

Low-tech fabrication and mechanical characterization of engineered bamboo beams from Nepalese species.

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TITLE

Low-tech fabrication and mechanical characterization of engineered bamboo beams from Nepalese species.

ABSTRACT

As a rapidly renewable lignocellulosic biomass, bamboo possesses immense potential to substitute commercial timber; however, its structural optimization is frequently restricted by its inherent hollow geometry, natural variability, and susceptibility to degradation. This study establishes a low-energy, accessible methodology for processing and fabricating engineered bamboo composites using a prominent regional South Asian species: *Bambusa nutans* subsp. *cupulata*. The fabrication protocol involved the manual splitting, planing, and dimensioning of raw culms into uniform rectangular laminae, which were subsequently synthesized into structural-grade laminated sections utilizing a commercially available Polyvinyl Acetate (PVA) adhesive matrix and a simplified press formwork. The macro-mechanical behavior of the resulting composites—specifically the **Modulus of Rupture (MOR)** and **Modulus of Elasticity (MOE)**—was rigorously characterized via static bending tests executed in accordance with ISO 22157 and **IS 1708** standards. The experimental results validate the technical feasibility of synthesizing high-performance engineered bamboo composites using simplified manual processing routes and cold-setting adhesives, yielding reliable elastomechanical properties that compare favorably with conventional structural timbers. This low-tech processing framework offers a scalable, high-value utilization route for small and medium enterprises (SMEs) and localized processing units. Furthermore, the established mechanical baseline provides crucial empirical data that directly supports the implementation of laminated bamboo lumber specifications within the newly enacted *Manual for Design of Bamboo Structures* (**DUDBC 2025**) in Nepal.

Keywords: *Bambusa nutans* subsp. *Cupulata*; Engineered bamboo; Mechanical characterization; Polyvinyl Acetate (PVA); Modulus of Elasticity (MOE); Laminated composite

1. Introduction

Bamboo is utilized globally as a sustainable construction material. In Nepal, its application has historically focused on non-engineered forms, such as mud-mortar fencing, roofing, footbridges, and temporary scaffolding. However, the structural use of raw bamboo is

frequently limited by its natural hollow circular geometry, susceptibility to insect infestation, and inherent durability challenges. Despite these limitations, bamboo offers extraordinary mechanical and environmental advantages. It reaches full maturity within only 3 to 6 years (W.K et al. 2002), whereas most hardwoods require five to six decades. Furthermore, bamboo cultivation is remarkably efficient, requiring no specialized pesticides or fertilizers. It is exceptionally resilient, capable of withstanding temperatures in excess of 40°C to prolonged frost, depending on the species (Leise W. 1987). A bamboo plantation can produce up to 10 tons of biomass per hectare (Janssen J.J.A 2000), with reported above-ground carbon storage as high as 61.05 tons per hectare (Nath A.J et al. 2009).

From a structural perspective, the strength-to-weight ratio of bamboo has been found to be comparable to that of steel and glass-reinforced plastics (Lakkad and Patel 1980). With an oven-dried density ranging between 500 and 800 kg/m³ (Leise W. 1987), bamboo is a remarkably lightweight yet strong material. According to the China National Bamboo Research Center, while the absolute tensile strength of steel is higher, the strength per unit weight of bamboo is three to four times greater than that of steel. Additionally, metabolic processes in bamboo do not produce organic or inorganic by-products like polyphenols, resins, or waxes. This characteristic is highly beneficial as such by-products typically influence physical properties like shrinkage, durability, and gluability (Leise W. 1992).

Bamboo serves as a viable alternative to traditional timber if its undesirable natural properties are mitigated through engineering. Previous studies have demonstrated the feasibility of hot-pressed bamboo mats for manufacturing laminated lumber with a modulus of rupture (MOR) and modulus of elasticity (MOE) comparable to laminated veneer lumber (Nugroho and Ando 2000, 2001). Investigations into parallel strand lumber (PSL) from Calcutta bamboo showed improved resistance to accelerated aging (Ahmad and Kamke 2003). Furthermore, the comparability of laminated bamboo with wood products (Mahadevi et al. 2011) and the effect of adhesive type and volume on the mechanical properties of glue-laminated *Guadua* (GLG) have been reported (Correal et al. 2010). Recently, Shrestha and Crews (2014) characterized engineered bamboo from *Dendrocalamus asper*, highlighting its advantages over natural culm forms.

