Nkeuwa, W. N., Zhang, J., Semple, K. E., Chen, M., Xia, Y., & Dai, C. (2022). Bamboo-based composites: A review on fundamentals and processes of bamboo bonding. *Composites Part B: Engineering*, *235*(December 2021), 109776. https://doi.org/10.1016/j.compositesb.2022.109776

Norhasliya, M. D., Norazman, M. N., Mohammed Alias, Y., Azrul Affandhi Mustaffa, A. B., & Amalina Aisyah, S. (2018). The physical and mechanical properties of treated and untreated Gigantochloa Scortechinii bamboo. *AIP Conference Proceedings*, *1930*. https://doi.org/10.1063/1.5022910

Nugroho, N., & Ando, N. (2001). Development of structural composite products made from bamboo II: Fundamental properties of laminated bamboo lumber. *Journal of Wood Science*, *47*(3), 237–242. https://doi.org/10.1007/BF01171228

Nur Amira, A., Paridah, M. T., Hamdan, H., Lee, S. H., Mohd Khairun, A. U., Mohamad Nasir, M. A., & Zaidon, A. (2021). Effect of ACQ treatment on surface quality and bonding performance of four Malaysian hardwoods and cross laminated timber (CLT). *European Journal of Wood and Wood Products*, *79*(2), 285–299. https://doi.org/10.1007/s00107-020-01609-7

Ogunsanwo, O. Y., Adenaiya, A. O., & Adedeji, C. A. (2019). Effect of adhesive quantity on selected physico-mechanical properties of bamboo glulam. *Maderas: Ciencia y Tecnologia*, *21*(1), 113–122. https://doi.org/10.4067/S0718-221X2019005000111

Osorio, L., Trujillo, E., Lens, F., Ivens, J., Verpoest, I., & Van Vuure, A. W. (2018). In-depth study of the microstructure of bamboo fibres and their relation to the mechanical properties. *Journal of Reinforced Plastics and Composites*, *37*(17), 1099–1113. https://doi.org/10.1177/0731684418783055

Özçifçi, A., Örs, Y., & Uysal, B. (2007). Determination of some physical and mechanical properties of laminated veneer lumber impregnated with boron compounds. *Journal of Applied Polymer Science*, *105*(4), 2218–2224. https://doi.org/10.1002/app.26217

Paridah, M. ., Zaidon, A., & A.M.E, C. (2001). Bonding properties of Azadirachta excelsa. *Journal of Tropical Forest Science*, *7*(2), 161–171

Paridah, M. T., Hafizah, A. W. N., Zaidon, A., Azmi, I., Nor, M. Y. M., & Yuziah, M. Y. N. (2009). Bonding properties and performance of multi-layered kenaf board. *Journal of Tropical Forest Science*, *21*(2), 113–122

Penellum, M., Sharma, B., Shah, D. U., Foster, R. M., & Ramage, M. (2018). Relationship of structure and stiffness in laminated bamboo composites. *Construction and Building Materials*, *165*, 241–246. https://doi.org/10.1016/j.conbuildmat.2017.12.166

Percin, O., Sofuoglu, S. D., & Uzun, O. (2015). Effects of boron impregnation and heat treatment on some mechanical properties of oak (Quercus petraea Liebl.) wood. *BioResources*, *10*(3), 3963–3978. https://doi.org/10.15376/biores.10.3.3963-3978

Prance, G. T., & Findlay, W. P. K. (1986b). Preservation of timber in the tropics. *Brittonia*, *38*(2), 188. https://doi.org/10.2307/2807280

prEN 16351: 2011 (2011). Timber structures – Cross laminated timber – Requirement. British Standards Institution, London, United Kingdom

Priadi, T., Lestari, M. D., & Cahyono, T. D. (2021). Posttreatment effects of castor bean oil and heating in treated jabon wood on boron leaching, dimensional stability, and decay fungi inhibition. *Journal of the Korean Wood Science and Technology*, *49*(6), 602–615. https://doi.org/10.5658/wood.2021.49.6.602

