

Experimental Investigation of the Structural Performance of Engineered Bamboo Composites (Dragonwood) in Jacking Applications

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of my thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Climate change has necessitated gravitation towards bio-based building materials. Many innovative, bio-based, structural products with exceptional strength and resistance, such as mass timber and bamboo composites have emanated from advances in adhesive chemistry and manufacturing to mitigate climate issues.

This study was conducted to investigate the structural performance of an engineered bamboo composite, namely Dragonwood, in jacking applications. While tropical hardwoods have been the common choice for jacking applications across North America; the decline in quality is now raising high level concerns with regards to their performance in jacking applications.

Engineered bamboo composites (EBCs) have been observed to be highly durable, resistant to fungal infection and show high strength to weight ratio. In terms of environmental sustainability, EBCs are a great substitute for tropical hardwoods since it can take as long as 60-80 years for hardwood to mature but bamboo can mature in 2-6 years. Furthermore, with EBCs showing superior long-term behavior under varying environmental exposure, many heavy-duty engineering companies involved in day-to-day jacking applications are incentivized to gravitate EBCs, soon.

The mechanical properties of the Dragonwood specimens were investigated experimentally in bending and compression based on the principal modes of failure to ascertain the performance of these beams in different orientations and loadings. Since the manufacture of Dragonwood involves face bonding two sections of parallel strand bamboo (PSB) boards to form a larger laminated veneer bamboo (LVB) section, glue line failure was also observed.

It was found that in bending, the primary failure mode in the specimens was simple tension as the fibers on the underside of the beams broke due to deflection. Horizontal shear failure was also observed along the glue line in some of the Dragonwood specimens. In compression, the failure mode of the Dragonwood specimens was an overall section buckling characterized by cracks and splits at the end. Regardless, the specimens still demonstrate bilinear behavior both in bending and compression as observed in the stress-strain graphs. With the Ekki specimens, the flexural response was independent of orientation. However, in compression, vertically oriented Ekki specimens were observed to fail in less time than horizontally oriented ones.

From the experimental results, the strength and modulus properties were evaluated, resulting deviations and variances were obtained, and Kolmogorov-Smirnov (K-S) tests were employed to determine the goodness of fit for comparison with known theoretical distributions. From the K-S tests, the experimental data demonstrated conformity with normal distribution.

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CHAPTER 1

Introduction

1.1 General

The carbon footprint impact of the construction industry has necessitated the adoption of sustainable structural materials (Ross et al., 2021). The production of cement and steel involves significant energy consumption and high temperatures that lead to substantial greenhouse gas emissions. The construction industry alone, through the dominance of concrete and steel, accounts for 40% of global carbon emission (IEA 2018), thus the need for carbon footprint reduction in the construction industry.

Bamboo is a bio-based material and originates from a lineage of perennial grasses which were major food sources for herbivores (Kelchner, 2013). Bamboo is renewable, fast growing and biodegradable in addition to possessing the capacity to sequester as much as four times the carbon storage per hectare of spruce forests (Bernsden et al., 2014; Bahru et al., 2021). Bamboo is endemic to every continent except Europe and Antarctica; thus, the global availability and strength of bamboo culms make them desirable structural material (Sun X. et al., 2020).

In its raw, untreated form, bamboo is estimated to be durable for 10-15 years under good storage conditions. However, like wood, bamboo is hygroscopic; it absorbs moisture from the environment and reaches a fiber saturation point after which excess moisture is accumulated in the bamboo culm walls decreasing the mechanical properties. Thus, the mechanical strength of bamboo is best retained at an air-dry condition of 12-15% (Xu et al., 2014).

For many years, the variation in the geometry of bamboo, its relative dryness and flammability limited its use in mainstream construction (Sun X. et al., 2020; Bahru et al., 2021). These inadequacies prompted manufacturing technologies to emerge with improved, sustainable and fire-resistant alternatives such as the engineered bamboo composites (EBC). EBCs such as

Dragonwood scrimber beams were developed to address the geometrical variation found in round, bamboo culms. Dragonwood is a suitable alternative to common wood products such as tropical hardwoods, which contributes to the rapid loss of green forests.

1.2 Research Justification

Tropical hardwoods like Ekki have been the common sustainable choice for jacking operations for many years. A few North American hardwoods like the white oak were also employed in jacking operations. However, due to deforestation, North American and tropical hardwoods are no longer viable. The potential of Dragonwood, a type of EBC, is now being considered as a suitable replacement for tropical and North American hardwoods in jacking applications. Experimentation is required to ascertain the mechanical properties of both horizontally oriented and vertically oriented Dragonwood and to establish strength and resistance properties that can be included in relevant design manuals. The choice of the mechanical properties to be investigated is based on the principal failure modes expected in jacking applications.

1.3 Research Objectives

The aim of this research is to investigate the structural performance of Dragonwood scrimber beams in jacking applications through experimental testing of key mechanical properties relating to such application. Furthermore, a comparison between Dragonwood and traditional hardwoods for such applications is investigated. Small and full-scale tests are to be conducted on specimens to evaluate their mechanical properties specifically compression perpendicular-to-grain ($\perp$) and bending parallel-to-grain ($\parallel$) through the following sub-objectives:

- i. Conduct small-scale tests on both Dragonwood and Ekki specimens in their horizontal and vertical orientations. The specimens for the small-scale tests are to be fabricated from the full-scale specimens according to the dimensions specified in the respective test standards.
- ii. Conduct full-scale flexural tests on both Dragonwood and Ekki specimens in horizontal and vertical orientations.

- iii. Employ statistical analysis in determining the strength grade of Dragonwood through two parameters: modulus and strength. Furthermore, a non-parametric approach is to be employed to assess the data conformity with established theoretical distributions.

1.4 Scope

These research objectives are met through the following steps:

1. Detailed literature review on EBC types, manufacture and material behaviour in bending and compression.
2. Investigation of relevant timber standards available for full-size and small clear specimen testing in bending and compression.
3. Testing of fifty 100mm x 100mm x 1000mm beams of both Dragonwood and Ekki in horizontal and vertical orientations to determine their behaviour in bending.
4. Testing of forty 100mm x 100mm x 250mm beams of both Dragonwood and Ekki in horizontal and vertical orientations to determine their behaviour in compression.
5. Establishing the load-displacement relationship from the experimental test results.
6. Comparing the stiffnesses and resistance of the tested Dragonwood and Ekki specimens and analyzing the effects of glue-line failure for Dragonwood in horizontal or vertical orientations.
7. Employing statistical analysis to evaluate the experimental data distribution.
8. Submitting conclusions and proposing future work recommendations.

1.5 Thesis Organization

This thesis focuses on the structural performance of Dragonwood and Ekki beams under varying loading conditions and orientations. Thus, the thesis is organized into the following six chapters:

- **Chapter 1** introduces the research topic and provides a justification, the key objectives and the scope of the research.

- **Chapter 2** provides a detailed literature review on wood as a construction material, innovative wood products, EBC types and manufacturing as well as utilization in jacking applications.
- **Chapter 3** presents the experimental program including testing methods and relevant standards/codes, the Procedures and a summary of the test matrix.
- **Chapter 4** presents the experimental results from three-point bending parallel-to-grain and compression perpendicular-to-grain tests as well as load-displacement flexural and compression resistance graphs.
- **Chapter 5** discusses the statistical methods and employs Kolmogorov-Smirnov tables in evaluating data distribution.
- **Chapter 6** presents summary of key findings, conclusions and recommendations for future work.

CHAPTER 2

Literature Review

2.1 General

Going by the 2015 Paris agreement, Canada is committed to reducing its greenhouse gas emissions by 40-45% by the year 2030. Thus, the desire to substitute traditional materials with sustainable alternatives is a priority in every sector.

In the heavy-duty engineering industry, such as the jacking industry, the use of sustainable materials such as tropical hardwood jacking timbers are being employed in day-to-day operations over steel. These developments make it evident that the Canadian building construction industry as well as the heavy equipment industry are shifting towards sustainable materials like wood.

2.2 Tropical Hardwood in Structural Applications

Tropical hardwoods have been a popular structural material for over a century. When sourced responsibly, tropical hardwoods have lower carbon footprint than concrete or steel. However, depending on the species, tropical hardwoods can be susceptible to fungi infection, shrinkage, swelling and warping.

Most tropical hardwood species have been classified into strength grades, thus guiding designers and engineers on which species are more suitable for heavy duty engineering or day-to-day structural uses like framing, beams and columns. Tropical hardwoods like Ekki are known for their superior mechanical strength and durability but even the most durable hardwoods can still be susceptible to warping depending on the maturity of the harvested trees.

Engineered wood was developed to overcome the natural limits of traditional wood and to encourage the utilization of lower-grade trees in such a way that their fibers can be combined to produce strong, large, structural boards. Furthermore, the perception of wood as a fire risk stalled high-rise timber construction for many years but with the advent of engineered wood, multi-storey timber construction is gradually gaining ground.

Engineered wood has been explored in construction depending on economics, energy, sustainability, architectural and ecological considerations. Hybrid timber-based structural system construction, which typically consists of combining timber with either concrete or steel, has been a popular choice in multi-storey construction. In this case, timber is the principal building material but concrete or steel acts as the load-bearing material in the structure. In recent years, the all-timber structural system construction has also been a leading choice in multi-storey construction where several innovative mass timber products can be used within the same structure to achieve aesthetic appeal and the same structural stability.

2.2.1 Wood Properties and Variability

Wood is an orthotropic and anisotropic material (i.e. its properties vary with orientation and the direction of grain). Wood also absorbs and releases moisture and is thus susceptible to swelling and shrinkage. Environmental factors such as climate and soil condition can have a notable effect on the quality of wood due to the cell structure that helps transfer moisture and nutrients. Furthermore, wood experiences natural variability due to factors such as the presence and size or location of knots and the coarseness of the wood grain (Kodur and Naser, 2020).

Lumber quality is graded accordingly and factored into nominal strength values and suitable applications to account for the natural variability of wood (Canadian Wood Council, 2017). Variability in raw harvested timber also affects the properties of the innovative wood products that are manufactured from it.

Temperature also plays a significant role in wood properties as distortion occurs in wood as temperature increases. At ambient temperatures, wood deteriorates mostly due to fungi infection, chemical attacks, weathering or moisture effect. These factors can be controlled to some extent, to preserve wooden structures for hundreds of years. At elevated temperatures, however, wood undergoes a series of chain reactions. As the wood dries, its density, stiffness, and strength properties decrease. Additionally, wood undergoes shrinkage due to moisture

changes, however, this distortion is relatively small compared to other building materials such as steel in elevated temperatures (Legg & Tingley, 2020).

2.2.2 Idealized Resistance Curve

Resistance curves are a visual representation of the load-displacement relationship in a material. In an ideal example, bending members behave elastically up to an ultimate load, P_{max} and maximum displacement (ΔP_{max}). The maximum displacement is the peak resistance and the point at which the members experience their first failure. Beyond the peak resistance, the post-peak behaviour of the beams can be observed.

In compression, the stress-strain relationship is generally described to be linear-elastic up to yielding. Stress increases linearly to a maximum value (yield point) beyond which the stress reduces linearly with increasing strain (Neely, 1898). The compressive strength of wood is greatly influenced by grain orientation as woods are stronger when loads are applied parallel-to-grain. Figure 2.1 illustrates the stress-strain curve for wood in compression. The initial linear elastic region is followed by a plastic region where the wood starts to deform permanently. Eventually, it reaches a point of failure, where the wood buckles or crushes.

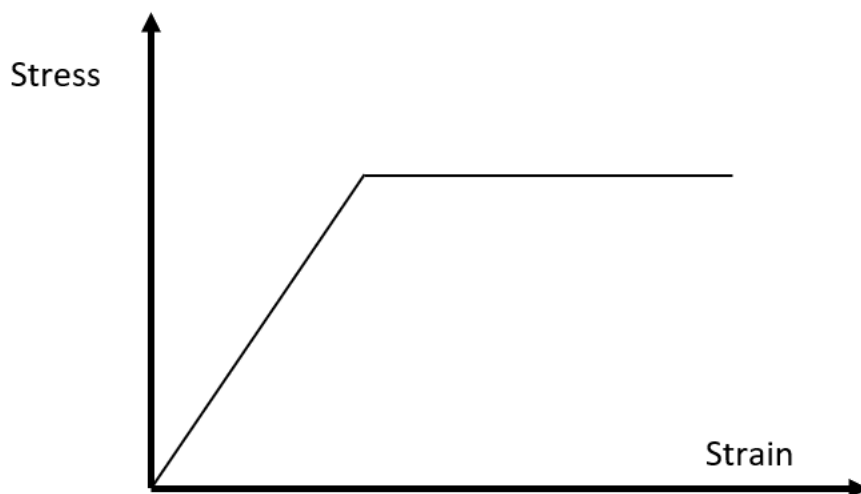


Figure 2.1 Stress-strain relationship for wood in compression

**Reproduced from Neely (1898)*

2.2.3 Perceived Barriers to the Application of Tropical Hardwoods in Jacking Operations

Tropical hardwoods like Ekki have been a common choice for jacking applications. Ekki demonstrates superior compressive and tensile strength when compared to other tropical hardwood (Osuji et al. 2017), thus its viability in jacking applications. However, the quality decline in Ekki jacking beams amidst deforestation concerns and susceptibility to decay has prompted researchers to explore new materials such as engineered bamboo composites. Engineered bamboo composites are sustainable in composition (80% bamboo fibers and 20% resin) and thus certified by the forest stewardship council. In addressing the concerns about the loss of green forests, bamboo maturity even for structural applications takes 2-6 years, making it a suitable replacement for tropical hardwoods which takes about 60-80 years to mature.

2.3 Engineered Bamboo Composites

2.3.1 Overview

Many countries have adopted strict forest protection policies, thereby restricting the use and exportation of wood. Canada has some of the most progressive legislation for forest management in the world, requiring all harvested forests to be duly regenerated. As a result, tropical hardwood salvaging is declining due to the sustainable limits policies.

With the scarcity of tropical hardwood, there is gravitation towards bamboo especially as a sustainable alternative to hardwood. There are more than 1200 species of bamboo worldwide and unlike hardwood, it is fast growing with some species reaching maturity within six months. Additionally, both the harvesting and application of bamboo offer reduced carbon emissions compared to steel and concrete (Sharma et al., 2015).

In seismic areas, lightweight building materials are preferred because of reduced dead loads thus providing increased seismic resilience and safety, in the event of collapse. As such, bamboo had been a popular choice for building construction in seismic parts of Asia long before it became globally accepted. Huang et al. (2024) investigated the viability of EBC framed structures in low-rise building construction in regions of high seismicity by designing and analyzing a 3-storey

balloon frame-type EBC building. The 3D finite element model was adopted for elastic analysis to determine the dynamic properties of the structure. Additionally, the structural performance of the structure was observed under ultimate state and serviceability limit states and was found to be adequate. Thus, EBC framed structures are suitable for contemporary low-rise building construction.

Bamboo has proven to have great mechanical performance owing to its high moment of inertia to cross-sectional area ratio. The strength and modulus of bamboo fibers in tension have been estimated to be as high as 400 MPa and 30,000 MPa, respectively, which is greater than steel (Zhou et al., 2012). Likewise, in compression, bamboo is said to demonstrate greater compressive strength than concrete (Janssen, 2000).

However, the dimensional instability, uneven material distribution, flammability and poor geometry of bamboo culms are high level concerns (Li et al., 2022). The hollow, irregular shape of the culms and the difficulty associated with making connections and joints suitable for variable sections makes it difficult for use in regular construction (Sharma et al. 2015). In Figure 2.2, the cross section of a bamboo culm is illustrated.

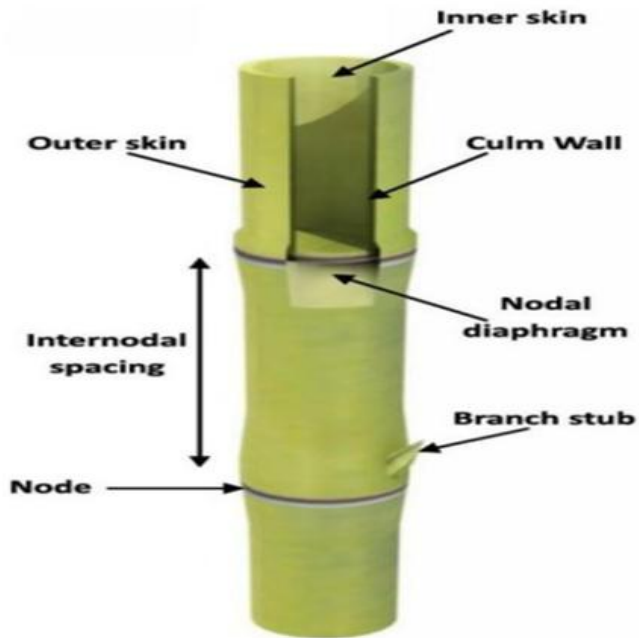


Figure 2.2: Structure of a Bamboo Culm

**Reproduced from Kaminski et al. (2016)*

The mechanical properties and wall thickness of bamboo culms are known to vary along the cross-section. Thus, traditional bamboo does not meet the dimensional and mechanical requirements needed for structural applications (Huang et al., 2024). To resolve these inadequacies in dimensional stability and geometry, engineered bamboo composites (EBCs) were invented. EBCs are found in many engineering and academic applications including large-scale building construction (Tang et al., 2021).

2.3.2 Types of EBC

Several bamboo composites have been developed in the last twenty years including bamboo scrimber, laminated bamboo and ply bamboo. However, some of the developed bamboo composites are not suitable for structural applications because of wide variability in material properties and the inability to satisfy the structural design and performance requirements. Parallel strand bamboo (PSB) and laminated veneer bamboo (LVB) are the two main EBC types for structural applications [Sun et al., 2020]. Tang et al., (2021) also conducted experimental tests

on small clear specimens of EBC's across seven manufacturers to compare the tensile, compressive and shear strengths and to present data for the strength grading and development of EBC standards in China.

In non-structural applications, EBC's can be a suitable replacement for traditional wood-based sheathing materials. For example, ply bamboo is now commonly adopted as an alternative to oriented strand boards sheathings and plywood panels [Nkeuwa et al., 2022].

Figure 2.3 illustrates the three main categories of bamboo composites employed in either structural or non-structural applications.