Building upon these advancements, this paper presents a systematic process for fabricating engineered bamboo into structural elements using a low-tech method tailored for resource-constrained regional contexts, such as those found in Nepal. The study focuses on the

determination of bending properties (strength and MOE) of *Bambusa nutans* in accordance with ISO 22157:2004 and IS 1708:1996. This research aims to provide a technical baseline for transitioning from traditional bamboo use to standardized Laminated Bamboo Lumber (LBL) in developing economies, specifically supporting the development of future engineered bamboo chapters in the DUDBC (2025) Manual for Design of Bamboo Structures.

2. Materials and Methods

This section details the raw materials selected for the study and the systematic low-tech fabrication process used to develop the engineered bamboo beams.

2.1 Material Selection

For this study, 3.5-year-old *Bambusa nutans subsp. cupulata* (locally known as “Mal bans”) was selected. This species was chosen based on its widespread availability in Nepal and its superior mechanical properties compared to other indigenous species. Furthermore, *B. nutans* is the most prevalent species used in the Nepalese construction sector for temporary applications, such as shuttering and scaffolding. To ensure the process remains accessible for local craftsmanship, a commercially available Polyvinyl Acetate (PVA) adhesive—a standard bonding agent in regional carpentry—was utilized.

2.2 Fabrication of Engineered Bamboo Beams

The fabrication process was designed to transform raw bamboo culms into reconstituted rectangular beams using a simplified, low-tech methodology. The procedure followed a systematic four-stage workflow:

2.2.1. Preparation of Bamboo Strips

The selected bamboo culms were first mechanically split into longitudinal strips (Fig. 1a). To ensure geometric uniformity and optimal bonding, both the innermost (pith) and outermost (skin) layers were removed using a table saw (Fig. 1b). The remaining material was planed into regularized rectangular strips of consistent dimensions.

2.2.2. Adhesive Application and Lay-up

The prepared strips were manually oriented within a custom plywood formwork with internal dimensions of 7cm x 7cm x 120cm (Fig. 2). A thin, uniform layer of Polyvinyl Acetate (PVA) adhesive was applied to each layer using a brush, building the assembly increment by increment (Fig. 3). To facilitate de-molding and prevent the adhesive from bonding to the formwork, a clear plastic wrap was employed as a release agent between the mold and the bamboo assembly.

2.2.3. Clamping and Curing

Once the target cross-section was achieved, the assembly was covered with a plywood top strip and secured with G-clamps (Fig. 4). A standardized hand-tight pressure was applied to ensure consistent bond-line thickness. The specimens were subsequently cured in a controlled indoor environment at an ambient temperature ($25\pm5^{\circ}\text{C}$) for a duration of 7 to 14 days. This extended curing period was strategically selected to allow for the complete evaporation of the aqueous carrier in the PVA adhesive and to ensure full polymerization within the porous bamboo microstructure. Furthermore, maintaining ambient conditions facilitated a gradual moisture equilibrium between the adhesive and the bamboo strips, preventing internal stresses or delamination that can occur during accelerated thermal curing.

2.2.4. Final Specimen Processing

Post-curing, the oversized beams were removed from the formwork and planed to their final rectangular dimensions (Fig. 5a). Specific test specimens (2cm x 2cm x 40cm) were then extracted from these beams in accordance with the dimensional requirements of **IS 1708** and **ISO 22157** for subsequent mechanical characterization (Fig. 5b).



Figure 1a: Mechanical splitting of bamboo culms into longitudinal strips.



Figure 1b: Removal of pith and skin layers and strip sizing using a table saw.



Figure 2: Custom plywood formwork designed for specimen fabrication.



Figure 3: Layer-by-layer adhesive application and lay-up within the formwork.

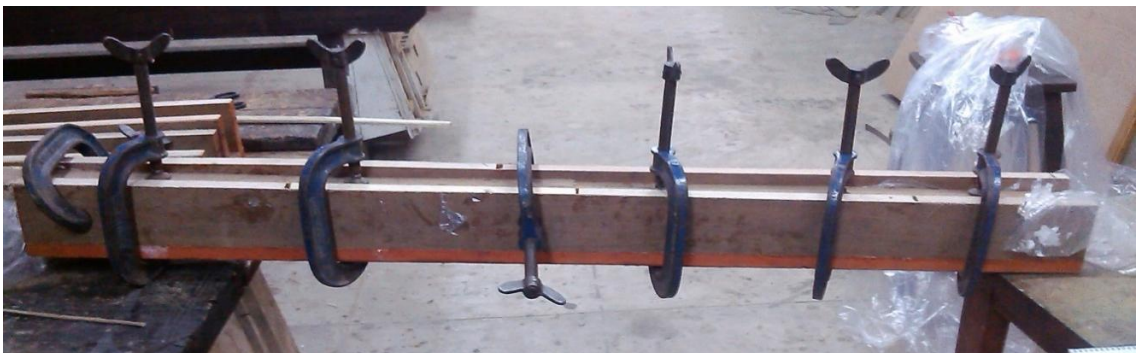


Figure 4: Clamping assembly using G-clamps to maintain bond-line pressure.