Putri, A. R., Alam, N., Adzkia, U., Amin, Y., Darmawan, I. W., & Karlinasari, L. (2022). Physical and Mechanical Properties of Oriented Flattened Bamboo Boards from Ater (Gigantochloa atter) and Betung (Dendrocalamus asper) Bamboos. *Jurnal Sylva Lestari : Journal of Sustainable Forest*, *11*(1), 1–21. https://doi.org/10.23960/jsl.v11i1.614

Rabbi, M. F., Islam, M. M., & Rahman, A. N. M. M. (2015). Wood preservation : Improvement of mechanical properties by vacuum pressure process. *International Journal of Engineering and Applied Sciences*, *2*(2), 75–79. http://www.gkpublication.in/IJRR_Vol.4_Issue.2_Feb2017/IJRR004.pdf

Rahman, A., & Farhana, N. F. (2015). *Strength and dimensional stability of phenolic-treated bamboo-laminated panel*. Universiti Putra Malaysia. http://psasir.upm.edu.my/id/eprint/69871/

Rassiah, K., Ahmad, M. Z., & Ali, A. (2014). Mechanical properties of laminated bamboo strips from Gigantochloa Scortechinii/polyester composites. *Materials in Engineering*, *57*, 551–559. https://doi.org/10.1016/j.matdes.2013.12.070

Razak, W. (1998). Effect of selected preservatives on the durability of *Gigantochloa scortechinii*. A PhD thesis, University of London, U.K

Razak, W., Mahmud, S., Janshah, M., & Awang Ahmad, M. Y. (2005). Penetration class and net dry salt retention of ammoniacal copper quartenary, borax boric acid and copper chrome arsenic in 2 and 4 year-old bamboo Gigantochloa scortechinii. *Journal of Biological Sciences*, *5*(4), 511–518. https://doi.org/10.3923/jbs.2005.511.518

Reynolds, T., Sharma, B., Serrano, E., Gustafsson, P., & Ramage, M. (2019). Fracture of laminated bamboo and the influence of preservative treatments. Composites Part B Engineering, 174, 107017. https://doi.org/10.1016/j.compositesb.2019.107017

Rittironk, S., & Elnieiri, M. (2008). Investigating laminated bamboo lumber as an alternate to wood lumber in residential construction in the United States. In *Taylor & Francis eBooks* (pp. 83–96). https://doi.org/10.1201/9780203888926.ch9

Rosyidah, A., Sucita, I. K., & Hidayat, F. (2018). The Bond Strength of Glass Fiber Reinforced Polymer (GFRP) Reinforcement with Monolith Concrete. *International Journal on Advanced Science, Engineering and Information Technology*, *8*(2), 495. https://doi.org/10.18517/ijaseit.8.2.4346

Roziela Hanim, A., Zaidon, A., Abood, F., & Anwar, U. M. K. (2010). Adhesion and Bonding Characteristics of Preservative-Treated Bamboo (Gigantochloa scortechinii) Laminates. *Journal of Applied Sciences*, *10*(14), 1435–1441. https://doi.org/10.3923/jas.2010.1435.1441

Roziela Hanim, A., Zaidon, A., Anwar, U. M. K., & Rafidah, S. (2013). Effects of chemical treatments on durability properties of Gigantochloa scortechinii strips and ply-bamboo. *Asian Journal of Biological Sciences*, *6*(3), 153–160. https://doi.org/10.3923/ajbs.2013.153.160

Ruiz-Sanchez, E., & Clark, L. G. (2018). Are There Wild Bamboos in Mexico? *Frontiers for Young Minds*, *6*(January), 1–8. https://doi.org/10.3389/frym.2018.00001

Rust, M. K., & Su, N. (2012). Managing social insects of urban importance. *Annual Review of Entomology*, *57*(1), 355–375. https://doi.org/10.1146/annurev-ento-120710-100634