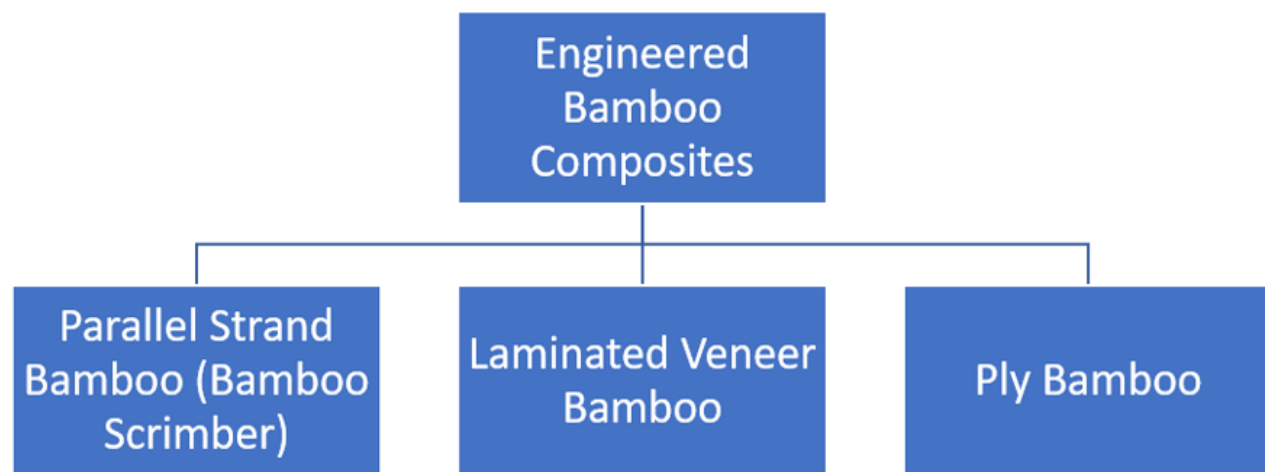


Figure 2.3: Engineered bamboo composite types

2.3.3 EBC Manufacturing

EBCs are considered low-carbon products, especially when compared to traditional materials like concrete or steel. However, the carbon footprint of EBCs depends on several factors, especially the manufacturing process. EBCs are infused with resin during manufacture but in line with the best global sustainability practices, manufacturers are mandated to observe the environmental product declarations (EPDs) showing the carbon footprint of all products used in the manufacturing process including resins.

EBC panels are made by splitting and cutting bamboo culms into thin strips or strands that are flattened with a wood planer or roller pressed on a mat and then planned to form panels. The choice of strand or strip depends on the structural functionality of the resulting EBC, but strands are now preferred for structural EBC's (Kelkar et al., 2023). Hygrothermal treatments such as bleaching or caramelized treatments are applied to the flattened or roller pressed strands after which they are piled in longitudinal layers and bonded with chemical adhesives to form large panels. Several adhesives and pre-treatment options have been reported for EBC manufacturing, but phenolic resin is one of the most widely used for bamboo impregnation (Sharma et al., 2020).

Researchers have compared different production methods of EBC panels while investigating the effects of production method on mechanical properties. Some heat treatments known for enhancing dimensional stability and improving the corrosion resistance of wood have been found to degrade bending performance (Li et al., 2022; Gao et al., 2023). Since dimensional stability is a major driver for shifting towards EBC, more physical and chemical modification methods aimed at improving dimensional stability are being adopted such as polymer impregnation and resin impregnation. Through overcoming the natural dimensional constraints associated with bamboo culms, to being aesthetically appealing, and structurally stable with excellent biodegradability, the advantages of EBC surfaces over other traditional construction materials is evident.

Recently, there have been significant advancements in the industrial production of EBCs. EBCs are made from thin strands of bamboo culms which are then used to form larger structural members with more structurally and geometrically stable properties. The most important physical and mechanical properties of EBCs for predicting strength are density and modulus of elasticity (MOE) [Tang et al., 2021]. The strength and durability of EBC are influenced by the bond or adhesion among bamboo strands, which has been severally improved due to modern industrial methods of manufacturing.

2.4 EBC Types

2.4.1 Parallel Strand Scrimber (PSB)

PSB, also known as bamboo scrimber, is a novel structural material which has demonstrated excellent mechanical properties and offers vast structural applications. Bamboo scrimbers are a composite of bamboo strand elements with the fibers primarily oriented along the member's longitudinal axis which is then combined with resin and pressed together to form a final sectional size. Research and technological advancements have led to the development of numerous industrial equipment for the manufacturing of bamboo scrimbers such as cold-press molds, hot-press molds, and bamboo fluffing machines (Yu et al., 2012, Yu et al., 2015).

Figure 2.4 illustrates the industrial manufacturing process of splitting bamboo culms into strands and impregnating the strands with resin before heat curing.



Figure 2.4: *Manufacturing process of Bamboo Scrimber*

**Reproduced from Sharma et al. (2015)*

The final PSB product is shown in Figure 2.5 below.

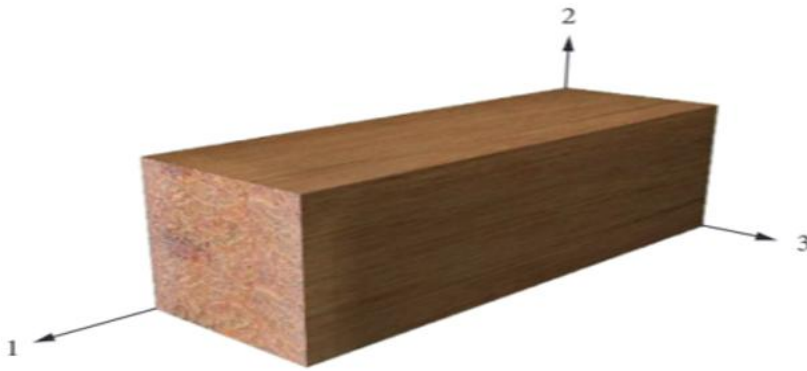


Figure 2.5: *Parallel Strand Bamboo, PSB*

**Reproduced from Tang et al, (2021)*

Experimental tests have been conducted to investigate the flexural behavior of PSB beams while comparing the results with theoretical models [Dongsheng H. et al., 2013]. Yu et al. (2015) investigated the dimensional stability, water absorption and mechanical properties of bamboo scrimber. The study employed mechanical fluffing, thermal treatment, and phenol formaldehyde (PF) impregnation coupled with cold-pressed and hot-pressed processes to fabricate different types of bamboo scrimber ideal for aesthetic, gardening and structural applications. Two types of mechanical testing namely bending and shear, were conducted on the bamboo scrimber to ascertain the effects of thermal treatment and PF resin loading on the specimens. The bending modulus of all specimens were observed to decrease slightly with increased PF resin loading. The shear strength was observed to decrease with increased thermal treatment but increased with increased PF resin loading as the bond strength improved.

2.4.2 Laminated Veneer Bamboo (LVB)

LVBs consist of individual PSB members (i.e. strand elements with the fibers oriented along the member's longitudinal axis), which are first edge-bonded and then face-bonded to form final product sizes larger than the individual members. For example, two 50mm x 100mm PSB sections can be face-bonded to form a larger section of a 100mm x 100mm LVB.

LVBs are also commonly used to manufacture glued-laminated bamboo (glubam) and cross-laminated timber-bamboo (CLTB), as alternatives to the North American and European wood-

based glued-laminated timber (glulam) and cross-laminated timber (CLT), respectively. It is important to note that the process of harvesting to the transformation into EBCs is in tune with established environmental sustainability practices and uses an eco-friendly resin [Sun et al., 2020; Sharma et al., 2015]. Although EBCs were initially employed in buildings and bridges, their durability, light weight, and high strength-to-weight ratio has made it an ideal candidate for railway ties, mats (e.g., access, rig, crane), and in jacking applications. Figure 2.6 illustrates the manufacturing process of LVB and the final 100mm x 100mm LVB product is shown in Figure 2.7.



Figure 2.6: Manufacturing process of laminated bamboo

*Reproduced from Sharma et al. (2015)

The final LVB product is as shown in Figure 2.7 below.



Figure 2.7: Laminated Veneer Bamboo

**Reproduced from Tang et al (2021)*

2.4.3 Ply Bamboo

Ply Bamboo is a composite of bamboo strips glued and pressed together to form boards or panels and is mostly used for non-structural applications such as sheathing. The glue line method is usually adopted in the manufacturing of ply bamboo which involves spraying urea formaldehyde resin using a glue spreader at a rate of 300 g/m^2 . Rahman et al (2012) investigated the mechanical and physical properties of bamboo mat-wood veneer plywood while comparing its mechanical properties to wood veneer plywood. The study adopted bamboo mats as an alternative to bamboo strips in the manufacturing of the ply bamboo panels in a bid to increase dimensional stability and to achieve higher panel size. The study also investigated the potential of incorporating wood veneers into bamboo. The resulting novel material: bamboo mat-wood veneer plywood, was concluded to demonstrate exceptional mechanical properties, satisfying design codes criteria for structural applications. A typical 3-ply bamboo is shown in Figure 2.8.



Figure 2.8: Ply Bamboo Panel (3-Ply)

2.4.4 Dragonwood

Dragonwood is a new innovative form of EBC and is gradually gaining wide acceptance and popularity. The manufacturing of Dragonwood involves face bonding two sections of 50mm x 100mm x 1000mm PSB boards to form a larger section of 100mm x 100mm x 1000mm LVB board. With respect to experimental testing, the glue-line between the two PSB boards in different orientations i.e. the vertical and horizontal orientations, are important in evaluating the glue-line failures and the resulting modulus of rupture and elasticity. Figure 2.9 captures some stacked Dragonwood beams.



Figure 2.9: Stacked Dragonwood Beams (100×100×1000mm)

It is worthy to note that Dragonwood has a fungal resistance edge over tropical hardwood mostly due to the coatings applied during manufacturing. In terms of environmental sustainability, Dragonwood like other EBC products are a great alternative to hardwoods; it takes about 60 – 80 years for hardwoods to mature but bamboo can mature in 2-6 years with some species being acknowledged as world’s fastest growing plants. Due to its lightweight, it is easily transported to job sites in addition to being stackable and crate friendly. These unique qualities make Dragonwood particularly suitable for jacking and rigging applications.

2.5 Bonding Performance in EBCs

Bonding strength plays a significant role in the performance of the resulting bamboo composites. Nkeuwa et al (2022) investigated the bonding performance as well as the adhesive penetration in wood and bamboo composites. The study reviewed several treatment methods and their effects on bondability. Some of these methods were seen to alter the composition of the bamboo polymers. Industrial treatments such as bleaching and carbonization alter the surface pH, surface roughness and permeability of the bamboo composites and thus having a direct

effect on the resin flow, resin penetration and in turn, bonding performance of bamboo composites.

Bleaching and carbonization are two of the most important treatments employed in EBC manufacturing. Bleaching often involves heating the bamboo strands in an open vat at a temperature of 70–80 °C for 4 hours in a hydrogen peroxide solution. Carbonization, on the other hand involves pressure heating the bamboo strands in a closed vessel at 120–130 °C for 4–8 hours. Both treatments are popular and widely used but researchers claim that while bleaching improves bonding strength, carbonization was observed to reduce bonding strength for carbonization temperatures above 180 °C. This is mostly due to the cellulose decomposition in bamboo at temperatures over 200 °C (Zhang et al., 2021). Temperature and time are known to affect the mechanical and physical properties of bamboo, hence the need to be mindful of the choice of bamboo pre-treatment.

Phenolic resin impregnation is known to improve the dimensional stability of bamboo and in turn, its mechanical properties. However, while phenolics are still commonly used for structural bamboo composite bonding, the industry is shifting away from formaldehyde systems as isocyanate-based resins offer viable solutions, especially for bamboo strand composites (Nkeuwa et al., 2022).

2.6 Mechanical Properties of EBCs

Mechanical properties often referred to as strength properties determine the resistance and capacity of the member under consideration. Compressive stress, flexural stress, shear stress, modulus of rupture in bending, modulus of elasticity, are all important in strength/resistance assessment. Specifically, the modulus of elasticity and the modulus of rigidity help estimate the elastic behavior of wood.

Under applied loads, the structural behavior of wood and wood-based composites differ in bending, compression, tension and shear, thus mechanical properties are important in characterizing the performance of these materials. In bending for example, both modulus of elasticity and modulus of rupture (bending strength) are important in characterizing the

properties of these materials in bending (Ross, 2021). Wood composites generally refer to wood-based materials that are bonded with adhesives. Notable wood-based composites used in structural applications are parallel strand lumber (PSL), laminated veneer lumber (LVL), and glued-laminated timber glulam. An understanding of the structural behavior of wood-based composites can guide the experimental investigation of the structural properties of bamboo composites. Previous studies have investigated the mechanical properties of many wood species and presented the results in strength tables. These findings have been the basis for the classification of woods into hardwoods or softwoods. The strength properties have also guided manufacturers on the suitability of each wood species as a raw material when producing different wood-based composites.

Few studies have reported the mechanical properties of EBCs in compression, shear and flexure. Dong et al. (2021) investigated the bending and planar (rolling) shear properties of Spruce-Pine-Fir (SPF) dimension lumber and three different engineered bamboo products (EBP). Verma et al. (2016) conducted mechanical tests (compressive, flexural and tensile) on bamboo culms and laminated bamboo composites and further compared the mechanical properties of laminated bamboo composites with the mechanical properties of softwoods and hardwoods from previous literature. The research findings showed superior mechanical properties in the laminated bamboo composites when compared with softwoods and comparable mechanical properties to hardwoods. Huang et al. (2013) investigated the mechanical properties of bamboo scrimber beams and observed simultaneous tensile failure modes in the bottom bamboo fibers and interlaminar shear failure near the neutral axis in some of the tested beams. Similarly, Zou et al. (2019) studied the influence of moisture content on the flexural strength parallel to grain, flexural modulus and stiffness of bamboo scrimber slabs while varying the applied load until the ultimate load was reached. The failure mode observed was mostly typical mid-span bottom failure characterized by deep cracks in the bottom mid-span of the specimens and due to tension. Additionally, the flexural strength parallel to grain and flexural modulus of the slabs were found to decrease significantly as moisture content increased. The fibre saturation point (FSP) for bamboo scrimber slabs obtained in this study was 19.9%. The FSP of engineered bamboo

composites is a topic of interest considering the exposure of the beams to rainfall and moisture during most structural and non-structural applications.

In another study by Xu et al. (2014), the effect of moisture content on the compressive, tensile and shear properties of untreated bamboo lumber was investigated, and the fiber saturation point was observed to be around 30%. Considering that the buckling behaviour of bamboo culms had been of interest in scaffold construction, Xu et al (2014) conducted splitting tests on different 1m length bamboo culms to gain a better understanding of their buckling behaviour when exposed to increased moisture from significant rain. The study observed that until the 30% moisture content was reached, the mechanical properties significantly decreased as moisture content increased. However, once the 30% moisture content was achieved, no significant degradation in mechanical properties were observed.

2.7 Fire Performance in EBC

The extent of fire safety measures usually depends on building occupancy and early detection. Structural designs that limit fire growth and spread by containing the fire within the affected compartment is recommended in most design codes. Design codes generally present material and building requirements for combustible materials prioritizing combustibility, flame spread and fire resistance (Ross, 2021).

In a bid to understudy the fire resistance of EBC beams, Chen et al. (2019) exposed two common types of EBC (laminated bamboo and bamboo scrimber); to three-sided standard fire conditions. The study was able to quantify the fire resistance and post-fire performance of the EBC beams, most notably especially the ultimate load capacity of the beams post-fire. The charring depths and rates were observed and calculated, and the impact of the adhesives used as a binding agent on the fire performance of the beams was also investigated. The test concluded that in all the cases investigated, regardless of fire exposure, flexural failure associated with tensile fracture of the extreme tension fibre was the principal failure mode in each beam. The results from the experimental tests were compared with results from sectional analysis and simplified methods such as the reduced cross-section method.

ASTM E84 highlights the various flame spread index of several wood species. The Class A flame-spread rating is assigned to bamboo composites meaning that it has the lowest flame spread rate and minimal smoke production. This is not surprising as several adhesives, coats and paintings are known to reduce the fire growth and spread in wood or bamboo composites.

2.8 Thermal Properties of EBCs

Thermal properties play a significant role in the long-term durability and performance of any building. Thus, to advocate for the incorporation of EBCs in relevant building design manuals or codes, the energy/environmental performance of EBC had to be well understood. This led to a series of research on the thermal properties of EBCs using transient plane source methods as well as micromechanical analysis (Shah et al., 2016, Mounika et al., 2012). While several factors such as external and internal coating had an impact on thermal conductivity, it was observed that fiber orientation and material density had a more substantial impact (Shah et al. 2016). Depending on the species of the bamboo, the manufacturing process and the amount of air gaps in the panel, the density of EBC is generally between 600kg/m^3 to 1000kg/m^3 . The substantial literature on the thermal properties of some innovative timber materials such as engineered wood, allowed for comparison with the thermal properties of EBC panels. EBC panels were concluded to be an energy-conserving structural materials through reduced heat transfer as well as an environmentally suitable construction material.

2.9 Predicting the Yield Point in EBCs

In limit states design, the prediction of the yield point is necessary as the applied load at the yield point is used to calculate yield stress, which dictates if the member of interest will fail. The point at which a member or assembly begins to plastically deform is referred to as the yield point. Beyond the yield point, the ductility of the member or assembly determines the extent of yielding that can be accommodated before losing significant strength. Yield point and ductility are particularly important in the seismic design of timber structures. While design codes expect structures to remain elastic under gravity loads, structures are designed for considerable ductility in seismic conditions (Munoz et al., 2008).

The yield point of EBC assemblies can be determined through the same standardized analyses for determining the yield point of other timber assemblies, that is, by analyzing the load-displacement curves resulting from destructive tests. While there are many standardized approaches relevant for obtaining the yield point, five of these approaches are more widely known and accepted. These include the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Karacabeyli and Ceccotti (K&C), European Committee for Standardisation (CEN), Equivalent Energy Elastic-Plastic Curve (EEEP) and Yasumura and Kawai (Y&K). Many researchers have suggested the need for a harmonized approach for more accurate yield point values thereby providing realistic ductility ratios for the seismic design of structures.