Figure 5a: Surface planing of the cured engineered bamboo beams.



Figure 5b: Final processed engineered bamboo beam ready for mechanical testing.

3. Experimental Investigation

The mechanical performance of the engineered *Bambusa nutans* beams was evaluated through static bending tests to determine the **Modulus of Rupture (MOR)** and **Modulus of Elasticity (MOE)**.

3.1. Test Setup and Procedure

Static bending tests were conducted under a **two-point loading configuration** in accordance with **IS 1708-Part 6 (1986)** and **ISO 22157**, as illustrated in Fig. 6. Specimens with nominal dimensions of 2cm x 2cm x 40cm were tested using a Universal Testing Machine (UTM). To account for the orthotropic nature of the engineered bamboo, specimens were tested in two distinct orientations:

1. **Radial Bending:** Load applied perpendicular to the growth rings (laminae).
2. **Tangential Bending:** Load applied parallel to the glue lines.

The load was applied at a constant rate of **6–10 mm/min** at the middle one-third of the span. Deflection measurements were recorded at the mid-span using a dial gauge (precision: 0.01 mm) to generate the load-deflection curve required for MOE calculation.

3.2. Physical Property Determination

Immediately following the mechanical tests, the moisture content (MC) of the specimens was determined in accordance with **IS 1708-Part 1 (1986)**. Small sections were extracted near the

failure zone, weighed, and oven-dried at $103\pm 2^{\circ}\text{C}$ until a constant mass was reached. This step is critical to correlate mechanical strength with the hygroscopic state of the bamboo.

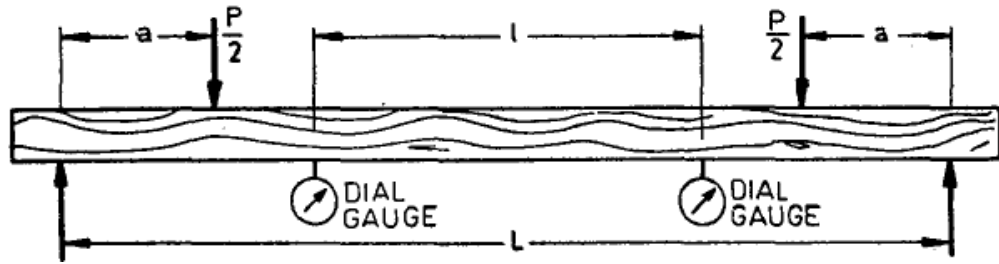


Figure 6: Schematic representation of the two-point static bending test configuration.

4. Results and Discussion

The modulus of rupture (MOR) and modulus of elasticity (MOE) for tested samples were calculated based on equations (1) and (2) and the results are summarized in Table 1.

$$\text{Modulus of Elasticity (MOE)} = \frac{3PaL^2}{4bh^3\Delta} \quad \dots\dots\dots (1)$$

$$\text{Modulus of Rupture (MOR)} = \frac{3P'a}{bh^2} \quad \dots\dots\dots (2)$$

where, P and Δ are load and deflection at limit of proportionality

P' is the ultimate load

a is the distance between points of application of load and support

L is the span

b and h are breadth and depth of the specimen

The following subsections detail the physical and mechanical characteristics of the fabricated *Bambusa nutans* beams, as derived from the aforementioned equations and experimental protocols:

4.1. Physical Properties and Moisture Content

The physical state of the engineered *Bambusa nutans* specimens was recorded to ensure data normalized to standard service conditions. The average **Moisture Content (MC)** was found to be for $10.3\% \pm 0.52$ for radial specimens and $9.5\% \pm 0.53$ for tangential specimens. These values fall within the ideal range (9%-12%) for indoor structural applications in the Nepalese climate, ensuring the mechanical results reflect a stabilized hygroscopic state.