Saikia, P., Dutta, D., Kalita, D., Bora, J., & Goswami, T. (2015). Improvement of mechano-chemical properties of bamboo by bio-chemical treatment. *Construction and Building Materials*, *101*, 1031–1036. https://doi.org/10.1016/j.conbuildmat.2015.10.106

Sewar, Y. Y., Zhang, Z., Meng, X., Wahan, M. Y., Qi, H., Al-Shami, Q. M., & Luo, S. (2022). Mechanical properties and constitutive relationship of the high-durable parallel strand bamboo. *Journal of Renewable Materials*, *10*(1), 219–235. https://doi.org/10.32604/jrm.2021.016013

Sewar, Y., Amran, M., Avudaiappan, S., Gamil, Y., & Rashid, R. S. M. (2024). Bonding strength performance of bamboo-based composite materials: An in-depth insight for sustainable construction applications. *Heliyon*, *10*(13), e32155. https://doi.org/10.1016/j.heliyon.2024.e32155

Shah, D. U., Bock, M., Mulligan, H., & Ramage, M. (2015). Thermal conductivity of engineered bamboo composites. *Journal of Materials Science*, *51*(6), 2991–3002. https://doi.org/10.1007/s10853-015-9610-z

Shah, D. U., Sharma, B., & Ramage, M. (2018). Processing bamboo for structural composites: Influence of preservative treatments on surface and interface properties. *International Journal of Adhesion and Adhesives*, *85*, 15–22.

Shanu, S., Das, A., Rahman, M., & Ashaduzzaman, M. (2015). Effect of chromate-copper-boron preservative treatment on physical and mechanical properties of Raj koroi (Albizia richardiana) wood. *Bangladesh Journal of Scientific and Industrial Research*, *50*(3), 189–192. https://doi.org/10.3329/bjsir.v50i3.25583

Sharma, B., & Van Der Vegte, A. (2020). Engineered bamboo for structural applications. In *Elsevier eBooks* (pp. 597–623). https://doi.org/10.1016/b978-0-08-102704-2.00021-4

Sharma, B., Bauer, H., Schickhofer, G., & Ramage, M. H. (2017). Mechanical characterisation of structural laminated bamboo. *Proceedings of the Institution of Civil Engineers: Structures and Buildings*, *170*(4), 250–264. https://doi.org/10.1680/jstbu.16.00061

Sharma, B., Gatóo, A., & Ramage, M. (2015). Effect of processing methods on the mechanical properties of engineered bamboo. *Construction and Building Materials*, *83*, 95–101. https://doi.org/10.1016/j.conbuildmat.2015.02.048

Sharma, B., Gatóo, A., Bock, M., & Ramage, M. (2015). Engineered bamboo for structural applications. *Construction and Building Materials*, *81*(September), 66–73. https://doi.org/10.1016/j.conbuildmat.2015.01.077

Sharma, B., Gatoo, A., Bock, M., Mulligan, H., & Ramage, M. (2015). Engineered bamboo: State of the art. *Proceedings of Institution of Civil Engineers: Construction Materials*, *168*(2), 57–67. https://doi.org/10.1680/coma.14.00020

Sharma, B., Shah, D. U., Beaugrand, J., Janeček, E. R., Scherman, O. A., & Ramage, M. H. (2018). Chemical composition of processed bamboo for structural applications. *Cellulose*, *25*, 3255-3266

Shen-xue, J., Qi-sheng, Z., & Shu-hai, J. (2002). On Structure, production, and market of bamboo-based panels in China. *Journal of Forestry Research*, *13*(2), 151–156. https://doi.org/10.1007/bf02857243

Shirmohammadi, M., & Leggate, W. (2021). Review of existing methods for evaluating adhesive bonds in timber products. In *Engineered Wood Products for Construction* (p. 30).