The failure in a timber assembly is a combination of the deformation of assemblies and connectors. While a few studies have investigated the yield points and deformation in timber assemblies, the variation of approaches employed by different researchers made it impossible to compare the findings of these studies. In search of a harmonized approach, Munoz et al. (2008) compared the yield points and loads from shear wall tests and several types of wooden and multiple fastener tests. The load-displacement curve from a static shear wall test is shown in Figure 2.10 and the yield point from each of the standardized approaches can be seen.

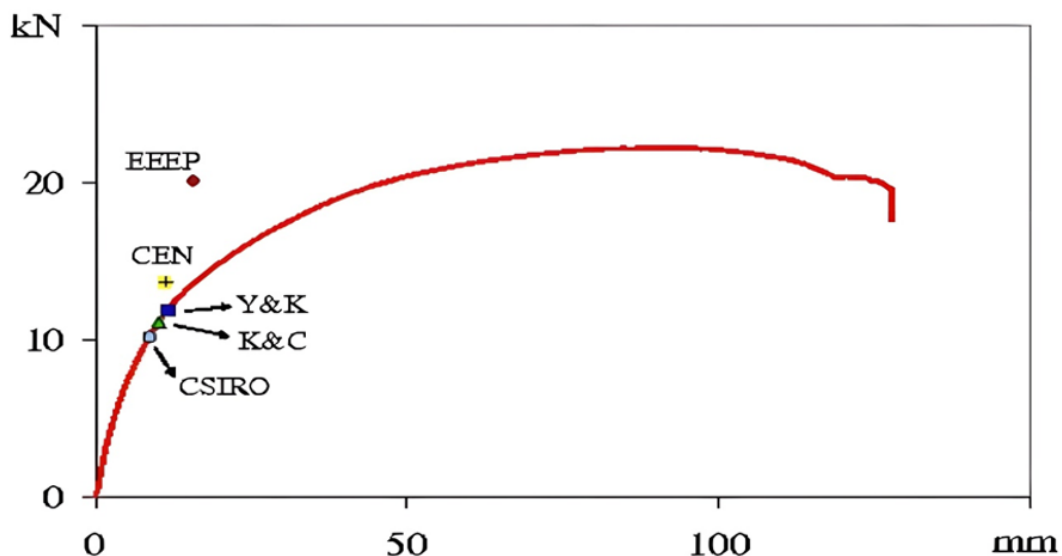


Figure 2.10: Load-displacement curve and yield point positions from five standardized approaches for a shear wall static test

**Reproduced from Munoz et al. (2008)*

From Figure 2.10, the yield point from the EEP and CEN were seen to be the highest while the yield point from the CSIRO was the lowest while producing a realistic value.

Other load-displacement curves from diverse timber connection assemblies were also investigated and the applicability of each approach was discussed. The yield loads were also expressed as a percentage of the P_{max} . In all the assemblies considered, the yield loads from the EEP method were deemed unrealistic. On the other hand, the yield load values from the CSIRO approach were the lowest and were always located within the elastic curve. Similarly, the yield load values from the K&C method were observed to be very realistic.

2.9.1 Karacabeyli and Ceccotti

This method has been proven to produce realistic values of load-deformation thereby preventing an overestimation of structural resistance. In this method the yield point is considered as the point on the load-deformation curve corresponding to 50% of its maximum capacity as shown in Figure 2.11.

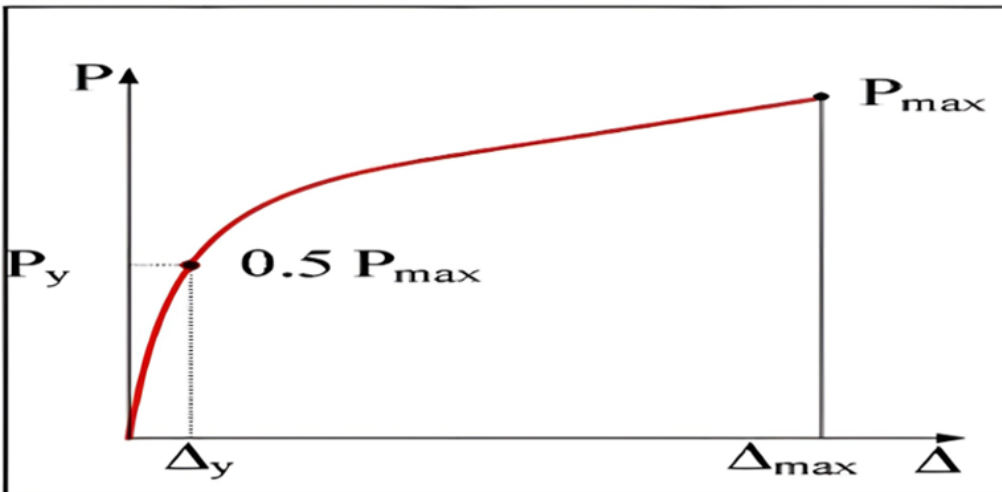


Figure 2.11: Load-displacement curve from K&C approach

**Reproduced from Karacabeyli E. and Cecceoti (1996)*

2.9.2 Commonwealth Scientific and Industrial Research Organization (CSIRO)

In this approach, the displacement at 40% of the peak load is multiplied by a peak factor of 1.25 to obtain the yield point displacement. Subsequently, the point of intersection formed by the new factored displacement value on the load-deformation curve is taken as the yield point. Figure 2.12 illustrates the relationship between the yield point and maximum capacity based on the peak factor recommended by the CSIRO.

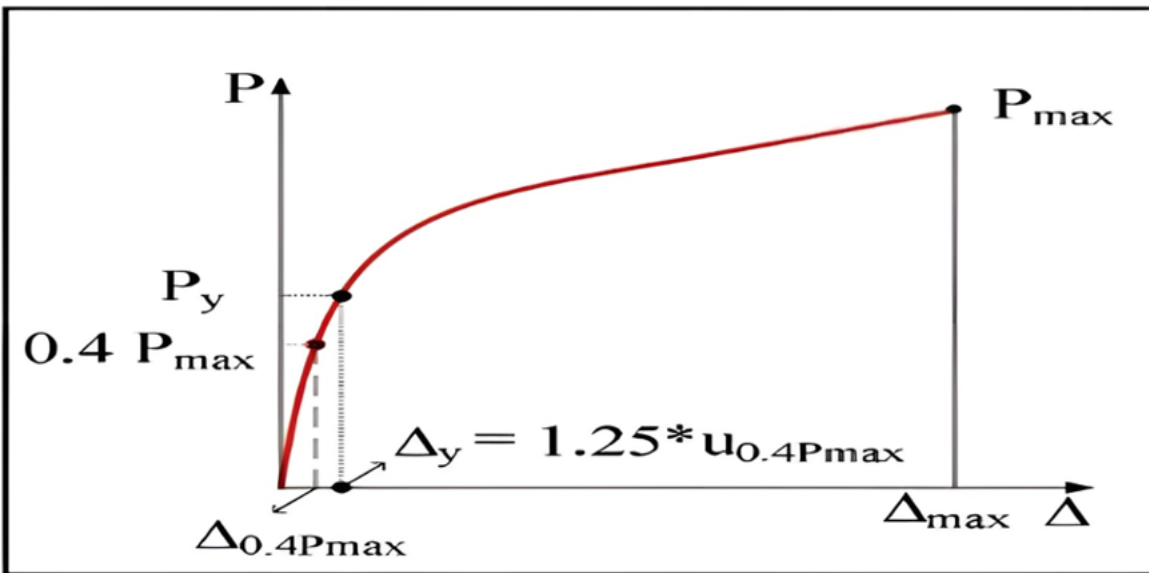


Figure 2.12: Load-displacement curve and yield point positions from CSIRO approach

**Reproduced from CSIRO (1996)*

2.10 EBC in Jacking Applications

Jacking timbers are stacked beams of wood used to form skidding tracks that support heavy structures in construction as they are being hauled from one point to another. Since dimensional stability and superior strength are important properties for jacking beams, steel jacks were traditionally the most used jacking and blocking systems by heavy engineering companies in North America. Gradually, as the world gravitated towards bio-based construction materials, jacking beams were manufactured from Canadian hardwoods (especially White Oak) and tropical hardwoods. However, it has been recently found that North American hardwoods inadequate in strength and durability for jacking applications due to swelling, shrinkage and cracking.

Ekki, a tropical hardwood and one of Africa's most durable species, is currently being employed in jacking applications because of its durability and fungal resistance. Osuji et al. (2017) investigated and compared the mechanical and physical properties of four notable structural timber species in Nigeria and concluded that Ekki had superior crushing strength, modulus of elasticity and modulus of rupture. The mechanical properties of Ekki is similar to North American hardwood, Red Oak. For example, Ekki has a crushing strength and elastic modulus of 6.2×10^7 N/mm² and 1.16×10^{10} N/mm² respectively, while Red Oak is reported as having crushing strength and elastic modulus of 4.7×10^7 N/mm² and 1.2×10^{10} N/mm² (Osuji et al., 2017).

In the UK and other parts of Europe, Ekki has been widely adopted for coastal and freshwater construction owing to its durability and resistance to marine borers (gribble and ship worm); Williams et al, 2010. Ekki, Opepe and Balau have been the preferred choice for marine construction applications in most parts of Europe, but this has raised concerns about the depletion of these tropical hardwoods. Williams et al (2010) explored the durability of a few lesser-known timber species in a bid to address the issue of narrowed timber inventory. The study identified Ekki and another tropical hardwood; Greenheart, as benchmark species and concluded that only a few species performed as good as Ekki in terms of resistance to marine borers but are mostly unavailable in commercial quantities. The durability, commercial availability, as well as current understanding of design values for Ekki in British design codes made it the ideal choice for marine and freshwater construction.

In regard to long-term environmental exposure, jacking operations are very similar to marine and freshwater construction. Similarly, Ekki has been widely adopted in jacking applications across Europe and North America owing to its fungal resistance and durability.

In Figure 2.13, a system of Ekki beams used in jacking applications can be seen. The base is made of Ekki beams that support steel tracks, and the system is sufficient for lifting up to 300 tonnes. Hydra-slide and many other heavy engineering companies have employed Ekki jacking timbers in their day-to-day skidding operations until recently.



Figure 2.13: Jacking operations with Ekki beams by Hydra-Slide Ltd.

**Image source: Hydra-slide.com*

Similarly, in Figure 2.14(a) and (b), typical jacking systems can be seen. In 2.14(a), the base of the system is made of tropical hardwood beams used to support rigid tracks as a large vehicle is being loaded on a rigid track.



(a): Jacking system supporting large vehicle



(b): Stacked Jacking beams

Figure 2.14: Heavy track skidding systems

**Image source: Hydra-slide.com*

Apart from heavy track skidding, engineering companies also employ the use of tropical hardwoods in other types of jacking operations. Figure 2.15 depicts a typical low-profile skidding system of tropical hardwood beams.



Figure 2.15: Tropical hardwoods in low-profile skidding systems

**Image source: Hydra-slide.com*

Heavy equipment companies have employed selected tropical hardwoods, especially Ekki, in their jacking operations for decades. However, there has been growing concerns about the quality decline of Ekki. The quality decline has been attributed mostly to the harvesting of immature trees thus leading to warping and shrinkage. Improper drying (seasoning) and the presence of knots have also been found to significantly reduce the bending and compressive performance.

Additionally, a major setback in global sustainability is the continuous harvesting of tropical hardwood. In terms of environmental sustainability, bamboo and EBCs are one of the most

suitable alternatives for wood due to its quick maturation and dimensional stability which limits warping and shrinkage.

The most important property in jacking applications is compression perpendicular-to-grain followed by bending and shear with a short and long span. Although bending and shear dominated failures are not expected when the jacking timbers are stacked appropriately, they can become the primary failure modes if used incorrectly by the client as seen in Figure 2.16 (b).



(a) Correct application

(b) Incorrect application

Figure 2.16: Illustration of the application of jacking beams on site

CHAPTER 3

Experimental Program

3.1 General

This chapter describes the specimen preparation and experimental investigation of the mechanical properties of Dragonwood and Ekki beams under applied loads.

Bamboo is an orthotropic material, having different material properties and strength in each mutually perpendicular axis. The longitudinal axis runs parallel to the grain, the tangential axis runs perpendicular to the grain, while the radial axis is normal to the growth rings. Due to the variability in properties in the different axes, mechanical tests are usually conducted in both parallel and perpendicular directions. However, due to the principal failure modes expected in jacking applications, only compression perpendicular-to-grain and bending parallel to grain will be prioritized in this research.

Ekki is a commercially available tropical hardwood popular in jacking applications whose mechanical properties have previously been studied, and its design values are available in BS 5268:2:2002. In this research however, gaining a fundamental understanding of the key mechanical properties of Dragonwood in relation to jacking applications at the beginning and end of their service lives is of utmost priority. Additionally, a comparison of the mechanical properties of Ekki and Dragonwood is important in evaluating the feasibility of Dragonwood scrimber as a replacement for Ekki in jacking applications.

3.2 Sample Collection, Measurement and Testing

The Dragonwood and Ekki beams were stored in a controlled environment before being cut into small, clear or structural sizes. The dimensions (length, width and depth) were carefully obtained before testing. The moisture content and specific gravity were determined immediately after testing from a small piece approximately (1" long), cut from each tested specimen in accordance with ASTM D 4442 *Standard test method for direct moisture content measurement of wood and*

wood-based materials and ASTM D 2395 *Standard Test Method for Specific Gravity of wood and wood-based materials*.

Figures 3.1 (a) and (b) are pictures of Ekki and Dragonwood beams stored in a controlled environment at the structural engineering laboratory of the University of Waterloo.



(a) Ekki Jacking beams

(b) Dragonwood beams

Figure 3.1: Skid of Ekki and Dragonwood beams

The choice of the mechanical properties to be investigated was based on the primary failure modes expected in jacking applications. As aforementioned, compression perpendicular to grain is the most likely failure mode in jacking applications while there is the possibility of bending and shear failures in the event of inappropriate stacking. Thus, the properties investigated were:

1. Bending parallel-to-grain
2. Compression perpendicular-to-grain

A total of 90 specimens were investigated for both flexural and compression tests. The flexural testing of full-size specimen was conducted with the lamination oriented in both horizontal and vertical directions. For Dragonwood, the orientation is with respect to the orientation of the bamboo strands. For Ekki, the orientation is based on the growth rings. Additionally, the flexural properties according to the field dimensions when applied in jacking applications were also investigated. The orthotropic nature of Dragonwood was considered, thus, the compression and

flexural tests with the glue-line being vertical (i.e., 0) and horizontal (i.e., 90) were both investigated. In Figure 3.2, the glue-line in Dragonwood is illustrated for both orientations.

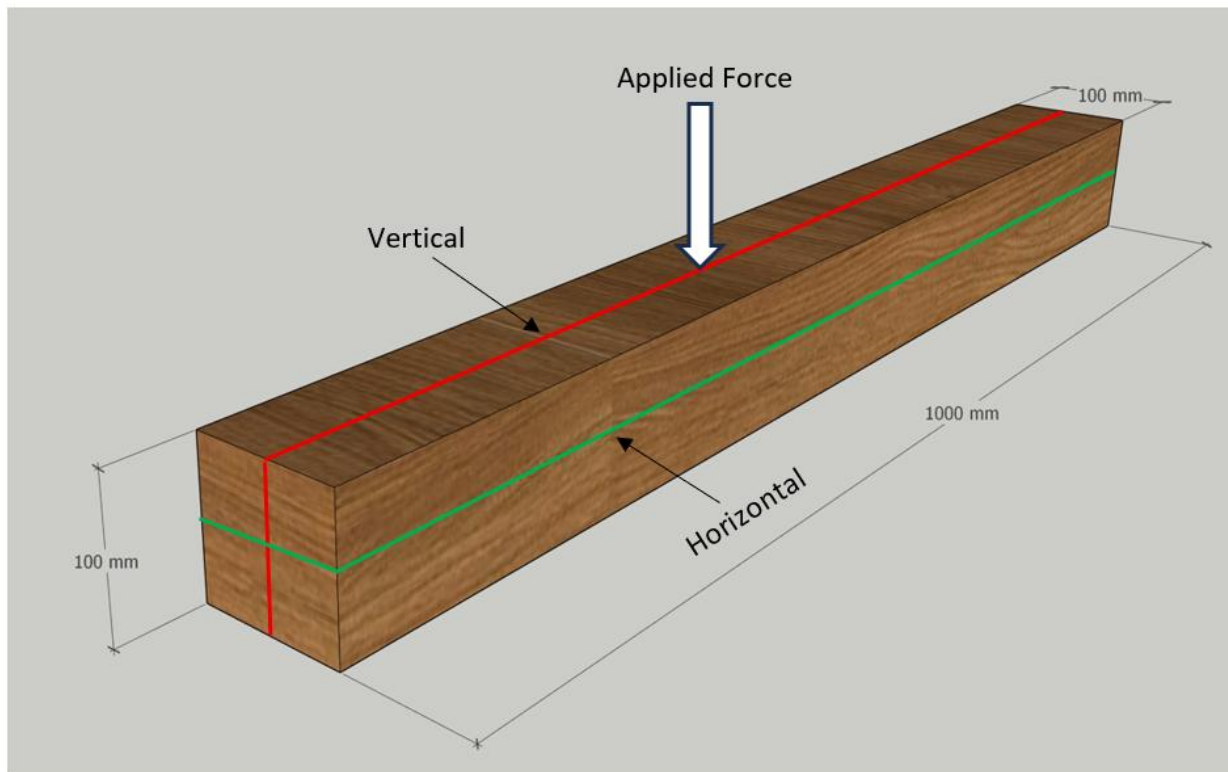


Figure 3.2: Illustration of vertical and horizontal orientation of glue-line in a flexural test

3.3 Brief Description of Tests

No testing standards have been established for conducting EBC experimental tests. In lieu of this, the tests for investigating the mechanical properties of both Dragonwood and Ekki beams were conducted in accordance with the *Standard test method for static test of lumber in structural sizes (ASTM D 198)*, and *Methods of testing small, clear specimens of timber (BS 373:1957)*. Both the dimensions of the specimen and the test set-up was in accordance with *ASTM D 198* since *BS 373:1957* cross references *ASTM D143-09*.