4.2. Static Bending Performance

The mechanical properties derived from the two-point bending tests are summarized in **Table 1**. The individual test values for each of the ten specimens per bending orientation are

detailed in Appendix A, Table A.1. The equations (1) and (2) were applied to the samples in each orientation to determine the **Modulus of Rupture (MOR)** and **Modulus of Elasticity (MOE)**.

Table 1: Summary of bending test results for engineered *Bambusa nutans*.

Orientation	Property	Mean	SD	COV (%)	Mean moisture content (%)
Radial (n = 10)	MOR (MPa)	50.87	16.72	32.86	10.3
	MOE (GPa)	6.91	1.71	24.68	
Tangential (n = 10)	MOR (MPa)	97.73	13.30	13.61	9.5
	MOE (GPa)	15.53	3.22	20.71	

4.3. Analysis of Anisotropic Behavior

A significant **mechanical anisotropy** was observed between the two loading directions. The mean **Tangential MOR (97.73 MPa)** was approximately **92% higher** than the Radial MOR (50.87 MPa). Similarly, the Tangential MOE (15.53 GPa) was more than double the Radial MOE (6.91 GPa).

- **Structural Efficiency:** In the tangential orientation (load parallel to glue lines), the high-density vascular bundles of the bamboo are distributed vertically across the depth of the beam. This orientation better resists longitudinal shear and bending stresses compared to the radial orientation, where the load is applied perpendicular to the laminae.
- **Adhesive Performance:** The **Coefficient of Variation (COV)** for Tangential MOR was notably low at **13.61%**. This suggests that the low-tech fabrication and manual PVA gluing process achieved a highly consistent and reliable **interfacial bond**, comparable to industrially manufactured laminated products. This structural integrity is further evidenced by the failure patterns observed during testing (Fig. 7), where the specimens typically failed through fiber rupture rather than adhesive delamination.

4.4. Comparative Analysis with Traditional Timber

The engineered *Bambusa nutans* beams outperformed many common structural timbers used in Nepal. With a peak MOR of **121.29 MPa** (Sample M6-B-V), this material displays a strength-to-weight ratio that justifies its use as a sustainable alternative for floor joists and roof rafters. The results confirm that even with **minimal machinery**, high-performance structural components can be fabricated from local bamboo species.

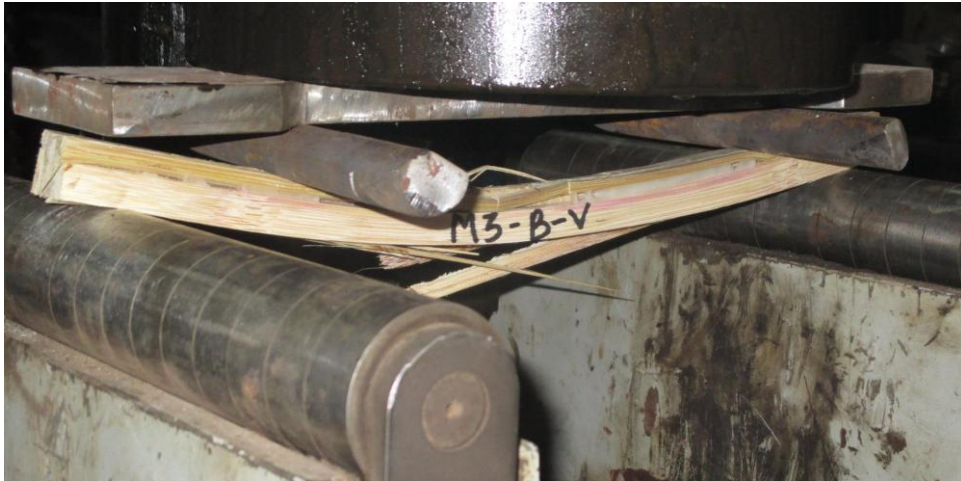


Figure 7: Representative failure modes of engineered *Bambusa nutans* specimens under two-point static bending (tangential)

4.5 Load–Deformation Relationships

The representative load–deflection behavior for both radial and tangential orientations is illustrated in Fig. 8. Both specimens exhibited a predominantly linear-elastic response during the initial loading phase, confirming that the manual lamination process and PVA adhesive achieved effective composite action. However, a distinct contrast in stiffness and peak load was observed between the two orientations. The Tangential specimens (Fig. 8b) displayed significantly steeper gradients compared to the Radial specimens (Fig. 8a), directly correlating with the higher MOE and MOR values reported in Table 1. Furthermore, the curves for the tangential orientation show higher consistency (lower spread), while the radial curves exhibit slightly more variability in the post-elastic zone. The abrupt termination of the curves at peak load suggests a brittle tensile fracture of the bamboo fibers as the primary failure mechanism, with no evidence of early interlaminar slip or bond failure.