Siam, N. A., Uyup, M. K. A., Hamdan, H., Mohmod, A. L., & Awalludin, M. F. (2019). Anatomical, physical, and mechanical properties of thirteen Malaysian bamboo species. *Bioresources*, *14*(2), 3925–3943. https://doi.org/10.15376/biores.14.2.3925-3943

Siam, N. A., Yusoh, A. S., & Uyup, M. K. A. (2023). Anatomical Properties of Bamboo. In *Multifaceted Bamboo: Engineered Products and Other Applications* (pp. 43-51). Singapore: Springer Nature Singapore

Sikora, K. S., McPolin, D. O., & Harte, A. M. (2016). Shear strength and durability testing of adhesive bonds in cross-laminated timber. *Journal of Adhesion*, *92*(7–9), 758–777. https://doi.org/10.1080/00218464.2015.1094391

Simsek, H., & Baysal, E. (2015). Some physical and mechanical properties of Borate-Treated Oriental Beech wood. *Drvna Industrija*, *66*(2), 97–103. https://doi.org/10.5552/drind.2015.1356

Siti Rafedah, A. K., Shahliney, L., & Azrai, S. (2020). Resistance of Dendrocalamus asper (Buluh Betong) treated with plants extracts to mold. *International Journal of Agriculture, Forestry Amd Plantation*, *10*(Sept), 252–261.

Skeist, I. (1977). *Handbook of adhesives*. http://ci.nii.ac.jp/ncid/BA20814278

Smith, S. T. (2020). Water-borne wood preservation and end-of-life removal history and projection. *Engineering*, *12*(02), 117–139. https://doi.org/10.4236/eng.2020.122011

Sousa, H. S., Branco, J. M., & Lourenço, P. B. (2013). Glulam mechanical characterisation. *Materials Science Forum*, *730–732*(January), 994–999. https://doi.org/10.4028/www.scientific.net/MSF.730-732.994

Su, J., Li, H., Xiong, Z., & Lorenzo, R. (2021). Structural design and construction of an office building with laminated bamboo lumber. *Sustainable Structures*, *1*(2). https://doi.org/10.54113/j.sust.2021.000010

Sukmawan, R., Takagi, H., & Nakagaito, A. N. (2016). Strength evaluation of cross-ply green composite laminates reinforced by bamboo fiber. *Composites Part B: Engineering*, *84*, 9–16. https://doi.org/10.1016/j.compositesb.2015.08.072

Sulastiningsih, I. M., & Nurwati. (2009). Physical and mechanical properties of laminated bamboo board. *Journal of Tropical Forest Science*, *21*(3), 246–251. https://www.cabdirect.org/cabdirect/abstract/20093279667

Syaifudin, T., Irawati, I., & Awaludin, A. (2022). Shear and bending performance of horizontal laminated bamboo lumber bonded with urea-formaldehyde and preserved with deltamethrin. Asean Engineering Journal, 12(4), 41-49. https://doi.org/10.11113/aej.v12.18301

Tame, N. W., Dlugogorski, B. Z., & Kennedy, E. M. (2007). Formation of dioxins and furans during combustion of treated wood. *Progress in Energy and Combustion Science*, *33*(4), 384–408. https://doi.org/10.1016/j.pecs.2007.01.001

Tan, W., Hao, X., Fan, Q., Sun, L., Xu, J., Wang, Q., & Ou, R. (2019). Bamboo particle reinforced polypropylene composites made from different fractions of bamboo culm: Fiber characterization and analysis of composite properties. *Polymer Composites*, *40*(12), 4619-4628. https://doi.org/10.1002/pc.25329

Tang, T. B., Chen, X., Zhang, B., Liu, X., & Fei, B. (2019). Research on the Physico-Mechanical Properties of Moso Bamboo with Thermal Treatment in Tung Oil and Its Influencing Factors. *Materials*, *12*(4), 599. https://doi.org/10.3390/ma12040599