Strength properties were determined by Universal Testing Machines (MTS 311 and 322) in the Main Structures Lab of the Civil Engineering Department, University of Waterloo. The three-point loading test method specified in *ASTM D 143* recommends a loading rate of 0.5mm/min for the

measurement of modulus of elasticity, a 2.0mm/min for the measurement of the modulus of rupture and a loading rate of 0.305mm/min for the compression tests (Malanit, 2009). These recommendations guided the loading rates for each test and in addition, a linear variable displacement transducer (LVDT) was attached to measure the relative displacement while the failure load (in kN) and time to reach failure of each specimen was observed and recorded. Table 3.1 is a summary of the testing matrix for both flexural and compressive tests.

Table 3.1: *Testing Matrix Summary for Dragon wood and Ekki Specimen*

<i>Orientation</i>	<i>Flexural Tests</i>	<i>Compressive tests</i>
<i>Horizontal lamination</i>		
Dragonwood Batch 1	10	10
Dragonwood Batch 2	10	
Ekki	10	10
<i>Vertical Lamination</i>		
Dragonwood	10	10
Ekki	10	10
<i>Sub-Total</i>	50	40
<i>Total</i>	90	

3.4 Beam in Bending Parallel to Grain

Thirty Dragonwood beams from two manufacturing batches and twenty Ekki beams were tested to investigate their bending performance with laminations oriented horizontally and vertically. The beams were tested to failure under three-point bending with simply supported boundary conditions using a 500kN Test Frame (MTS 322 CNC testing machine). Each of the beams were 100mm × 100mm × 1000mm in dimension (width, depth and length). As the testing progressed, the maximum load at failure and the time to failure were also recorded. Photographs, video recordings and documentation of the failed specimens were documented. Figure 3.3 illustrates the three-point bending test set-up.

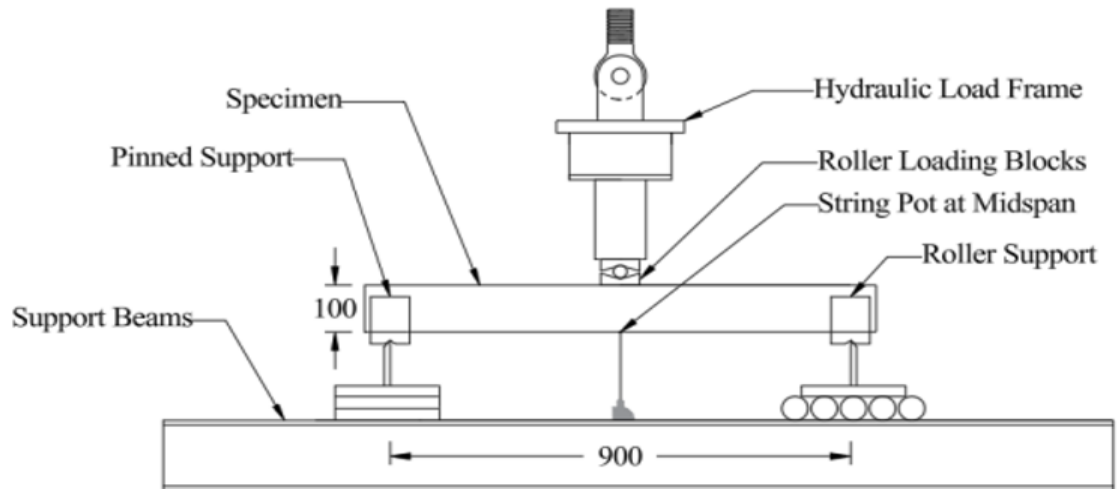


Figure 3.3: Static bending test set-up

From the experimental tests, the failure modes and load-displacement curves, the modulus of elasticity (MOE) and the modulus of rupture (MOR) were obtained for both Dragonwood and Ekki. For the Dragonwood, it was observed that the orientation of the glue-line has a significant impact on the strength of the member resulting in a 38% strength loss when the glue-line is oriented horizontally. The failure mode is characterized by a shear failure of the glue-line resulting in the loss of composite action between the two PSB sections as seen in Figure 3.5. When the glue-line is oriented vertically, the failure mode is characterized by a splintering tensile failure of the extreme bamboo fibres, and the MOR is comparable to that of the Ekki specimens. In both horizontal and vertical orientation, the MOE of the Dragonwood specimens are comparable to those of Ekki specimens.

3.5 Beam in Compression Perpendicular to Grain

Compression perpendicular-to-grain is the primary loading scenario in jacking applications hence the glue-line failure points were carefully observed during testing. Forty 100mm x 100mm x 250mm (w x h x l) specimens of both Dragonwood and Ekki were loaded in compression perpendicular-to-grain and tested for failure.

3.5.1 Compression Test Set-up and Instrumentation

The specimens were placed on the universal test frame bed, and the load was applied over a 100mm x 100mm steel plate. A CNC Testing machine (MTS 311) was used to test the specimens and tests were performed at a displacement rate of 0.305mm/min until a maximum displacement of 7.5mm was reached. The compression test set-up for both horizontal and vertical orientations is as illustrated in Figure 3.4.

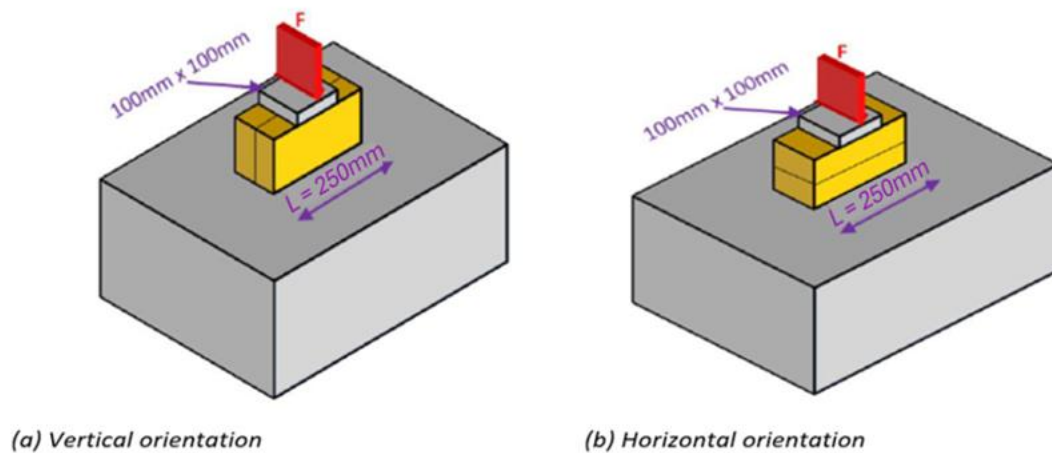


Figure 3.4: Illustration of Compression Test in Vertical and Horizontal orientations

In Figure 3.5, Dragonwood and Ekki specimens can be seen under the compressive test set-up prior to testing.



Figure 3.5: Images of Dragonwood and Ekki Specimens under compression perpendicular to grain test set-up

CHAPTER 4

Results and Discussion

4.1 General

The experimental test results from the flexural and compression tests are presented in this section. A total of ninety Dragonwood and Ekki beams were tested in flexure and compression, and the representative failure modes and load-displacement curves are presented.

4.2 Flexural Tests

Figures 4.1 and 4.2 illustrate the failure modes in flexure of different Dragonwood and Ekki specimens in both horizontal and vertical orientations.



Figure 4.1: Dragonwood and Ekki beams tested under static test set-up

In Figure 4.2, a horizontally oriented Dragonwood beam is tested to failure under flexural loads.



Figure 4.2: Shear failure of Dragonwood glue-line

With the Ekki specimens, in both horizontal and vertical orientation, the failure was characterized by the splintering tension failure occurring almost simultaneously with localized compression perpendicular to grain at the load application point as can be seen in Figure 3.6. The coefficient of variation for the load at failure was observed to be lower for the Dragonwood specimens with the glue-line being oriented vertically when compared to the Ekki specimens.

After observing the failure modes in the first batch of tested Dragonwood specimens, an additional ten 100mm × 100mm × 1000mm Dragonwood beams were tested to failure using a three-point bending test but only in the horizontal orientation. EBCs from different manufacturers or production batches can have a slight variation in their strength properties (Tang et al., 2021) hence the need to investigate the mechanical properties of the second batch of Dragonwood specimens.

Figure 4.3 demonstrates the splintering tensile failure in tested Ekki beams.



Figure 4.3: Splintering tension failure of Ekki beams in both horizontal and vertical orientations

4.2.1 Failure Modes of Dragonwood Scrimber Beams

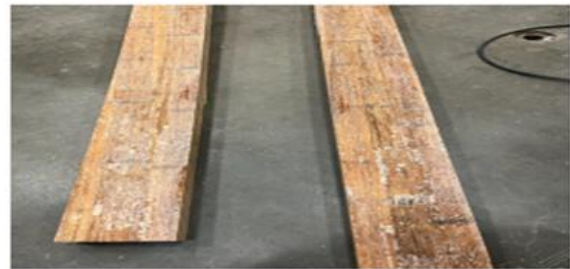
The representative failure modes for the Dragonwood specimens are presented in Figures 4.3 and 4.4. The Dragonwood beams were oriented horizontally and vertically with respect to the bamboo fiber orientation. Once the maximum load was attained, the specimens began to fail, and the resistance was seen to decline immediately. The orientation of the Dragonwood specimens was observed to impact the maximum loading attained, specimens with horizontal laminations were observed to have a 38% loss in strength than the specimens with vertical

laminations. The failure along the glue-line was also observed in each tested specimen to understand the effect of glue-bond on the failure mode, MOE and MOR.

Figures 4.4 and 4.5 demonstrate the glue-line failure and splintering tensile failure in Dragonwood beams.



(a) Dragonwood: horizontal lamination



(b) Split at glue-line in tested Dragonwood

Figure 4.4: Failure mode illustration in horizontally oriented Dragonwood beams

In Figure 4.5, the zoomed image of the splintering tension failure in a vertically oriented Dragonwood beam can be seen.



(a) Dragonwood: vertical orientation



(b) Failure in Dragonwood

Figure 4.5: Failure mode illustration in vertically oriented Dragonwood beam

4.2.2 Flexural Resistance Curves

Figures 4.5 and 4.6 represent the load-displacement curves for selected Dragonwood and Ekki beams in horizontal and vertical orientations. In both Dragonwood and Ekki, the beams initially behave linearly and then continue to show post peak resistance even after maximum load is attained.

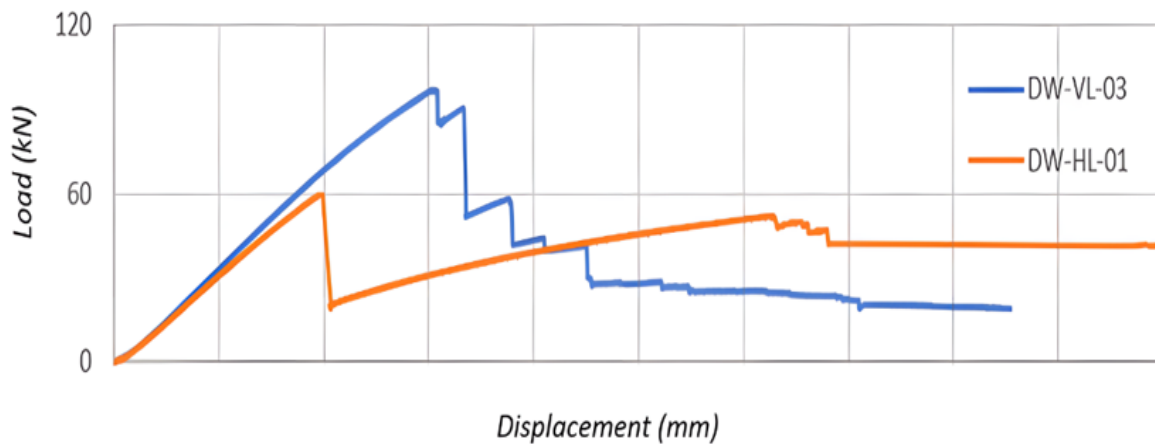


Figure 4.6: Flexural load-displacement graph for selected Dragonwood specimens in horizontal and vertical orientation

As can be observed, the bending stiffness is comparable for both types of beams when tested in the same orientation.

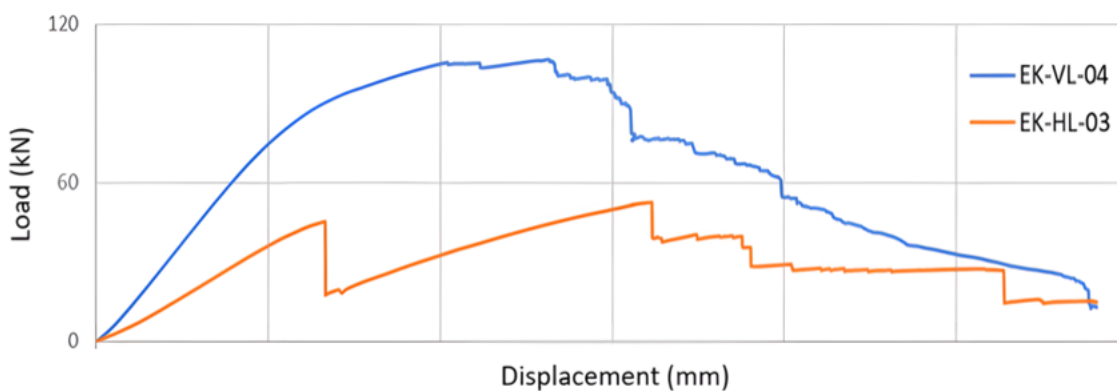


Figure 4.7: Flexural load-displacement graph for selected Ekki specimens in horizontal and vertical orientation

The bending stiffness is calculated by measuring the displacements and strains during the initial elastic portion of the resistance curve. The average of the stiffnesses obtained from 10% to 40% of the maximum load are calculated and applied in the MOR and MOE calculations. The MOE and MOR can be deduced from the maximum load, bending stiffnesses, moment of inertia, section modulus and beam span as shown in Equations [3.1] and [3.2].

$$MOE = \frac{K \times L^3}{48 \times I} \quad [3.1]$$

$$MOR = \frac{P_{max} \times L}{4 \times S} \quad [3.2]$$

Where K is the stiffness obtained from 10 to 40 % of the experimental load-deflection relationship, L is the span length, I is the moment of inertia of the Beam and S is the section modulus.

4.2.3 Flexural Test Results of Dragonwood Scrimber Beams

The flexural tests results for Dragonwood are presented in Table 4.1 along with the stiffnesses, maximum load, displacement and the resulting MOE and MOR for the Dragonwood specimens in both horizontal and vertical orientations.

Table 4.1: Summary of experimental results for Dragonwood flexural tests (Batch 1)

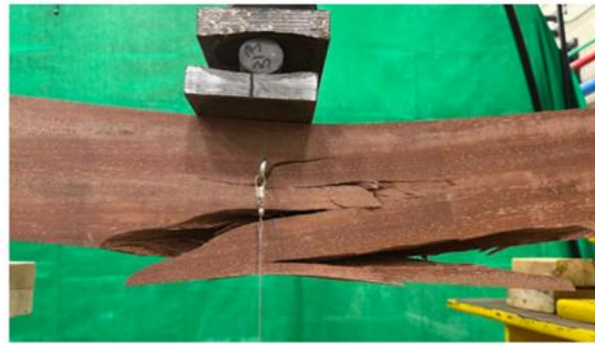
Specimen	MOE^d (MPa)	MOR^e (MPa)
DW-HL-01	8,486	71.2
DW-HL-02	8,034	96.1
DW-HL-03	7,957	54.2
DW-HL-04	7,505	45.7
DW-HL-05	8,378	79.8
DW-HL-06	7,428	43.7
DW-HL-07	8,185	76.1
DW-HL-08	8,129	91.4
DW-HL-09	7,626	65.1
DW-HL-10	8,063	76.2
Average	7,979	70.0
Std. Dev.	338	16.9
CoV	0.04	0.24
DW-VL-01	8,765	106.0
DW-VL-02	8,235	116.1
DW-VL-03	9,434	116.4
DW-VL-04	8,301	110.5
DW-VL-05	7,739	121.4
DW-VL-06	7,956	111.6
DW-VL-07	7,545	104.8
DW-VL-08	8,363	113.6
DW-VL-09	8,573	116.4
DW-VL-10	8,139	119.2
Average	8,305	113.6
Std. Dev.	511	5.12
CoV	0.06	0.05

4.2.4 Flexural Test Results of Ekki Specimens

The Ekki specimens were oriented based on the orientation of the growth rings. Based on the flexural response observed in the Ekki beams, it can be concluded that the performance of Ekki in bending is not significantly affected by orientation. The representative failure modes of selected Ekki beams can be seen in Figures 4.3 and 4.4. Images of the failure modes of all Ekki specimens in both horizontal and vertical lamination are attached in Appendices C and D.



(a) Ekki: horizontal orientation



(b) Zoomed image of Ekki at failure

Figure 4.8: Failure mode illustration in horizontally oriented Ekki beams



(a) Ekki: Vertical orientation



(b) Zoomed image of Ekki at failure

Figure 4.9: Failure mode illustration in vertically oriented Ekki beams

Table 4.2 presents the MOE and MOR for Ekki specimens in horizontal and vertical orientations.

Table 4.2: Summary of experimental results for the Ekki flexural tests

Specimen	MOE^a (MPa)	MOR^b (MPa)
EK-HL-01	10,134	139.4
EK-HL-02	8,792	120.4
EK-HL-03	6,571	82.8
EK-HL-04	9,876	127.6
EK-HL-05	9,737	91.8
EK-HL-06	10,220	121.6
EK-HL-07	10,418	107.6
EK-HL-08	10,317	98.5
EK-HL-09	7,135	85.0
EK-HL-10	9,210	99.4
Average	9,241	107.4
Std. Dev.	1.293	18.2
CoV	0.14	0.17
EK-VL-01	9,900	127.3
EK-VL-02	9,188	113.8
EK-VL-03	9,278	106.4
EK-VL-04	10,348	126.7
EK-VL-05	10,522	138.8
EK-VL-06	8,040	102.8
EK-VL-07	8,314	109.0
EK-VL-08	8,618	103.4
EK-VL-09	8,322	104.9
EK-VL-10	7,400	95.6
Average	8,993	112.9
Std. Dev.	980	13.0
CoV	0.11	0.11

^a Modulus of elasticity

^b Modulus of rupture

4.3 Comparison of Dragonwood and Ekki in Flexure

Table 4.3 presents the average MOE and MOR for both Dragonwood and Ekki when oriented horizontally and vertically. The experimental results show that in both Dragonwood and Ekki, the MOE is independent of orientation. However, the MOR is significantly affected by the beam's orientation when loaded in flexure. The MOR in Dragonwood and Ekki is only comparable when the glue-line of the Dragonwood beams is oriented vertically.