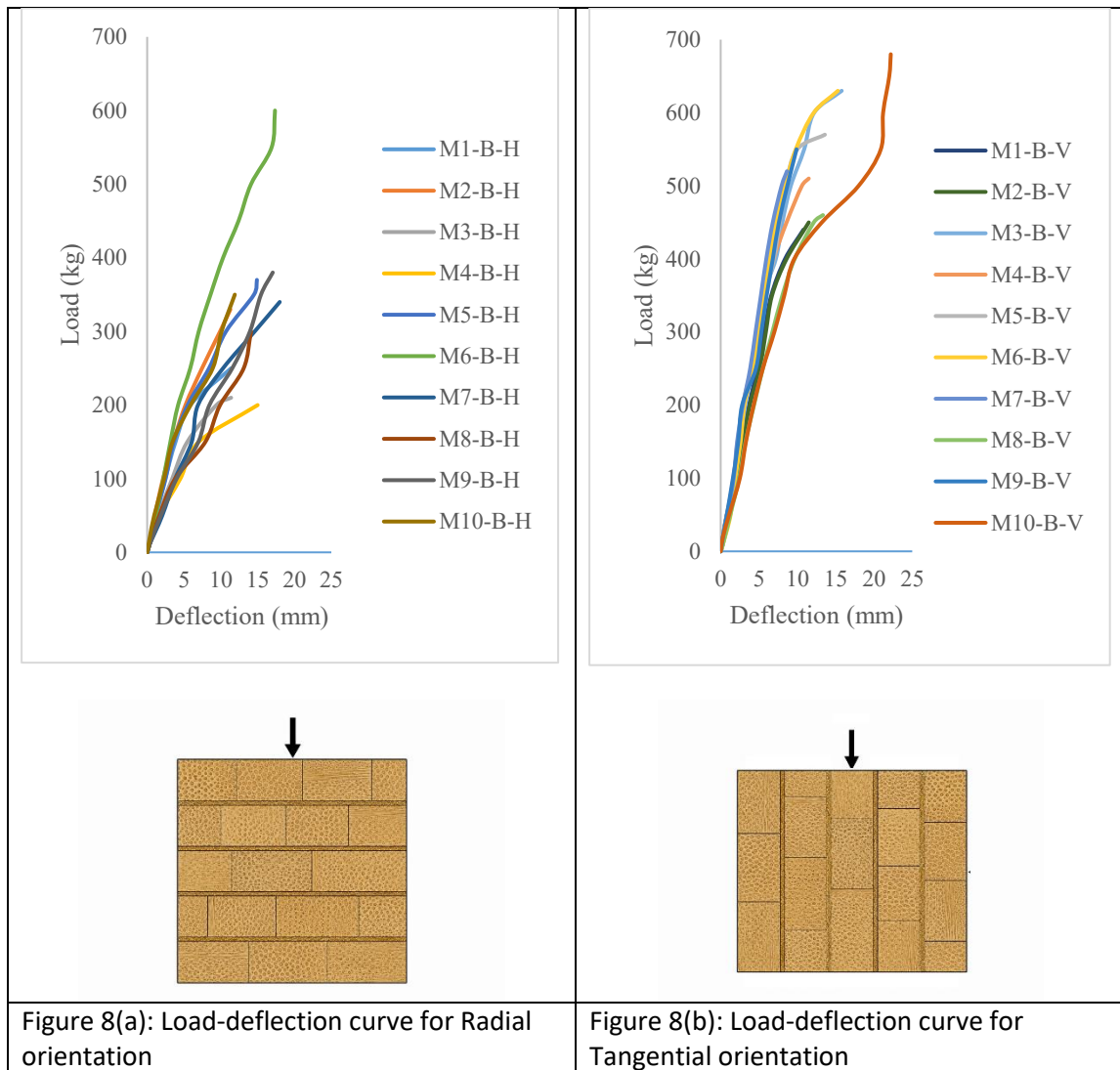


Fig. 8. Load–deflection characteristics of engineered *Bambusa nutans* specimens: (a) radial orientation and (b) tangential orientation.