Taşçıoğlu, C., Goodell, B., Lopez-Anido, R., & Gardner, D. J. (2004). Surface energy characterization of preservative-treated wood and E-glass/phenolic composites. *Forest Products Journal*, *54*(12), 262–268. https://www.researchgate.net/profile/Douglas_Gardner/publication/216694125_Surface_energy_characterization_of_preservative treated_wood_and_Eglassphenolic_composites/links/541828ce0cf203f155ad9acc.pdf

Taylor, D., Kinane, B., Sweeney, C., Sweetnam, D., O'Reilly, P., & Duan, K. (2014). The biomechanics of bamboo: investigating the role of the nodes. Wood Science and Technology, 49(2), 345-357. https://doi.org/10.1007/s00226-014-0694-4

Temiz, A., Akbas, S., Aydin, I., & Demirkir, C. (2015). The effect of plasma treatment on mechanical properties, surface roughness and durability of plywood treated with copper-based wood preservatives. *Wood Science and Technology*, *50*(1), 179–191. https://doi.org/10.1007/s00226-015-0773-1

Tomak, E. D. (2022). Surface Wettability Of Boron And Oil-Treated Wood. *Cerne*, *28*(1). https://doi.org/10.1590/01047760202228013058

Truong, G. T., Tran, H. V., Choi, K. K. (2019). Tensile behavior of carbon fiber-reinforced polymer composites incorporating nanomaterials after exposure to elevated temperature. Journal of Nanomaterials, 2019(1),4139208. DOI 10.1155/2019/4139208

Tuswan, T., Manik, P., Samuel, S., Suprihanto, A., Sulardjaka, S., Nugroho, S., & Pakpahan, B. F. (2023). Correlation between lamina directions and the mechanical characteristics of laminated bamboo composite for ship structure. *Curved and Layered Structures*, *10*(1). https://doi.org/10.1515/cls-2022-0186

Verma, C. S., & Chariar, V. M. (2012). Development of layered laminate bamboo composite and their mechanical properties. *Composites Part B: Engineering*, *43*(3), 1063–1069. https://doi.org/10.1016/j.compositesb.2011.11.065

Verma, C., Sharma, N. K., Chariar, V., Maheshwari, S., & Hada, M. (2014). Comparative study of mechanical properties of bamboo laminae and their laminates with woods and wood based composites. *Composites Part B Engineering*, *60*, 523–530. https://doi.org/10.1016/j.compositesb.2013.12.061

Wahab, M. J. A., Jumaat, M. Z., & Khaidzir, M. O. M. (2014). Strength assessment of Malaysian timbers in structural size. In *Springer eBooks* (pp. 15–26). https://doi.org/10.1007/978-981-4585-02-6_2

Wang, F., Liu, J., & Lyu, W. (2019). Effect of Boron Compounds on Properties of Chinese Fir Wood Treated with PMUF Resin. *Journal of Bioresources and Bioproducts*, *4*(1), 60–66. https://doi.org/10.21967/jbb.v4i1.182

Wang, G., Yu, Y., Shi, S. Q., Wang, J., Cao, S., & Cheng, H. (2011). Microtension test method for measuring tensile properties of individual cellulosic fibers. *Wood and Fiber Science*, *43*(3), 251–261. https://wfs.swst.org/index.php/wfs/article/download/894/894

Wang, R., Xiao, Y., & Li, Z. (2017). Lateral Loading Performance of Lightweight Glubam Shear Walls. *Journal of Structural Engineering*, *143*(6), 04017020. https://doi.org/10.1061/(asce)st.1943-541x.0001751

Wang, W., Hui, C., Chen, Y., Fu, H., & Yang, Y. (2000). A study for mold and rot fungi. *Journal of Bamboo Research*, *19*(4), 26-35

Wang, X., Huang, Z., Cooper, P., Scientist, R., Zhang, Y., & Casilla, R. (2010). The ability of wood to buffer highly acidic and alkaline adhesives. *Wood and Fiber Science*, *42*(3), 398–405