Table 4.3: Comparison of MOE and MOR values of Dragonwood and Ekki

		Dragonwood		Ekki	
Property (MPa)		Vertical	Horizontal	Horizontal	Vertical
^a MOE	Average	8,305	7,979	9,241	8,993
	Std. Dev.	511	338	1,293	980
	Cov	0.06	0.04	0.14	0.11
^b MOR	Average	113.6	70.0	107.4	112.9
	Std. Dev.	5.1	16.9	18.2	13.0
	CoV	0.05	0.24	0.17	0.11

^a Modulus of elasticity

^b Modulus of rupture

It should be noted that the values presented for the flexural strength of Dragonwood and Ekki jacking timber are at the 50th percentile (i.e., experimental analysis) and that statistical and reliability analysis is required to bring these experimental values to a design value corresponding to North American codes. However, given the lower coefficient of variation, CoV observed in the Dragonwood when the glue-line is vertical, it is anticipated to have a higher flexural design strength when compared to the Ekki.

A second batch of Dragonwood specimens were tested to further investigate the flexural strength of Dragonwood when the glue-line is oriented horizontally. The experimental results are presented in Tables 4.4 and 4.5. The MOR of the Dragonwood when the glue-line is oriented horizontally is seen to significantly differ from that of Ekki (i.e. the MOR average for Dragonwood is 61.23MPa and 107.4MPa for Ekki).

Table 4.4: Summary of flexural test results for horizontally oriented Dragonwood specimen (Batch 2)

Specimen	K (kN/mm)	Pmax (kN)	Δpmax (mm)
DW2-HL-01	6.63	71.05	9.97
DW2-HL-02	7.46	49.49	7.11
DW2-HL-03	7.51	40.58	5.7
DW2-HL-04	7.36	55.04	8.19
DW2-HL-05	7.31	35.78	5.11
DW2-HL-06	8.03	70.68	9.51
DW2-HL-07	6.31	28.87	5.33
DW2-HL-08	7.61	80.73	11.41
DW2-HL-09	6.54	28.43	4.6
DW2-HL-10	7.33	49.77	7.18
Average	7.21	51.04	7.41
Std. Dev	0.54	18.36	2.31
CoV	0.07	0.36	0.31

^a Stiffness

^b Maximum load

^bMaximum Displacement

The resulting modulus of rupture for the Dragonwood specimens was obtained in addition to the modulus of elasticity and presented in Table 4.5. The values of the MOE and MOR for the Batch 2 Dragonwood specimens when compared to the values obtained for the Batch 1 specimens were not significantly different. Though the manufacturer improved the glue-bond slightly during the manufacturing process of the Batch 2 Dragonwood specimens, it did not significantly impact the specimens' performance. However, when compared with the Ekki specimens, the average MOR from the batch 2 Dragonwood specimens were significantly different from the MOR values for the horizontally oriented Ekki Specimens as can be seen in Table 4.6.

Table 4.5: Modulus of elasticity and rupture for Dragonwood specimens (Batch 2)

Specimen	MOE (MPa)	MOR (MPa)
DW2-HL-01	8,486	85.23
DW2-HL-02	9,543	59.36
DW2-HL-03	9,618	48.68
DW2-HL-04	9,419	66.03
DW2-HL-05	9,363	42.92
DW2-HL-06	10,273	84.78
DW2-HL-07	8,076	34.63
DW2-HL-08	9,743	96.84
DW2-HL-09	8,372	34.10
DW2-HL-10	9,384	59.70
Average	9,228	61.23
Std. Dev	691	22.01
CoV	0.07	0.36

^a Modulus of elasticity ^b Modulus of rupture

Table 4.6: Comparison of MOE and MOR values of Dragonwood Batch 2 and horizontally oriented Ekki Specimens

Property (MPa)	Dragonwood (Batch 2)	Ekki (HL)
^a MOE <i>Average</i>	<i>9,228</i>	<i>9,241</i>
<i>Std. Dev.</i>	<i>691</i>	<i>1.293</i>
<i>Cov</i>	<i>0.07</i>	<i>0.14</i>
^b MOR <i>Average</i>	<i>61.23</i>	<i>107.4</i>
<i>Std. Dev.</i>	<i>22.01</i>	<i>18.2</i>
<i>CoV</i>	<i>0.36</i>	<i>0.17</i>

^a Modulus of elasticity ^b Modulus of rupture

4.4 Flexural Resistance Curves of Dragonwood Specimens

The flexural resistance curves of tested specimens were compared. Figures 4.10 and 4.11 present the flexural resistance curves of vertically oriented and horizontally oriented Dragonwood specimens respectively.

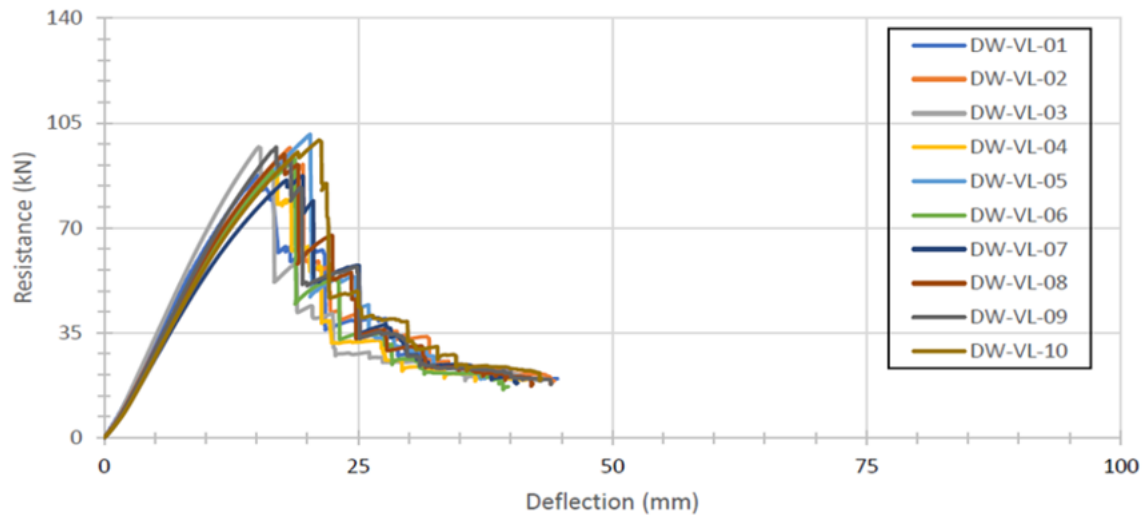


Figure 4.10: Flexural Resistance Curves of vertically oriented Dragonwood Specimens

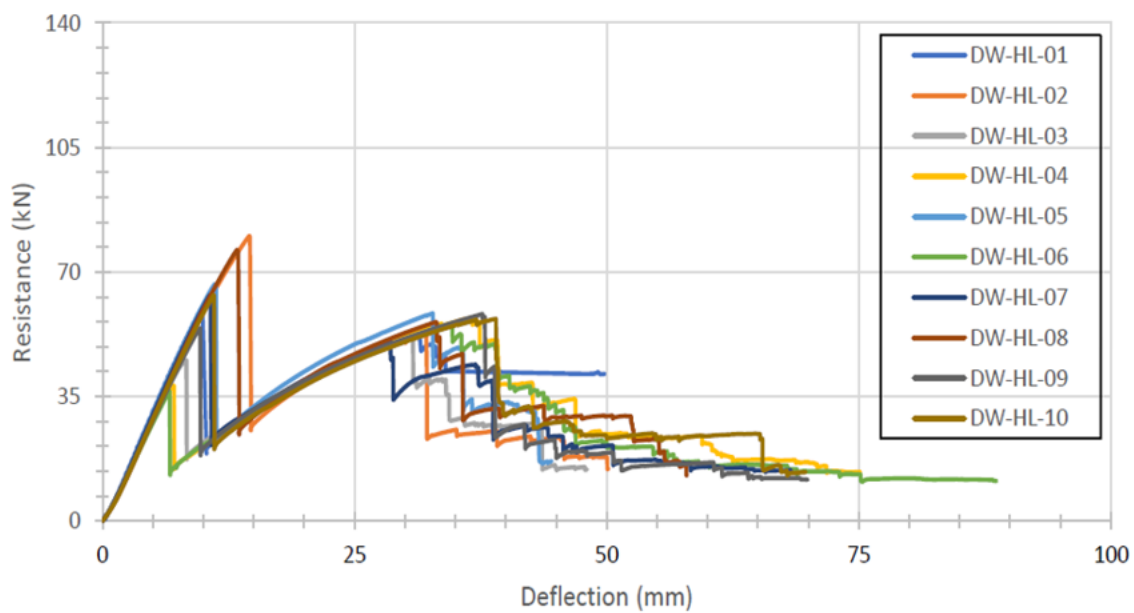


Figure 4.11: Flexural Resistance Curves of horizontally oriented Dragonwood Specimens

4.5 Flexural Resistance Curves of Ekki Specimens

Similarly, the flexural resistance curves of Ekki specimen in vertical and horizontal oriented are presented in figures 4.12 and 4.13.

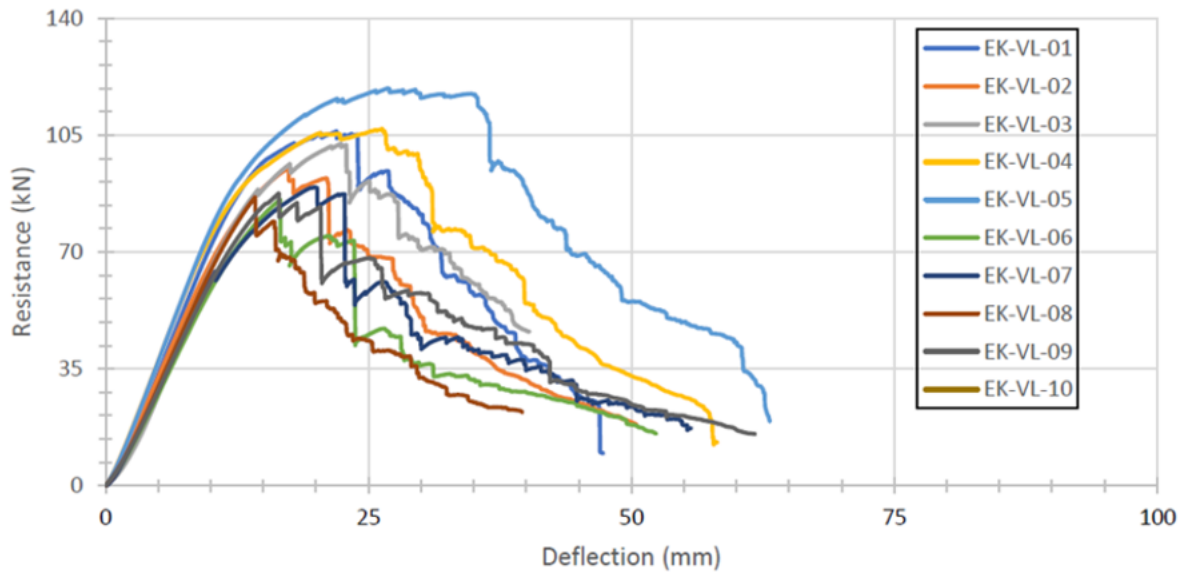


Figure 4.12: Flexural Resistance Curves of vertically oriented Ekki Specimens

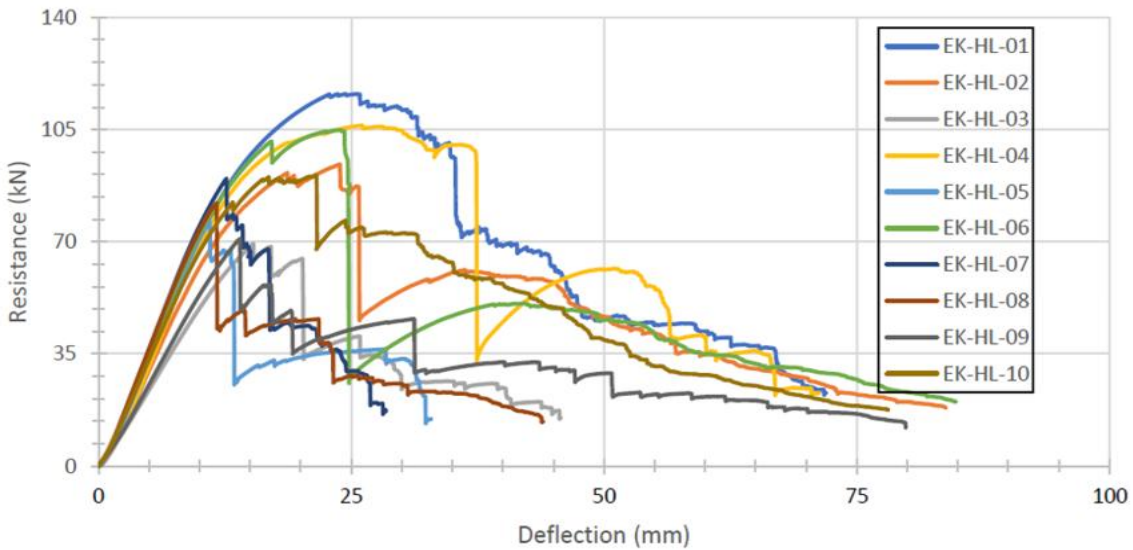


Figure 4.13: Flexural Resistance Curves of horizontally oriented Ekki Specimens

4.6 Compression Tests

4.6.1 Failure Modes of Dragonwood and Ekki Beams

At the initial loading stage, the Dragonwood and Ekki specimens were observed to be in an elastic state with no visible damage observed on the specimens. As compressive force was increased, cracks propagated along the grain of the specimens and the cracks continued to expand. The specimens reached the maximum stress at their yield point before descending linearly into failure. Figures 4.14 (a) and (b) captures the image of a Dragonwood specimen tested to failure.



Figure 4.14: Images from failure during compression tests (Dragonwood; horizontal orientation)

In Figure 4.15, different sides of a Dragonwood specimen show the cracks resulting from failure during the compressive perpendicular-to-grain tests.

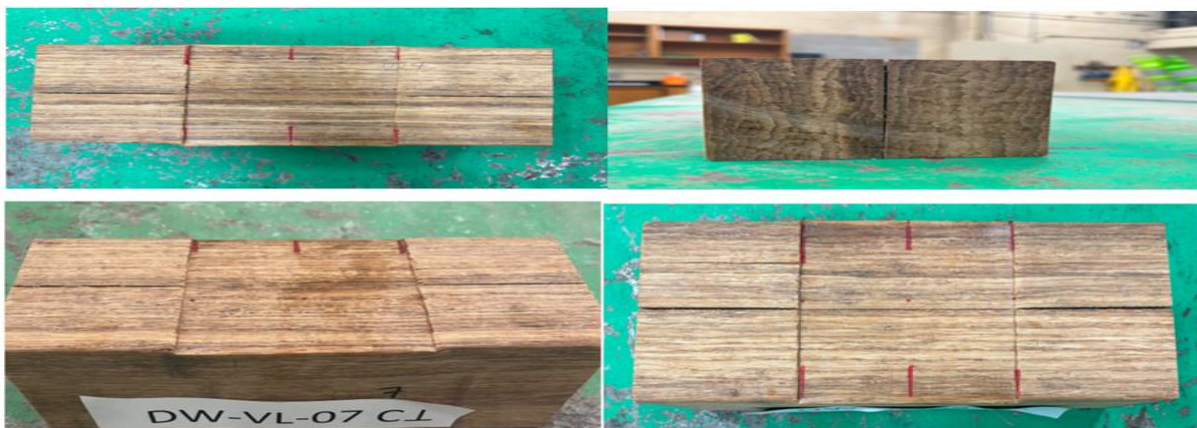


Figure 4.15: Images from failure during compression tests (Dragonwood; vertical orientation)

For the Ekki specimens, the compression strength was significantly impacted by the orientation. There was a significantly shorter time to failure for most of the Ekki specimens in vertical orientation as compared to the specimens in horizontal orientation (i.e. the beams have less compressive strength perpendicular-to-grain than in the vertical orientations). In Figure 4.16 tested Ekki specimens in horizontal orientation is shown.



Figure 4.16: Images from failure during compression tests (Ekki beams; horizontal orientation)

Likewise, In Figure 4.17, the observed failure in a vertically oriented Ekki beam is shown.



Figure 4.17: Images from failure during compression tests (Ekki beams; vertical orientation)

4.6.2 Compression Test Results of Dragonwood Scrimber Beams

Table 4.7 presents a summary of experimental results for the compressive tests. The yield stresses were obtained from two globally recognized approaches; Karacabeyli and Cecceotti, and CSIRO.