5. Conclusion

This study investigated the feasibility of manufacturing engineered bamboo beams from Nepalese *Bambusa nutans* subsp. *cupulata* using a simplified, low-tech fabrication process. Based on the experimental results and mechanical characterization, the following conclusions are drawn:

- **Manufacturing Feasibility:** The study demonstrates the feasibility of fabricating engineered bamboo beams using a low-tech manufacturing process, minimal machinery, and commercially available PVA adhesive. The low **Coefficient of Variation (13.61%)** in the tangential orientation demonstrates that manual clamping and basic formwork can produce consistent, structural-grade components.
- **Mechanical Superiority:** The engineered beams exhibited significant **mechanical anisotropy**. The tangential orientation (load parallel to glue lines) provided superior

performance, with a mean **MOR of 97.73 MPa** and **MOE of 15.53 GPa**, nearly doubling the values observed in the radial orientation.

- **Structural Integrity:** Failure analysis confirmed a reliable interfacial bond between the bamboo laminae. The primary failure mode was fiber rupture rather than adhesive delamination, validating the use of PVA glue for secondary structural elements.
- **Sustainable Alternative:** With a peak rupture strength exceeding **120 MPa**, engineered *Bambusa nutans* outperforms many traditional Nepalese timbers. The results demonstrate the potential of the fabricated material for structural applications and establish a preliminary mechanical baseline.

While this research validates the structural feasibility of low-tech engineered bamboo, further studies are recommended to evaluate long-term durability and fire resistance. Given that the Government of Nepal's Department of Urban Development and Building Construction has recently published the "Manual for Design of Bamboo Structures – 2025", the findings of this study provide a critical technical foundation for future iterations of such guidelines.

Specifically, this data supports the inclusion of a dedicated chapter on Laminated Bamboo Lumber (LBL), effectively transitioning national building standards from traditional culm construction to high-performance Engineered Bamboo Structural Elements (EBSE).

Nomenclature

Roman Symbols

α	Distance between the load point and the nearest support (mm)
b	Width of the specimen (mm)
h	Depth (height) of the specimen (mm)
L	Total test span (mm)
P	Load at the limit of proportionality (N)
P'	Ultimate breaking load (N)

Greek Symbols

Δ	Mid-span deflection at the proportional limit (mm)
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Abbreviations

<i>COV</i>	Coefficient of Variation (%)
<i>EBSE</i>	Engineered Bamboo Structural Elements
<i>LBL</i>	Laminated Bamboo Lumber
<i>MC</i>	Moisture Content (%)
<i>MOE</i>	Modulus of Elasticity (GPa)
<i>MOR</i>	Modulus of Rupture (MPa)
<i>PVA</i>	Polyvinyl Acetate
<i>SD</i>	Standard Deviation

Appendix A

Table A.1: Summary of bending test results for *Bambusa nutans* sub sp. *cupulata* (Mal bans)

Radial Bending				Tangential Bending			
Specimen	MOR (Mpa)	MOE (Gpa)	Moisture content (%)	Specimen	MOR (Mpa)	MOE (Gpa)	Moisture content (%)
M1-B-H	37.31	7.01	9.6	M1-B-V	72.72	12.93	9.5
M2-B-H	50.42	8.17	10.4	M2-B-V	86.64	15.44	9.2
M3-B-H	35.23	6.93	10.4	M3-B-V	116.8	17.86	9.6
M4-B-H	28.83	4.3	11.2	M4-B-V	96.5	18.19	9.9
M5-B-H	53.11	7.26	10.2	M5-B-V	98.15	15.51	9.1
M6-B-H	93.4	10.31	10.4	M6-B-V	121.29	18.57	9.8

Radial Bending				Tangential Bending			
Specimen	MOR (Mpa)	MOE (Gpa)	Moisture content (%)	Specimen	MOR (Mpa)	MOE (Gpa)	Moisture content (%)
M7-B-H	54.01	6.75	11.1	M7-B-V	100.16	20.17	8.9
M8-B-H	49.64	4.99	9.6	M8-B-V	89.97	13.44	8.4
M9-B-H	57.98	5.09	9.8	M9-B-V	93.4	14.59	10.1
M10-B-H	48.76	8.32	10	M10-B-V	101.67	8.59	10
Mean	50.87	6.91	10.3		97.73	15.53	9.5
Standard deviation	16.72	1.71			13.3	3.22	
COV	32.86%	24.68%			13.61%	20.71%	

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