Wang, X., Luo, X., Ren, H., & Zhong, Y. (2023). Asymmetric bending characteristics and failure mechanism of bamboo under different loading directions. *Industrial Crops and Products*, *198*, 116721

Wang, Z., & Yin, T. (2021). Cross-Laminated Timber: A review on its characteristics and a introduction to chinese practices. In *Engineered Wood Products for Construction* (p. 17). https://doi.org/http://dx.doi.org/10.5772/intechopen.98956

Wang, Z., Wei, Y., Jiang, J., Zhao, K., & Zheng, K. (2020). Comparative Study on Mechanical Behavior of Bamboo-Concrete Connections and Wood-Concrete Connections. *Frontiers in Materials*, *7*(September), 1–18. https://doi.org/10.3389/fmats.2020.587580

Wardle, M. W. (2000). ArAmid Fiber Reinforced Plastics—Properties. In *Elsevier eBooks* (pp. 199–229). https://doi.org/10.1016/b0-08-042993-9/00182-0

Weber, A., Caspari, C., Pahn, M. (2022). Tensile tests at GFRP rebars, pp. 918–927. Cham: Springer International Publishing

Wei, Y., Zhou, M., Zhao, K., Zhao, K., & Li, G. (2020). Stress–strain relationship model of glulam bamboo under axial loading. *Advanced Composites Letters*, *29*, 1–11. https://doi.org/10.1177/2633366X20958726

Wu, J., (2018) Global bamboo market and trade development. In: INBAR (2018) Seminar on Science and Technology Innovation and Standardization of Bamboo Industries for the Belt and Road Countries. pp. 1-49

Xiao, X., Liang, X., Peng, H., Wang, K., Liu, X., & Li, Y. (2022). Multi-scale evaluation of the effect of thermal modification on chemical components, dimensional stability, and anti-mildew properties of moso bamboo. Polymers, 14(21), 4677. https://doi.org/10.3390/polym14214677

Xiao, Y. (2016). Engineered Bamboo. *Nonconventional and Vernacular Construction Materials*, 433–452. https://doi.org/10.1016/b978-0-08-100038-0.00015-9

Xiao, Y. (2019). Research development of glued laminated bamboo (glubam) and cross-laminated bamboo and timber (CLBT). *Academic Journal of Civil Engineering*, *37*(2), 658-663.

Xiao, Y., Shan, B., Chen, G., Zhou, Q., & She, L. Y. (2008). Development of a new type Glulam-GluBam. *Proceedings of 1st International Conference on Modern Bamboo Structures, ICBS-2007, March 2017*, 41–47. https://doi.org/10.1201/9780203888926.ch5

Xiao, Y., Shan, B., Yang, R. Z., Li, Z., & Chen, J. (2014). Glue laminated bamboo (Glubam) for structural applications. In *Materials and Joints in Timber Structures* (Vol. 9, Issue October). Springer Dordrecht. https://doi.org/10.1007/978-94-007-7811-5

Xie, J., Huang, X., Qi, J., Hse, C., & Shupe, T. F. (2013). Effect of anatomical characteristics and chemical components on microwave-assisted liquefaction of bamboo wastes. *Bioresources*, *9*(1). https://doi.org/10.15376/biores.9.1.231-240

Xing, C., Zhang, S. Y., & Deng, J. (2004). Effect of wood acidity and catalyst on UF resin gel time. *Holzforschung*, *58*(4), 408–412. https://doi.org/10.1515/HF.2004.061

Xing, W., Hao, J., & Sikora, K. S. (2019). Shear performance of adhesive bonding of Cross-Laminated bamboo. *Journal of Materials in Civil Engineering*, *31*(9). https://doi.org/10.1061/(asce)mt.1943-5533.0002854

Xing, W., Hao, J., Galobardes, I., Wei, S. Q., Chen, Z., & Sikora, K. S. (2018). Engineered Bamboo's Further Application: an empirical study in China. *MATEC Web of Conferences*, *206*, 02005. https://doi.org/10.1051/matecconf/201820602005

Xu, G., Wang, L., Liu, J., & Wu, J. (2013). FTIR and XPS analysis of the changes in bamboo chemical structure decayed by white-rot and brown-rot fungi. *Applied Surface Science*, *280*, 799–805. https://doi.org/10.1016/j.apsusc.2013.05.065

Yadav, M., & Mathur, A. (2021). Bamboo as a sustainable material in the construction industry: An overview. *Materials Today: Proceedings*, *43*, 2872-2876.