Table 4.7: Experimental results and analytical data for Dragonwood in Compression (Horizontal and Vertical Laminations)

Specimen	Stress (MPa)			Strain ($\times 10^{-3}$)		
	$\sigma_{\max}$	$\sigma_y^{(a)}$	$\sigma_y^{(c)}$	$\epsilon_{P\max}$	$\epsilon_y^{(a)}$	$\epsilon_y^{(c)}$
DW01-HL	74.4	36.7	36.7	70.6	19.26	20.56
DW02-HL	71.5	35.7	33.6	70.9	20.03	18.36
DW03-HL	80.0	40.0	39.8	66.4	22.63	22.58
DW04-HL	79.6	39.6	38.4	71.1	19.26	18.99
DW05-HL	65.9	32.9	31.4	47.4	13.83	12.97
DW06-HL	62.6	31.3	30.8	75.1	23.83	23.39
DW07-HL	84.2	41.6	39.2	75.1	21.90	21.80
DW08-HL	72.2	36.1	35.2	75.1	23.40	22.69
DW09-HL	71.5	35.7	34.9	75.1	22.82	22.11
DW10-HL	71.4	35.7	35.0	75.0	24.35	23.75
Average	73.3	36.5	35.5	70.15	21.12	20.72
Std. Dev.	6.5	3.1	3.1	8.06	3.00	3.08
CoV	0.09	0.08	0.09	0.11	0.14	0.15
DW01-VL	59.5	29.7	30.4	63.7	14.50	14.81
DW02-VL	67.8	33.9	34.4	65.2	16.68	16.93
DW03-VL	77.6	38.8	39.8	58.4	14.58	15.00
DW04-VL	74.4	37.2	37.7	75.0	18.17	18.45
DW05-VL	76.3	38.1	37.8	75.0	18.09	17.89
DW06-VL	72.1	36.0	37.8	75.0	20.13	21.05
DW07-VL	78.8	39.4	39.6	75.1	18.44	18.53
DW08-VL	66.0	33.0	33.4	75.0	17.58	17.82

Specimen	$\sigma_{\max}$	$\sigma_y^{(a)}$	$\sigma_y^{(c)}$	$\epsilon_{P\max}$	$\epsilon_y^{(a)}$	$\epsilon_y^{(c)}$
DW09-VL	69.2	34.6	36.4	75.0	21.76	22.72
DW10-VL	69.9	34.9	35.7	72.8	18.98	19.4
Average	71.2	35.6	36.3	71.03	17.89	18.26
Std. Dev.	5.9	3.0	2.9	5.34	2.13	2.32
CoV	0.08	0.08	0.08	0.08	0.12	0.13
$\sigma_{\max}$ Maximum Stress		$\sigma_y^{(a)}$ Yield Stress (K&C)		$\sigma_y^{(c)}$ Yield Stress (CSIRO)		
$\epsilon_{P\max}$ Maximum Strain		$\epsilon_y^{(a)}$ Yield Strain (K&C)		$\epsilon_y^{(c)}$ Yield Strain (CSIRO)		

4.6.3 Compression Test Results of Ekki Specimens

Table 4.8 presents the experimental test results for Ekki specimens in compression. Twenty Ekki specimens were tested in compression in both vertical and horizontal orientations.

Table 4.8: Experimental results and analytical data for Ekki in Compression

Property		Stress (MPa)			Strain ($\times 10^{-3}$)	
Specimen	$\sigma_{\max}$	$\sigma_y^{(a)}$	$\sigma_y^{(c)}$	$\epsilon_{P\max}$	$\epsilon_y^{(a)}$	$\epsilon_y^{(c)}$
EK01-HL	47.1	23.5	24.1	75.1	18.65	19.13
EK02-HL	42.7	21.3	22.0	75.0	23.79	24.52
EK03-HL	45.5	22.6	21.5	75.0	19.10	18.31
EK04-HL	47.3	23.7	25.0	71.8	13.67	14.36
EK05-HL	41.0	20.5	19.6	75.2	20.64	19.37
EK06-HL	44.3	22.1	22.3	75.6	17.11	17.22
EK07-HL	38.4	19.2	20.0	74.0	14.60	15.18
EK08-HL	49.9	25.0	26.7	75.0	19.80	21.05
EK09-HL	44.7	22.3	23.6	74.5	17.03	17.97
EK10-HL	43.5	21.7	22.6	75.1	19.13	19.94
Average	44.4	22.2	22.7	74.6	18.35	18.70
Std. Dev.	3.3	1.6	2.2	1.03	2.78	2.75
CoV	0.07	0.07	0.10	0.01	0.15	0.15

Specimen	$\sigma_{\max}$	$\sigma_y^{(a)}$	$\sigma_y^{(c)}$	$\epsilon_{P\max}$	$\epsilon_y^{(a)}$	$\epsilon_y^{(c)}$
EK01-VL	44.0	22.0	23.0	75.1	22.00	23.00
EK02-VL	36.2	18.0	18.2	75.0	16.81	16.93
EK03-VL	37.4	18.7	17.5	75.0	14.43	13.31
EK04-VL	49.8	24.9	27.4	75.0	19.48	20.95
EK05-VL	46.4	23.2	23.7	75.3	23.32	23.82
EK06-VL	44.3	22.1	22.3	75.6	17.11	17.22
EK07-VL	38.4	19.2	21.3	73.5	18.77	20.31
EK08-VL	43.2	21.6	24.7	75.0	31.58	34.67
EK09-VL	34.3	17.1	16.6	75.0	17.95	17.11
EK10-VL	40.8	20.4	21.6	75.0	22.17	23.35
Average	41.5	20.7	21.6	74.95	20.34	21.07
Std Dev.	4.9	2.5	3.4	0.52	4.56	5.57
CoV	0.12	0.12	0.16	0.01	0.22	0.26

$\sigma_{\max}$ Maximum Stress	$\sigma_y^{(a)}$ Yield Stress (K&C)	$\sigma_y^{(c)}$ σ Yield Stress (CSIRO)
$\epsilon_{P\max}$ Maximum Strain	$\epsilon_y^{(a)}$ Yield Strain (K&C)	$\epsilon_y^{(c)}$ σ Yield Strain (CSIRO)

4.7 Comparison of Dragonwood and Ekki in Compression

In Dragonwood, the CoV of yield stresses and strains obtained from the CSIRO and Karacabeyli & Cecceotti approaches were very similar in both horizontal and vertical orientations. With Ekki, the compression strength was significantly impacted by the orientation i.e., vertically oriented specimens were observed to fail in less time. Thus, the CoV of yield stresses and strains for specimens slightly varied.

4.8 Compression Resistance Curves of Dragonwood Specimens

Figures 4.18 and 4.19 show the load-displacement relationship in compression of ten specimens each of either Dragonwood or Ekki in horizontal or vertical laminations.

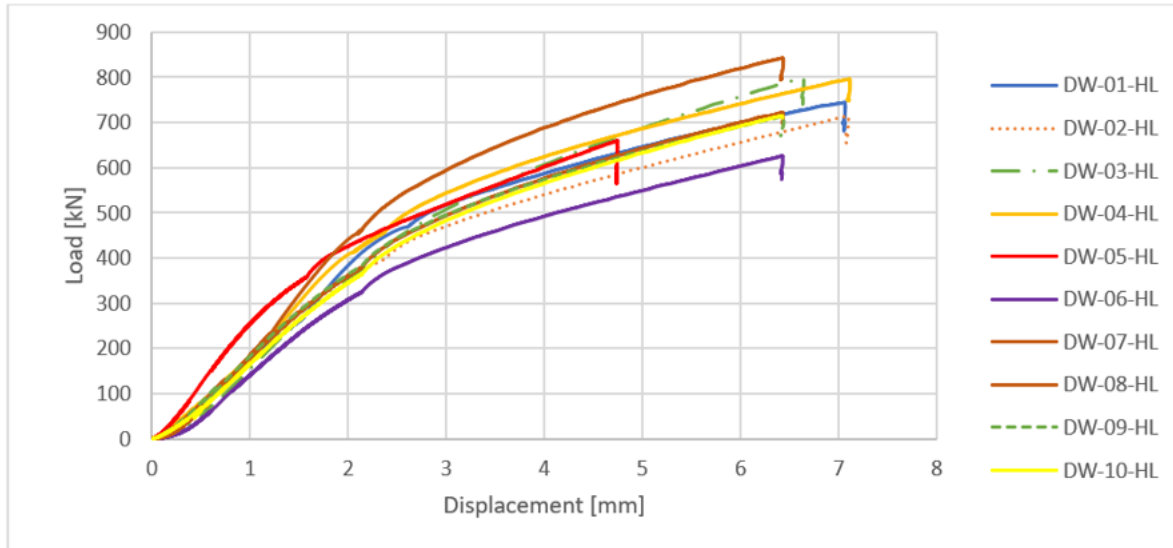


Figure 4.18: Load-Displacement curves of horizontally laminated Dragonwood in compression

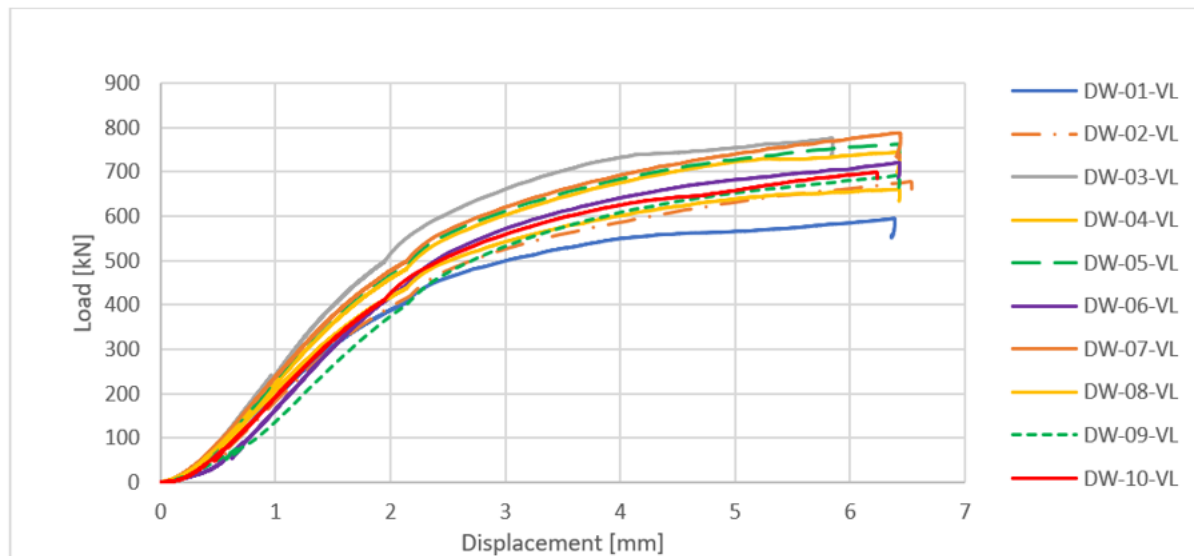


Figure 4.19: Load-Displacement curves of vertically laminated Dragonwood in compression

4.9 Compression Resistance Curves of Ekki Specimens

Similarly, the compression resistance curves of horizontally and vertically oriented Ekki specimens are presented in figures 4.20 and 4.21.

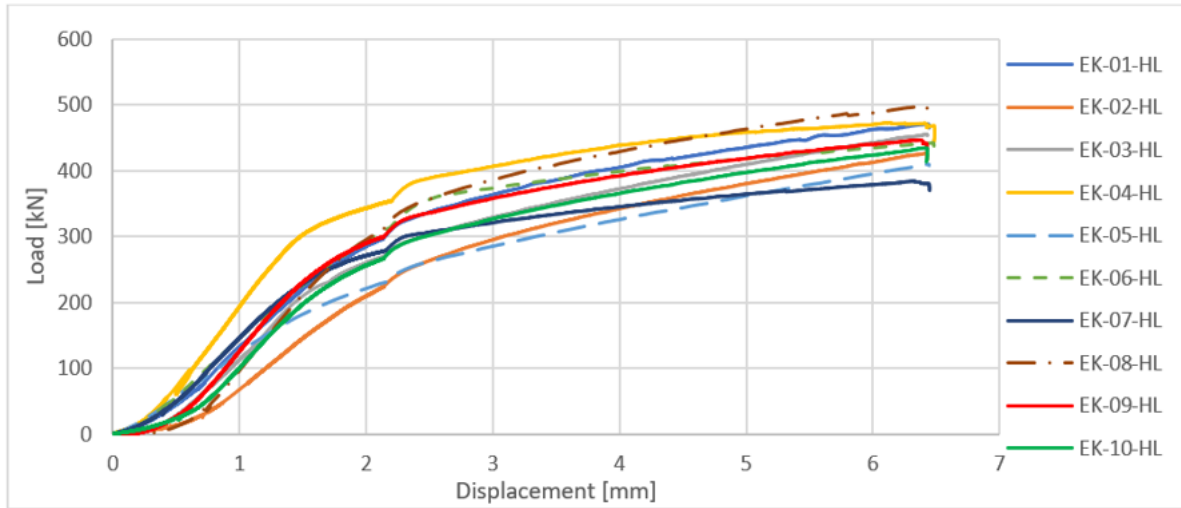


Figure 4.20: Load-Displacement curves of horizontally laminated Ekki in compression

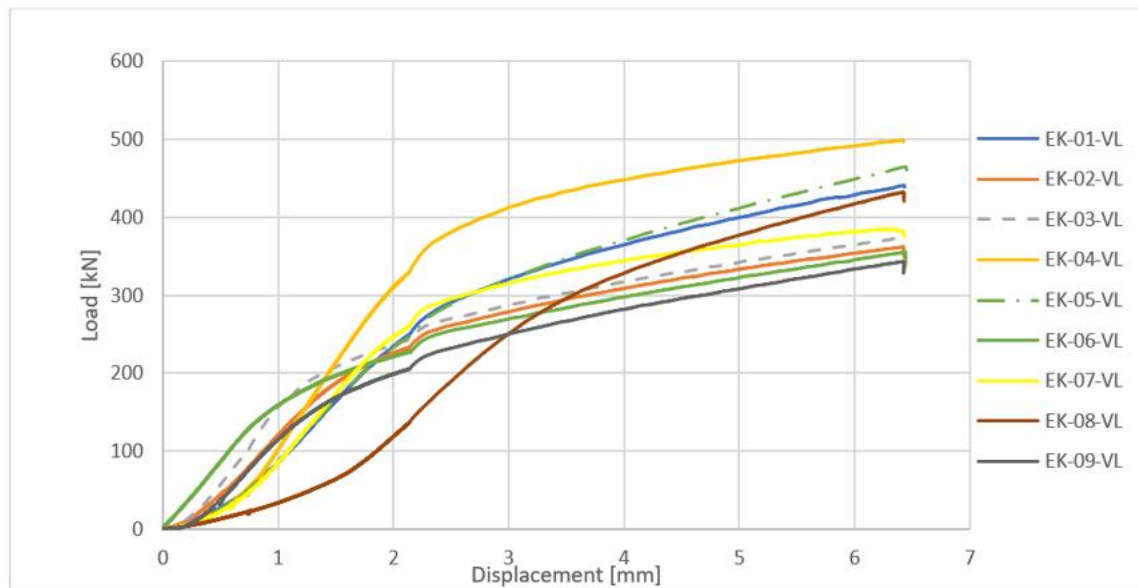


Figure 4.21: Load-Displacement curves of vertically laminated Ekki in compression

4.10 Harmonized Yield Stress Approach

There are several approaches for yield point and deformation analysis, but a harmonized approach is beneficial in obtaining realistic ductility ratios. Two widely accepted approaches; the *CSIRO* and *K&C* approach were employed in this study. Similar to the comparison of yield points from different approaches made by Munoz et al. (2008), the yield points from the *CSIRO* AND *K&C* approaches of selected specimens were observed and compared. The yield points were seen to be very close in both approaches, and no significant difference was observed. The yield points of both Ekki and Dragonwood specimens can be seen to be very close from the graphs in Figures 4.22 to 4.24.

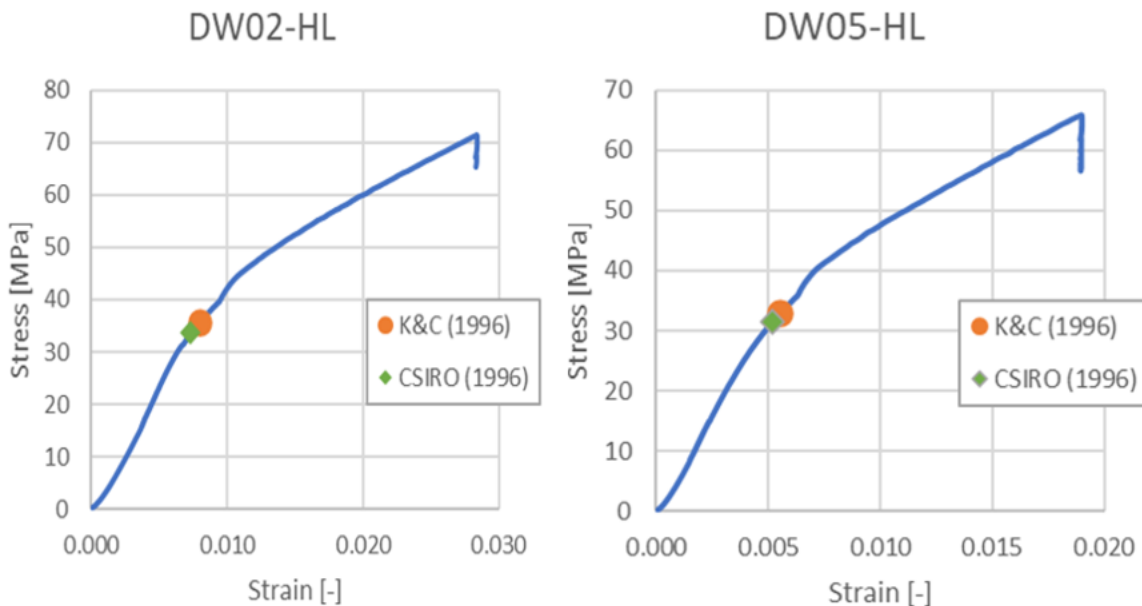


Figure 4.22 Comparison of Yield Stresses from two widely accepted approaches for two horizontally oriented Dragonwood specimens

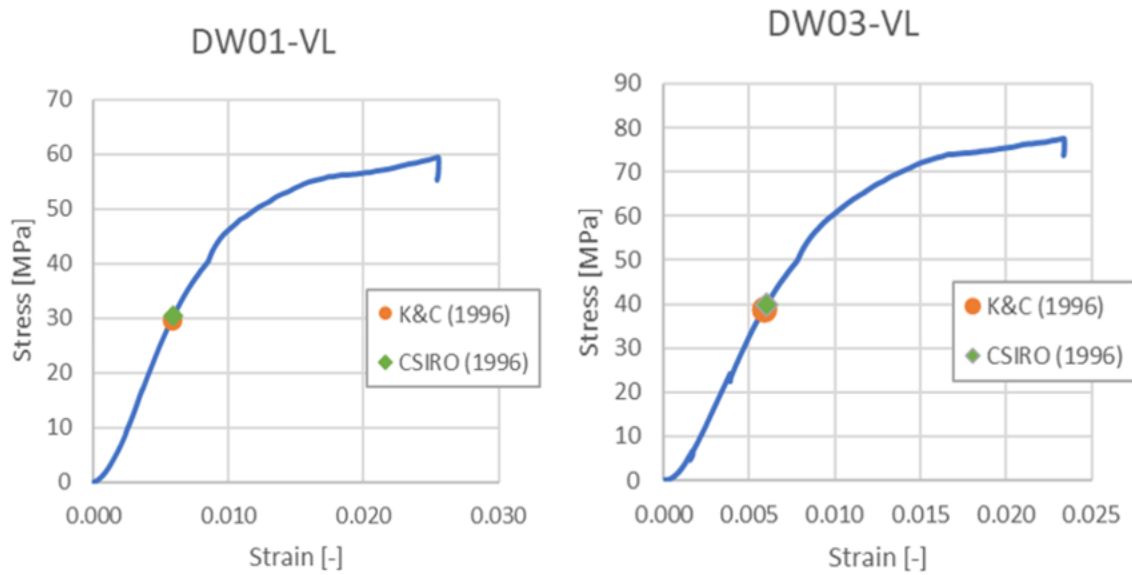


Figure 4.23 Comparison of Yield Stresses from two widely accepted approaches for two vertically oriented Dragonwood specimens

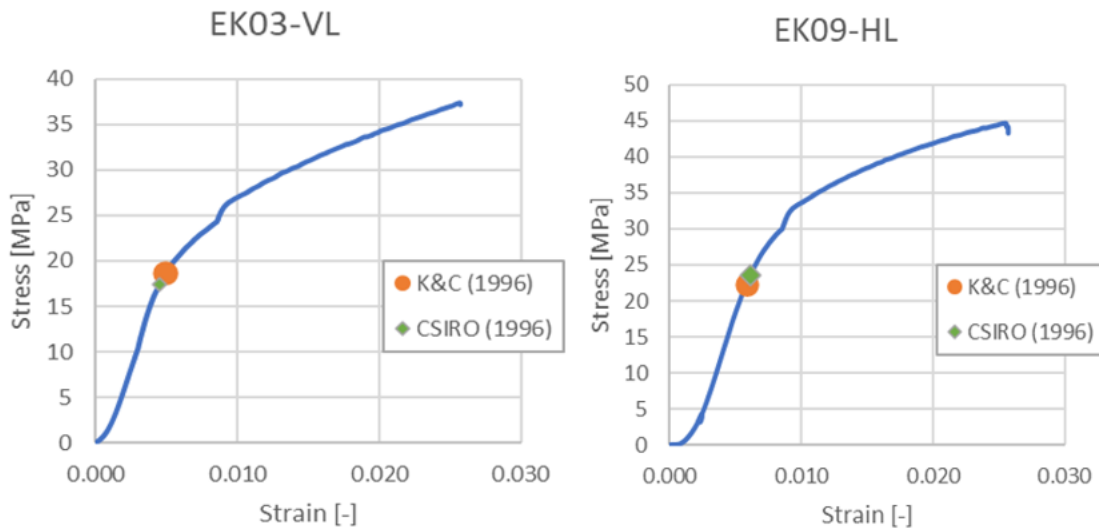


Figure 4.24: Comparison of Ekki Yield Stresses from two widely accepted approaches for two Ekki specimens

CHAPTER 5

Statistical Methods

5.1 General

Statistical methodologies are employed in establishing the mean and near-minimum property estimates of specimens as recommended in ASTM standards. The ASTM D2915 (2022) provides methodologies for analysis procedures and property estimation of wood and wood-based composites. These estimates serve as the basis for assigning structural design values. The mean estimate is used in serviceability design criteria where strength is not the primary consideration. The near-minimum property estimate on the other hand, is mostly employed where strength is the primary design consideration such as in axial compression, tension, bending and shear. In addition, this chapter presents some indicating properties which are excellent in predicting the compressive strength of the specimens.

5.2 Indicating Properties for Compressive Strength Determination

Moisture content, density and grain orientation have proven to significantly influence the compressive strength of EBCs. As moisture content in EBC increases, compressive strength is observed to decline. EBCs with higher density are also observed to demonstrate greater mechanical strength. However, the importance of developing statistical models to accurately predict strength properties cannot be overemphasized. Beyond establishing the relationship between variables in the material being investigated, it is an apt method of predicting the structural performance of similar materials in future research.

In this chapter, parameters like sample size and characteristic value of strength at different confidence levels were determined from the experimental results.

5.2.1 Sample Size

It is common practice to employ a two-stage method in determining the required sample size. The sample size is valuable in assessing the generalizability and reliability of strength predictions

in wood mechanical tests. Equation 5.1 shows the relationship between the mean strength or mean modulus of elasticity of the sampling population and the sample size.

$$n = \left(\frac{ts}{\alpha \bar{X}} \right)^2 = \left(\frac{1}{\alpha} CV \right)^2 \quad [5.1]$$

where n is the sample size, t is the value of t statistic corresponding to the intended confidence interval and S is the standard deviation of specimen values. The estimate of precision, α is taken as 0.05, $\bar{X}$ is the mean of sample population and CV is the coefficient of variation which can be obtained from $s\sqrt{\bar{X}}$.

A Parametric approach assuming normality and a known distribution was employed in this study, and the Kolmogorov-Smirnov test of normality was used to substantiate this choice by verifying the goodness of fit analysis as to whether the sample data conforms to a normal, lognormal or Weibull distribution.

5.2.2 Characteristic Value of Strength

Another important parameter is the characteristic value. As with most structural materials, the characteristic value is important in structural designs and application because it is representative of the mechanical properties used in structural design. The mean property estimate for the modulus of elasticity is usually the average of the sample distribution. The mean value for the best fit distribution is taken to be the 5th percentile lower value usually obtained at 75% confidence level. The near-minimum property estimate is the characteristic value of strength corresponding to the 5th percentile value with 75% confidence level. This characteristic value of strength for Normal, Lognormal and Weibull distributions can be obtained from the following equations (Tang et al. 2021).

$$f_{k,0.05} = \mu - K_N \sigma \quad [5.2]$$

$$f_{k,0.05} = \mu_{ln} - K_{ln} \sigma_{ln} \quad [5.3]$$

$$f_{k,0.05} = \bar{X} - K_W S \quad [5.4]$$

where μ is the mean of the normal distribution, σ is the standard deviation of the normal distribution, and K_N is the confidence level factor of the normal distribution. μ_{ln} is the mean of the lognormal distribution, σ_{ln} is the standard deviation of the lognormal distribution and K_{ln} is the confidence level factor of the lognormal distribution. For the Weibull distribution, the mean is taken as $\bar{X}$, S is the standard deviation of the Weibull distribution and K_W is the confidence level factor of the Weibull distribution.

5.3 K-S Test for Normality

K-S Tests were used to assess the distributional properties of the experimental data. By comparing the empirical cumulative distribution function (ECDF) of the data to the cumulative distribution function (CDF), a null hypothesis stating that the experimental data is of normal distribution is presented. In all the K-S distribution tables for both Ekki and Dragonwood, the observed data supported the null hypothesis.

5.3.1 K-S Tests for Dragonwood Specimens in Compression

Stress values from the K&C and CSIRO approaches were applied in the K-S tests for horizontally oriented Dragonwood specimens. From the results obtained, the data was found to be normally distributed. Table 5.1 summarizes the K-S distribution table for horizontally laminated Dragonwood Specimens based on stress values from the K&C approach.

Table 5.1: K-S Distribution Table (from stress values) for Dragonwood in Compression (Horizontal Lamination)

Specimen	$\sigma_y^{(a)}$	Rank	ECDF
D06-HL	31.3	1	0.1
D05-HL	32.9	2	0.2
D02-HL	35.7	3	0.3
D09-HL	35.7	4	0.4
D10-HL	35.7	5	0.5
D08-HL	36.1	6	0.6
D01-HL	36.7	7	0.7
Specimen	$\sigma_y^{(a)}$	Rank	ECDF
D04-HL	39.6	8	0.8
D03-HL	40	9	0.9
D07-HL	41.6	10	1
Sample Size(n)	10		
Mean		36.53	
Standard Deviation		3.161943847	
Max D1		0.178561438	
Max D2		0.196469243	
<i>D (Test Statistic)</i>		<i>0.196469243</i>	
<i>Critical Value (D*)</i>		<i>0.430069762</i>	
Decision		Fail to Reject Null Hypothesis	
$\sigma_y^{(a)}$ Stress values (K&C)			

Furthermore, the critical value, D^* , for horizontally oriented Dragonwood specimens was determined by K-S tests using strain values. The sample data is also observed to follow a normal distribution as observed in Table 5.2.

Table 5.2: K-S Distribution Table (from strain values) for Dragonwood in Compression (Horizontal Lamination)

Specimen	$\epsilon_y^{(a)}$	Rank	ECDF
D05-HL	5.53	1	0.1
D01-HL	7.7	2	0.2
D04-HL	7.7	3	0.3
D02-HL	8.01	4	0.4
D07-HL	8.76	5	0.5
D03-HL	9.05	6	0.6
D09-HL	9.13	7	0.7
D08-HL	9.36	8	0.8
D06-HL	9.53	9	0.9
D10-HL	9.74	10	1
Sample Size (n)		10	
Mean		8.451	
Standard Deviation		1.265880897	
Max D1		0.154276433	
Max D2		0.196422847	
D (Test Statistic)		0.196422847	
Critical Value (D*)		0.430069762	
Decision		Fail to Reject Null Hypothesis	

$\epsilon_y^{(a)}$ Strain values (K&C)

Similarly, the K-S Tests are repeated for vertically oriented Dragonwood specimens. Stress values obtained from the K&C approach were employed and results prove that the data conforms to a normal distribution (Table 5.3).

Table 5.3: K-S Distribution Table (from stress values) for Dragonwood in Compression (Vertical Lamination)

Specimen	$\sigma_y^{(a)}$	Rank	ECDF
D01-VL	29.7	1	0.1
D02-VL	33.9	2	0.2
D08-VL	33	3	0.3
D09-VL	34.6	4	0.4
D10-VL	34.9	5	0.5
D06-VL	36	6	0.6
D04-VL	37.2	7	0.7
D05-VL	38.1	8	0.8
D03-VL	38.8	9	0.9
D07-VL	39.4	10	1
Sample Size (n)		10	
Mean		35.56	
Standard Deviation		2.973662164	
Max D1		0.105351054	
Max D2		0.188342226	
<i>D (Test Statistic)</i>		0.188342226	
<i>Critical Value (D*)</i>		0.430069762	
Decision		Fail to Reject Null Hypothesis	

$\sigma_y^{(a)}$ Stress values (K&C)

Likewise, Dragonwood specimens in vertical lamination were considered and strain values from the K&C approach were applied in performing the K-S tests. The test statistic obtained was significantly less than the critical value as can be seen in Table 5.4 indicating that the data is normally distributed as there isn't enough data to conclude that the data deviates significantly from a normal distribution.

Table 5.4: K-S Distribution Table (from K&C strain values) for Dragonwood in Compression (Vertical Lamination)

Specimen	$\epsilon_y^{(a)}$	Rank	ECDF
D01-VL	5.8	1	0.1
D03-VL	5.83	2	0.2
D02-VL	6.67	3	0.3
D08-VL	7.03	4	0.4
D05-VL	7.24	5	0.5
D04-VL	7.27	6	0.6
D07-VL	7.38	7	0.7
D10-VL	7.59	8	0.8
D06-VL	8.05	9	0.9
D09-VL	8.7	10	1
Sample Size (n)		10	
Mean		7.156	
Standard Deviation		0.90005185	
Max D1		0.129657973	
Max D2		0.144333181	
<i>D (Test Statistic)</i>		0.144333181	
<i>Critical Value (D*)</i>		0.430069762	
Decision		Fail to Reject Null Hypothesis	

$\epsilon_y(a)$ Strain values from K&C approach

To further investigate the data distribution of vertically oriented Dragonwood specimens, the strain values from the CSIRO approach were applied in performing K-S tests. The results also indicate that the data is normally distributed (Table 5.5).

Table 5.5: K-S Distribution Table (from CSIRO strain values) for vertically oriented Dragonwood in Compression

Specimen	$\epsilon_y^{(c)}$	Rank	ECDF
D01-VL	5.92	1	0.1
D03-VL	6	2	0.2
D02-VL	6.77	3	0.3
D08-VL	7.13	4	0.4
D05-VL	7.16	5	0.5
D04-VL	7.38	6	0.6
D07-VL	7.41	7	0.7
D10-VL	7.76	8	0.8
D06-VL	8.42	9	0.9
D09-VL	9.09	10	1
Sample Size (n)		10	
Mean		7.304	
Standard Deviation		0.978220607	
Max D1		0.156855059	
Max D2		0.12941097	
<i>D (Test Statistic)</i>		0.156855059	
<i>Critical Value (D*)</i>		0.430069762	
Decision		Fail to Reject Null Hypothesis	

$\epsilon_y^{(c)}$ Strain values from CSIRO approach

5.3.2 K-S Tests for Ekki Specimens in Compression

The distributional properties of the test data of Ekki specimens in compression were investigated using K-S tests. Table 5.6 to 5.9 summarize the K-S distribution table from stress values for horizontally and vertically oriented Ekki specimens.

Table 5.6: K-S Distribution Table (from stress values) for Ekki in Compression

Specimen	$\sigma_y^{(a)}$	Rank	ECDF
EK07-HL	19.2	1	0.1
EK05-HL	20.5	2	0.2
EK02-HL	21.3	3	0.3
EK10-HL	21.7	4	0.4
EK06-HL	22.1	5	0.5
EK09-HL	22.3	6	0.6
EK03-HL	22.6	7	0.7
EK01-HL	23.5	8	0.8
EK04-HL	23.7	9	0.9
EK08-HL	25	10	1
Sample Size (n)		10	
Mean		22.19	
Standard Deviation		1.663630568	
Max D1		0.10266736	
Max D2		0.096333731	
D (Test Statistic)		0.10266736	
Critical Value (D*)		0.430069762	
Decision		Fail to Reject Null Hypothesis	

Table 5.7 presents the K-S distribution table of horizontally oriented Ekki specimens. The k-s values were obtained by running the k-s tests on strain values.

Table 5.7: K-S Distribution Table (from strain values) for horizontally oriented Ekki in Compression

Specimen	$\epsilon_y^{(a)}$	Rank	ECDF
EK04-HL	5.47	1	0.1
EK07-HL	5.84	2	0.2
EK09-HL	6.81	3	0.3
EK06-HL	6.85	4	0.4
EK03-HL	6.85	5	0.5
EK01-HL	7.46	6	0.6
EK10-HL	7.65	7	0.7
EK08-HL	7.92	8	0.8
EK05-HL	8.26	9	0.9
EK02-HL	9.52	10	1
Sample Size (n)		10	
Mean		7.263	
Standard Deviation		1.178247757	
Max D1		0.137025948	
Max D2		0.150315351	
D (Test Statistic)		0.150315351	
Critical Value (D*)		0.430069762	
Decision		Fail to Reject Null Hypothesis	

$\epsilon_y^{(a)}$ Strain values (K&C)

From the results of the experimental tests, it is observed that specimen orientation in Ekki has a huge impact on failure time i.e. vertically oriented Ekki beams are expected to fail in less time as compared to horizontally oriented ones. The K-S tests were employed in further probing the data distribution of the vertically oriented Ekki specimens to investigate if the sample population was adequate to support the null hypothesis. They prove to be assertive for checking the distribution in small sample population or in a continuous data situation. Table 5.8 and 5.9 summarizes the critical values, test statistic and z-scores of vertically oriented Ekki specimens.

Table 5.8: K-S Distribution Table (from stress values) for vertically oriented Ekki in Compression

Specimen	$\sigma_y^{(a)}$	Rank	ECDF
E09-VL	17.1	1	0.1
E02-VL	18	2	0.2
E03-VL	18.7	3	0.3
E07-VL	19.2	4	0.4
E10-VL	20.4	5	0.5
E08-VL	21.6	6	0.6
E01-VL	22	7	0.7
E06-VL	22.1	8	0.8
E05-VL	23.2	9	0.9
E04-VL	24.9	10	1
Sample Size (n)		10	
Mean		20.72	
Standard Deviation		2.470627451	
Max D1		0.130798029	
Max D2		0.139148921	
D (Test Statistic)		0.139148921	
Critical Value (D*)		0.430069762	
Decision		Fail to Reject Null Hypothesis	

$\sigma_y^{(a)}$ Stress values (K&C)

Table 5.9 presents the mean, z-scores and critical value for vertically oriented Ekki beams. The low z-score values and in turn, critical value ≥ 0.05 indicate that the data aligns with the null hypothesis.

Table 5.9: K-S Distribution Table (from strain values) for vertically oriented Ekki in Compression

Specimen	$\epsilon_y^{(a)}$	Rank	ECDF	Z-Score	Theoretical CDF
E03-VL	5.77	1	0.1	-1.23607	0.108216375
E02-VL	6.73	2	0.2	-0.73665	0.230668386
E06-VL	6.85	3	0.3	-0.67422	0.250085824
E09-VL	7.18	4	0.4	-0.50254	0.307642671
E07-VL	7.51	5	0.5	-0.33087	0.370372447
E04-VL	7.79	6	0.6	-0.1852	0.426535173
E01-VL	8.8	7	0.7	0.340231	0.633158802
E10-VL	8.87	8	0.8	0.376647	0.64678218
E05-VL	9.33	9	0.9	0.615954	0.731037493
E08-VL	12.63	10	1	2.332717	0.990168496
Sample Size (n)			10		
Mean			8.146		
Standard					
Deviation			1.922222094		
Max D1			0.173464827		
Max D2			0.130668386		
D (Test					
Statistic)			0.173464827		
Critical Value					
(D*)			0.430069762		
Decision			Fail to Reject Null Hypothesis		

$\epsilon_y^{(a)}$ Strain values (K&C)

Table 5.10: Summary of t-statistic and p-values for Dragonwood and Ekki

	Dragonwood HL	Dragonwood VL	Ekki HL	Ekki VL
Mean Stress	36.53	35.56	22.19	20.72
Mean Strain	8.451	7.156	7.263	8.146
D-Test Statistic	0.20	0.19	0.10	0.14
Critical Value	0.43	0.43	0.43	0.43

5.3.3 Significance of the K-S Tests Results

Non-parametric tests like the K-S tests are very useful in understanding the population distribution of a data set. An understanding of the population distribution guides future research work on similar materials and helps in establishing near-minimum property estimates. The K-S tests in this study proved particularly valuable in comparing the statistical similarity of the two tested manufacturing batches of Dragonwood. For all the data investigated for both Dragonwood and Ekki, the experimental data were seen to be normally distributed thereby supporting the null hypothesis originally proposed.