Yalinkilic, M. K., Imamura, Y., Takahashi, M., Ilhan, R., Yalinkilic, A. C., & Demirci, Z. (1999). FTIR studies of the effects of outdoor exposure on varnish-coated wood pretreated with CCB or water repellents. *Journal of Coatings Technology*, *71*(895), 103–112. https://doi.org/10.1007/bf02697928

Yang, D., Li, H. T., Xiong, Z., Mimendi, L., Lorenzo, R., Corbi, I., Corbi, O., & Hong, C. (2020). Mechanical properties of laminated bamboo under off-axis compression. *Composites Part A: Applied Science and Manufacturing*, *138*, 106042. https://doi.org/10.1016/j.compositesa.2020.106042

Yang, G., Wang, K. (2020). Evaluation on the application of GLB structures. Journal of Materials Science and Chemical Engineering, 8(5), 21–37. https://doi.org/10.4236/msce.2020.85003.

Yu, Y., Liu, R., Huang, Y., Meng, F., & Yu, W. (2017). Preparation, physical, mechanical, and interfacial morphological properties of engineered bamboo scrimber. *Construction and Building Materials*, *157*, 1032–1039. https://doi.org/10.1016/j.conbuildmat.2017.09.185

Yusof, N. M. (2018). Physico-mechanical properties of cross-laminated timber manufactured from Acacia mangium Willd. wood. (Master's thesis, Universiti Putra Malaysia). http://psasir.upm.edu.my/id/eprint/79322/

Yusof, N. M., Lee, S. H., Tahir, P. M., James, R. M. S., Al-Edrus, S. S. O., Dahali, R., Roseley, A. S. M., Fatriasari, W., Kristak, Ľ., Lubis, M. a. R., & Réh, R. (2023). Effects of boric acid pretreatment on the properties of four selected Malaysian bamboo strips. *Forests*, *14*(2), 196. https://doi.org/10.3390/f14020196

Yusof, N. M., Tahir, P. M., Lee, S. H., Khan, M. A., & James, R. M. S. (2019). Mechanical and physical properties of Cross-Laminated Timber made from Acacia mangium wood as function of adhesive types. *Journal of Wood Science*, *65*(1). https://doi.org/10.1186/s10086-019-1799-z

Yusof, N. M., Tahir, P. M., Lee, S. H., Uyup, M. K. A., James, R. M. S., Al-Edrus, S. S. O., Krišťák, Ľ., Réh, R., & Lubis, M. a. R. (2023). Effects of Adhesive Types and Structural Configurations on Shear Performance of Laminated Board from Two Gigantochloa Bamboos. *Forests*, *14*(3), 460. https://doi.org/10.3390/f14030460

Yusof, N. M., Tahir, P. M., Roseley, A. S. M., Lee, S. H., Halip, J. A., James, R. M. S., & Ashaari, Z. (2019). Bond integrity of cross laminated timber from Acacia mangium wood as affected by adhesive types, pressing pressures and loading direction. *International Journal of Adhesion and Adhesives*, *94*, 24–28. https://doi.org/10.1016/j.ijadhadh.2019.05.010

Zaidon, A., Lee, S. H., & Muhamad Rapie, Z. (2016). Performance of compreg laminated bamboo/wood hybrid using phenolic-resin-treated strips as core layer. *European Journal of Wood and Wood Products*, *74*(4), 621–624. https://doi.org/10.1007/s00107-016-1027-0