5.4 Significance of the T-Tests Results

Parametric tests like t-tests assume that the data is normally distributed. The k-s tests had been employed to verify the normality of the data prior to the t-tests. With t-tests, p-values less than 0.05 implies the variation in the data is statistically significant. Though a 38% loss in strength was observed in horizontally oriented Dragonwood specimens as compared to vertically oriented specimens, the resulting t-statistic and p-values were all observed to be greater than 0.05 proving that there is not much statistical variation in the mechanical properties of Dragonwood specimens in either orientation. The t-tests were also employed in comparing the p-values of two manufacturing batches of Dragonwood and p-values were greater than 0.05. This is quite expected considering the consistency in mechanical strength values in different bamboo species. Similarly, for the Ekki specimens, despite the known variation in the mechanical properties of

wood, the p-value was higher than 0.05 in all tested sets and it can be concluded that the statistical variation in the experimental data is not significant.

CHAPTER 6

Conclusion and Recommendations

6.1 Summary

This chapter summarizes the research described in the preceding chapters of this study as well as recommendations for future work.

- Fifty 100mm × 100mm × 1000mm Dragonwood and Ekki beams were tested for flexure under three-point bending. The Dragonwood specimens were selected from two manufacturing batches to observe any variations in mechanical properties. Glue-line failure was also carefully observed in Dragonwood specimens.
- Forty 100mm x 100mm x 250mm specimens of both Dragonwood and Ekki were loaded in compression perpendicular-to-grain and tested for failure. In total, Ninety Specimens of Dragonwood and Ekki were tested in flexure and compression.
- For flexure, the moduli of elasticity and rigidity of Ekki and Dragonwood were compared, and flexural resistance graphs were presented. Similarly, in compression, the yield points of tested specimens in compression were evaluated, from which the yield stresses and strains were calculated. Several approaches were compared but yield point determination was narrowed down to two widely accepted approaches: the K&C and CSIRO.
- Statistical methods were applied to experimental results for compressive strength estimation by indicating properties. The Statistical method employed was the K-S test of normality which was selected based on its assertiveness in determining data distribution for structural materials with likely property variations. K-S tests were conducted and distribution tables presented. All Dragonwood and Ekki specimens were observed to conform to a normal distribution.

6.2 Conclusions

- Dragonwood delivers consistent durability in the vertical orientation but performs poorly in the horizontal orientation (an average of 38% loss in strength was observed for horizontally oriented beams).
- Dragonwood demonstrates excellent mechanical strength in one orientation only.
- The strength properties of vertically oriented Dragonwood scrimber beams are comparable to tropical hardwoods.

6.3 Recommendations

Based on the research conducted in the current thesis, the following recommendations for future work are made:

- Investigate the performance of a Dragonwood in a single-lift (i.e., no glue-line).
- Conduct accelerated aging tests on Dragonwood scrimber beams to estimate their mechanical properties at varying conditions.
- Investigate the rate of decline in strength in insect-infested Dragonwood beams.
- Exposure duration of Dragonwood Scrimber beams should be varied to verify the impact of medium and long-term environmental exposure on strength and stiffness.

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Appendix A
Summary of flexural test results for Dragonwood Specimens (Horizontal Lamination)

Specimen	K^a (kN/mm)	P_{Max}^b (kN)	Δ_{Pmax}^c (mm)	MOE^d	MOR^e
DW-HL-01	6.63	59.3	9.7	8,486	71.2
DW-HL-02	6.28	80.1	14.5	8,034	96.1
DW-HL-03	6.22	45.2	8.3	7,957	54.2
DW-HL-04	5.86	38.1	7.1	7,505	45.7
DW-HL-05	6.55	66.5	11.1	8,378	79.8
DW-HL-06	5.80	36.5	6.7	7,428	43.7
DW-HL-07	6.39	63.4	10.6	8,185	76.1
DW-HL-08	6.35	76.2	13.3	8,129	91.4
DW-HL-09	5.96	54.2	9.7	7,626	65.1
DW-HL-10	6.30	63.5	11.1	8,063	76.2
Average	6.23	58.3	10.2	7,979	70.0
Std. Dev.	0.26	14.1	2.38	338	16.9
CoV	0.04	0.24	0.23	0.04	0.24

^a Stiffness ^b Maximum load ^cMaximum Displ. ^d Modulus of elasticity ^e Modulus of rupture

Appendix B

Summary of flexural test results for Dragonwood Specimens (Vertical Lamination)

Specimen	K^a (kN/mm)	P_{Max}^b (kN)	Δ_{Pmax}^c (mm)	MOE^d	MOR^e
DW-VL-01	6.85	88.3	15.4	8,765	106.0
DW-VL-02	6.43	96.7	18.2	8,235	116.1
DW-VL-03	7.37	97.0	15.2	9,434	116.4
DW-VL-04	6.48	92.1	17.0	8,301	110.5
DW-VL-05	6.05	101.2	20.2	7,739	121.4
DW-VL-06	6.22	93.0	18.8	7,956	111.6
DW-VL-07	5.89	87.4	19.5	7,545	104.8
DW-VL-08	6.53	94.6	17.7	8,363	113.6
DW-VL-09	6.70	97.0	16.9	8,573	116.4
DW-VL-10	6.36	99.3	21.1	8,139	119.2
Average	6.49	94.7	18.0	8,305	113.6
Std. Dev.	0.40	4.3	1.9	511	5.12
CoV	0.06	0.05	0.10	0.06	0.05

^a Stiffness ^b Maximum load ^cMaximum Displ. ^d Modulus of elasticity ^e Modulus of rupture

Appendix C

Summary of flexural test results for Horizontally oriented Dragonwood (Batch 2)

Specimen	K (kN/mm)	Pmax (kN)	Δpmax (mm)	MOE (MPa)	MOR (MPa)
DW2-HL-01	6.63	71.05	9.97	8,486	85.23
DW2-HL-02	7.46	49.49	7.11	9,543	59.36
DW2-HL-03	7.51	40.58	5.7	9,618	48.68
DW2-HL-04	7.36	55.04	8.19	9,419	66.03
DW2-HL-05	7.31	35.78	5.11	9,363	42.92
DW2-HL-06	8.03	70.68	9.51	10,273	84.78
DW2-HL-07	6.31	28.87	5.33	8,076	34.63
DW2-HL-08	7.61	80.73	11.41	9,743	96.84
DW2-HL-09	6.54	28.43	4.6	8,372	34.10
DW2-HL-10	7.33	49.77	7.18	9,384	59.70
Average	7.21	51.04	7.41	9,228	61.23
Std. Dev	0.54	18.36	2.31	691	22.01
CoV	0.07	0.36	0.31	0.07	0.36

^a Stiffness

^b Maximum load

^bMaximum Displacement

^d Modulus of elasticity

^e Modulus of rupture

Appendix D

Summary of flexural test results for Ekki (Horizontal Lamination)

Specimen	K^a (kN/mm)	P_{Max}^b (kN)	Δ_{Pmax}^c (mm)	MOE^d	MOR^e
EK-HL-01	7.92	116.2	24.4	10,134	139.4
EK-HL-02	6.87	91.5	18.7	8,792	120.4
EK-HL-03	5.13	69.4	15.3	6,571	82.8
EK-HL-04	7.72	106.3	26.6	9,876	127.6
EK-HL-05	7.61	76.5	11.0	9,737	91.8
EK-HL-06	7.98	104.4	24.3	10,220	121.6
EK-HL-07	8.14	89.6	12.7	10,418	107.6
EK-HL-08	8.06	82.1	11.7	10,317	98.5
EK-HL-09	5.57	70.8	14.0	7,135	85.0
EK-HL-10	7.20	90.7	21.6	9,210	99.4
<i>Average</i>	<i>7.22</i>	<i>89.8</i>	<i>18.0</i>	<i>9,241</i>	<i>107.4</i>
<i>Std. Dev.</i>	<i>1.0</i>	<i>14.8</i>	<i>5.56</i>	<i>1.293</i>	<i>18.2</i>
<i>CoV</i>	<i>0.14</i>	<i>0.17</i>	<i>0.31</i>	<i>0.14</i>	<i>0.17</i>

Appendix E

Summary of flexural test results for Ekki Specimens (Vertical Lamination)

Specimen	K^a (kN/mm)	P_{Max}^b (kN)	Δ_{Pmax}^c (mm)	MOE^d	MOR^e
EK-VL-01	7.73	105.4	23.4	9,900	127.3
EK-VL-02	7.18	94.9	17.2	9,188	113.8
EK-VL-03	7.25	102.4	22.4	9,278	106.4
EK-VL-04	8.08	106.8	26.5	10,348	126.7
EK-VL-05	8.22	119.0	26.8	10,522	138.8
EK-VL-06	6.28	85.7	52.4	8,040	102.8
EK-VL-07	6.50	109.0	20.8	8,314	109.0
EK-VL-08	6.73	86.2	14.2	8,618	103.4
EK-VL-09	6.50	87.4	16.4	8,322	104.9
EK-VL-10	5.78	79.6	16.4	7,400	95.6
<i>Average</i>	<i>7.03</i>	<i>97.6</i>	<i>23.7</i>	<i>8,993</i>	<i>112.9</i>
<i>Std. Dev.</i>	<i>0.77</i>	<i>12.1</i>	<i>10.5</i>	<i>980</i>	<i>13.0</i>
<i>CoV</i>	<i>0.11</i>	<i>0.12</i>	<i>0.44</i>	<i>0.11</i>	<i>0.11</i>

Appendix F

Summary of compression test results for horizontally and vertically oriented Dragonwood

Specimen	Applied Load (kN)			Displacement(mm)			Stress (MPa)			Strain ($\times 10^{-3}$)		
	$P_{\max}$	$P_Y^{(a)}$	$P_Y^{(c)}$	$\Delta P_{\max}$	$\Delta Y^{(a)}$	$\Delta Y^{(c)}$	$\sigma_{\max}$	$\sigma_Y^{(a)}$	$\sigma_Y^{(c)}$	$\epsilon_{P_{\max}}$	$\epsilon_Y^{(a)}$	$\epsilon_Y^{(c)}$
DW01-HL	744	367	367	7.06	1.93	2.06	74.4	36.7	36.7	70.6	19.26	20.56
DW02-HL	715	357	336	7.09	2.00	1.84	71.5	35.7	33.6	70.9	20.03	18.36
DW03-HL	800	400	398	6.64	2.26	2.26	80.0	40.0	39.8	66.4	22.63	22.58
DW04-HL	796	396	384	7.11	1.93	1.90	79.6	39.6	38.4	71.1	19.26	18.99
DW05-HL	659	329	314	4.74	1.38	1.30	65.9	32.9	31.4	47.4	13.83	12.97
DW06-HL	626	313	308	7.51	2.38	2.34	62.6	31.3	30.8	75.1	23.83	23.39
DW07-HL	842	416	392	7.51	2.19	2.18	84.2	41.6	39.2	75.1	21.90	21.80
DW08-HL	722	361	352	7.51	2.34	2.27	72.2	36.1	35.2	75.1	23.40	22.69
DW09-HL	715	357	349	7.51	2.28	2.21	71.5	35.7	34.9	75.1	22.82	22.11
DW10-HL	714	357	350	7.50	2.43	2.38	71.4	35.7	35.0	75.0	24.35	23.75
Average	733	365	355	7.02	2.11	2.07	73.3	36.5	35.5	70.15	21.12	20.72
Std. Dev.	65	31	31	0.85	0.32	0.33	6.5	3.1	3.1	8.06	3.00	3.08
CoV	0.09	0.08	0.09	0.12	0.15	0.16	0.09	0.08	0.09	0.11	0.14	0.15
DW01-VL	595	297	304	6.37	1.45	1.48	59.5	29.7	30.4	63.7	14.50	14.81
DW02-VL	678	339	344	6.52	1.67	1.69	67.8	33.9	34.4	65.2	16.68	16.93
DW03-VL	776	388	398	5.84	1.46	1.50	77.6	38.8	39.8	58.4	14.58	15.00
DW04-VL	744	372	377	7.50	1.82	1.84	74.4	37.2	37.7	75.0	18.17	18.45
DW05-VL	763	381	378	7.50	1.81	1.79	76.3	38.1	37.8	75.0	18.09	17.89
DW06-VL	721	360	378	7.50	2.01	2.11	72.1	36.0	37.8	75.0	20.13	21.05
DW07-VL	788	394	396	7.51	1.84	1.85	78.8	39.4	39.6	75.1	18.44	18.53
DW08-VL	660	330	334	7.50	1.76	1.78	66.0	33.0	33.4	75.0	17.58	17.82
DW09-VL	692	346	364	7.50	2.18	2.27	69.2	34.6	36.4	75.0	21.76	22.72
DW10-VL	699	349	357	7.28	1.90	1.94	69.9	34.9	35.7	72.8	18.98	19.4

	$P_{\max}$	$P_y^{(a)}$	$P_y^{(c)}$	$\Delta P_{\max}$	$\Delta_y^{(a)}$	$\Delta_y^{(c)}$	$\sigma_{\max}$	$\sigma_y^{(a)}$	$\sigma_y^{(c)}$	$\epsilon P_{\max}$	$\epsilon_y^{(a)}$	$\epsilon_y^{(c)}$
Average	712	356	363	7.10	1.79	1.83	71.2	35.6	36.3	71.03	17.89	18.26
Std. Dev.	59	30	29	0.62	0.23	0.24	5.9	3.0	2.9	5.34	2.13	2.32
CoV	0.08	0.08	0.08	0.09	0.13	0.13	0.08	0.08	0.08	0.08	0.12	0.13

Appendix G

Summary of compression test results for horizontally and vertically oriented Ekki specimens

Property	Applied Load (kN)			Displacement (mm)			Stress (MPa)			Strain ($\times 10^{-3}$)		
Specimen	P _{max}	P _y ^(a)	P _y ^(c)	Δ P _{max}	Δ _y ^(a)	Δ _y ^(c)	σ _{max}	σ _y ^(a)	σ _y ^(c)	ϵ P _{max}	ϵ _y ^(a)	ϵ _y ^(c)
EK01-HL	471	235	241	7.51	1.87	1.91	47.1	23.5	24.1	75.1	18.65	19.13
EK02-HL	427	213	220	7.50	2.38	2.45	42.7	21.3	22.0	75.0	23.79	24.52
EK03-HL	455	226	215	7.50	1.91	1.83	45.5	22.6	21.5	75.0	19.10	18.31
EK04-HL	473	237	250	7.18	1.37	1.44	47.3	23.7	25.0	71.8	13.67	14.36
EK05-HL	410	205	196	7.52	2.06	1.94	41.0	20.5	19.6	75.2	20.64	19.37
EK06-HL	443	221	223	7.56	1.71	1.72	44.3	22.1	22.3	75.6	17.11	17.22
EK07-HL	384	192	200	7.40	1.46	1.52	38.4	19.2	20.0	74.0	14.60	15.18
EK08-HL	499	250	267	7.50	1.98	2.10	49.9	25.0	26.7	75.0	19.80	21.05
EK09-HL	447	223	236	7.45	1.70	1.80	44.7	22.3	23.6	74.5	17.03	17.97
EK10-HL	435	217	226	7.51	1.91	1.99	43.5	21.7	22.6	75.1	19.13	19.94
Average	444	222	227	7.46	1.84	1.87	44.4	22.2	22.7	74.6	18.35	18.70
Std. Dev.	33	16	22	0.11	0.29	0.29	3.3	1.6	2.2	1.03	2.78	2.75
CoV	0.07	0.07	0.10	0.01	0.16	0.16	0.07	0.07	0.10	0.01	0.15	0.15
EK01-VL	440	220	230	7.51	2.20	2.30	44.0	22.0	23.0	75.1	22.00	23.00
EK02-VL	362	181	182	7.50	1.68	1.69	36.2	18.0	18.2	75.0	16.81	16.93
EK03-VL	374	187	175	7.50	1.44	1.33	37.4	18.7	17.5	75.0	14.43	13.31
EK04-VL	498	249	274	7.50	1.95	2.10	49.8	24.9	27.4	75.0	19.48	20.95
EK05-VL	464	232	237	7.53	2.33	2.38	46.4	23.2	23.7	75.3	23.32	23.82
EK06-VL	443	221	223	7.56	1.71	1.72	44.3	22.1	22.3	75.6	17.11	17.22
EK07-VL	384	192	213	7.35	1.88	2.03	38.4	19.2	21.3	73.5	18.77	20.31
EK08-VL	432	216	247	7.50	3.16	3.47	43.2	21.6	24.7	75.0	31.58	34.67
EK09-VL	343	171	166	7.50	1.79	1.71	34.3	17.1	16.6	75.0	17.95	17.11

Specimen	P_{max}	P_y^(a)	P_y^(c)	Δ_{Pmax}	Δ_y^(a)	Δ_y^(c)	σ_{max}	σ_y^(a)	σ_y^(c)	ε_{Pmax}	ε_y^(a)	ε_y^(c)
EK10-VL	408	204	216	7.50	2.22	2.34	40.8	20.4	21.6	75.0	22.17	23.35
<i>Average</i>	<i>415</i>	<i>207</i>	<i>216</i>	<i>7.50</i>	<i>2.04</i>	<i>2.11</i>	<i>41.5</i>	<i>20.7</i>	<i>21.6</i>	<i>74.95</i>	<i>20.34</i>	<i>21.07</i>
<i>Std Dev.</i>	<i>49.24</i>	<i>24.61</i>	<i>33.9</i>	<i>0.06</i>	<i>0.48</i>	<i>0.59</i>	<i>4.9</i>	<i>2.5</i>	<i>3.4</i>	<i>0.52</i>	<i>4.56</i>	<i>5.57</i>
<i>CoV</i>	<i>0.12</i>	<i>0.12</i>	<i>0.16</i>	<i>0.01</i>	<i>0.24</i>	<i>0.28</i>	<i>0.12</i>	<i>0.12</i>	<i>0.16</i>	<i>0.01</i>	<i>0.22</i>	<i>0.26</i>