Zakikhani, P., Zahari, R., Sultan, M., & Majid, D. (2017). Morphological, mechanical, and physical properties of four bamboo species. Bioresources, 12(2). https://doi.org/10.15376/biores.12.2.2479-2495

Zhang, H., Li, H., Hong, C., Xiong, Z., Lorenzo, R., Corbi, I., & Corbi, O. (2021). Size Effect on the Compressive Strength of Laminated Bamboo Lumber. *Journal of Materials in Civil Engineering*, *33*(7). https://doi.org/10.1061/(asce)mt.1943-5533.0003776

Zhang, X., Que, Y., Wang, X., Li, Z., Zhang, L., Han, C., Que, Z., & Komatsu, K. (2018). Experimental behavior of laminated veneer lumber with round holes, with and without reinforcement. *BioResources*, *13*(4), 8899–8910. https://doi.org/10.15376/biores.13.4.8899-8910

Zhang, X., Zou, G., & Shen, Z. (2008). Experimental research on continuous basalt fiber and basalt-fibers-reinforced polymers. *Proceedings of SPIE*. https://doi.org/10.1117/12.839375

Zhao, W., Zhou, J., & Long, Z. (2016). Compression tests on square, thin-walled steel tube/bamboo-plywood composite hollow columns. *Science and Engineering of Composite Materials*, *23*(5), 511–522. https://doi.org/10.1515/secm-2014-0117

Zhiyong, C., & Robert J., R. (2021). *Wood Handbook: Wood as an Engineering Material: Mechanical properties of Wood-Based composite materials* (pp. 1–543). https://www.fs.usda.gov/treesearch/pubs/62200

Zhou, F. (2000). Selected Works of Bamboo Research. Nanjing Forestry University, Nanjing

BIODATA OF STUDENT

Norhazaedawati binti Baharuddin is born on 3rd August 1984 in Tapah, Perak. She completed her primary and secondary school in Gombak, Selangor, in 1996 and 2001, respectively. In 2002, the author completed her science matriculation programme and pursued study at Universiti Putra Malaysia in 2003. The author graduated with her Bachelor's in Forestry Science in 2006. In 2019, she started her Master of Science in Biocomposite Technology and Design at the Institute of Tropical Forestry and Forest Product (INTROP), Universiti Putra Malaysia.

The author currently works as a Senior Research Officer at the Malaysian Timber Industry Board (MTIB) since 2009. With almost 15 years working experience, she has been involved in numerous research projects in upstream and mid-stream industries consists of plantation tree species, the utilisation of geographic information system in forest plantation as well as the development of high value-added bamboo and fibre products. She also holds a position as Quality Manager in MTIB Accredited Testing Laboratory under ISO 17025:2017 and currently been appointed as Approved Signatory in the mechanical laboratory by the Department of Standard Malaysia.

LIST OF PUBLICATIONS

Baharuddin, N., Lee, S., Uyup, M. A., & Tahir, P. M. (2022). Effect of preservative treatment on physical and mechanical properties of bamboo (Gigantochloa scortechinii) strips. *BioResources*, *17*(3), 5129.

Presented paper:

Norhazaedawati, B., Lee, S.H., Anwar U.M.K., Paridah, M.T. (2021). Effects of boron and copper chrome boron (CCB) treatment on physical and mechanical properties of *Gigantochloa scortechinii*. Paper presented at 5th Wood and Biofibre International Conference (WOBIC): November 23-24; Hotel Bangi Resort, Bangi, Selangor

Norhazaedawati, B., Balkis, F.A.B., Anwar U.M.K., Lee, S.H, Paridah, M.T. (2023). The influence of preservatives treatment on bonding properties of 3-ply laminated bamboo. Paper presented at 6th Wood and Biofibre International Conference (WOBIC): November 23-25; Hotel Adya Langkawi, Langkawi, Kedah.