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Suitability Assessment of Bamboo (Bambusa Bambos) As A Building Material

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Abstract

Bamboo is one of the oldest renewable building materials available in nature, which has superior properties such as high strength, lightweight, and low cost. In this paper, the results of tests carried out to assess the suitability of Bambusa bambos, a variety of bamboo plant found in the forests of India as a building material is presented. The culm characteristics and properties such as moisture content, density, and structural behaviour of bottom, middle, and top portions of a three-year-old bamboo specimen, Bambusa bambos is assessed. The tests are performed as per ISO 22157-1. The bottom part of bamboo, which is larger in diameter and wall thickness, withstands more loads than the middle and top portions of the bamboo. Various species of bamboo found in other parts of the world and their application in construction have been discussed. The results obtained for Bambusa bambos species have been compared with other species of bamboo. It is found that compressive strength is much better for Bambusa bambos than other species of bamboo. Also, the bond behaviour and interaction with concrete has been studied. In addition, thermal performance has also been investigated.

Keywords: *Bambusa bambos, culm, Dendrocalamus, SEM, thermal performance*

Introduction

In the current scenario, the resources used for construction are predominantly non-renewable. They are rapidly depleting reserves, causing pollution, increasing the emission of greenhouse gases, leading to severe disasters around the world [1, 2]. In this situation, bamboo is gaining importance as a construction material which can be used as a remedy for the aforesaid problems as it is renewable, lightweight, easily available, low-cost, eco-friendly, and has high strength.

Bamboo is a giant grass and it is also known as “Green Gold” due to its emergence as a valuable renewable resource in the global economy. Bamboo is one of the fastest-growing plants that grows mainly in sub-tropical countries. It grows nearly 30cm to 100cm per day and attains maximum size in 2-3 months (60-90 days). Bamboo can be harvested for up to 3-6years[3].

Bamboo has been identified as a potential building material in most developing countries. Nearly 80% of bamboo is produced in China, India, and Myanmar, India being the second-largest producer of bamboo. Nearly 65 species of bamboo are used for construction purposes in Asian countries. Gauda augustifolia is the most popular bamboo species in Latin American countries. Bambusa arundinaceae and Bambusa vulgaris species are used for construction in Africa. Major bamboo species used in construction belongs to Guadua, Dendrocalamus, Bambusa, and Phyllostachys genera [4]. Bambusa nutans, Dendrocalamus strictus, Dendrocalamus hamiltonii, Bambusa balcooa, Bambusa bambos, Bambusa vulgaris, and Phyllostachys bamusoides are the major species found in Asian countries [3]. Bambusa bambos contributes to nearly 15% of all bamboo species in India and are also called “Giant thorny bamboo”.

Research on Bamboo as a construction material was started in 1914 by H.KChow[5]. Small diameter, bamboo was used as a replacement for steel and as reinforcement in concrete. Detailed research on bamboo has been carried out since 1950. In 1995 K.Ghavami[6] determined the properties of bamboo by conducting physical and mechanical tests on bamboo. The outcomes proved that bamboo composites could be used in load-bearing structures. Many researchers across the world have made attempts to use bamboo as an efficient replacement for steel and in other structural components, such

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as walls, flooring, and wall panelling. etc.[5-7]. Some of the properties of bamboo are tabulated in Table.1.

Table.1 Properties of Bamboo

Sl.No	Property	Bamboo	References
1	Moisture Content	8.40%-13.44%	S.K.Paudel et.al[3],Kitti chaowana et.al[4]
2	Density (kg/m^3)	594-933	Kitti chaowana et.al [4]
3	Compressive Strength (MPa)	25–100	Kitti chaowana et.al [4], Vishal puri [5]
4	Tensile Strength(MPa)	65 – 400	Kitti chaowana et.al [4], Vishal puri [5], K.Ghavami[6]
5	Modulus of Elasticity (MPa)	610-15891	S.K.Paudel et.al [3], Kitti chaowana et.al [4], Vishal puri [5],K.Ghavami [6]
6	Modulus of Rupture (MPa)	29.3-129.25	S.K.Paudel et.al [3], Kitti chaowana et.al [4]

Bamboo has been a widely accepted heterogeneous construction material. In terms of energy-saving, the thermal performance has to be known. There arises difficulty in determining the thermal property due to the curved surface of bamboo, the properties such as density, and porosity vary with bamboo species and with different sections of the bamboo[8]. The thermal property on the curved surface of the bamboo is not possible, but by transforming it into boards the thermal conductivity can be determined with minimal error. The thermal conductivity of other building materials is 16-80W/mK, 1.4W/mK,1.05W/mK, and 0.62W/mK for steel, concrete, glass, and brick respectively [9].

Before accepting bamboo as a construction material, study of the culm properties is mandatory. The use of bamboo culm for construction is opted based on their physical and mechanical properties. Three specimens each were taken from the bottom, middle, and top portions of bamboo for assessing the density, moisture content and flexural strength. Three samples with nodes are used to determine the tensile strength of bamboo, while three samples from the bottom bamboo without nodes are used to determine the compressive strength. In addition to physical and mechanical properties, Scanning Electron Microscopy (SEM) has been used to determine the microstructure. The presence of parenchyma cells, vascular bundles, and fibres affect the density. Therefore it is necessary to determine the microstructure. Studies on the thermal performance of bamboo are lacking and this study aims to determine the simulation parameters such as thermal conductivity, thermal effusivity, and thermal diffusivity which can be used for modeling the thermal behaviour.

Silviculture and vernacular names of bamboo

Bambusa bambos grows in tropical, subtropical, and temperate regions of China, India, Myanmar, Bangladesh, and most Asian countries. Bambusa bambos species has its origin in India. In India, this species is grown in all states except in Jammu Kashmir, and Himachal Pradesh. Bambusa bambos grows in a humid tropical climate and grows best along river banks or river valleys with rich, moist soil. It has large bright green thick-walled culms with two forms one form reaching 25m and the other is dwarf, a commonly available form that is 7m tall. Thornless forms also exist. It can be used as hedges around the houses and gardens. The vernacular names of bamboo are Bambu duri in Indonesia, kya-kat-wa in Myanmar, rüssèi khléi, rüssèi préi in Cambodia, phai-pa (general), phai-nam in Thailand, tre là ngà, tre gai rưngin Vietnam, and Indian bamboo in Philipines[10,11]. The

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Bambusa bambos has been known by other names in different parts of India such as Kotoha (Assam); Behor bans (West Bengal); Mula (Malayalam); Kanta bans (Orissa); Nal bans (Punjab); Saneibo (Manipur); **Mungil (Tamil Nadu)**; Mulla veduru (Andhra Pradesh)[12].
Bambusa bambos has numerous applications in construction, such as foundation, roofing, flooring beams, columns, and non-load-bearing walls. It is used as scaffolding and as ladder due to its strong nature and variable length [5].

Material and methods

Material sampling and preparation

Three-year-old Bambusa bambos is considered for this study. The bamboo poles were procured in lengths of 3m. The untreated bamboo was air-dried for 30 days and then transported to the laboratory for testing.
Figure1. shows a typical bamboo culm.

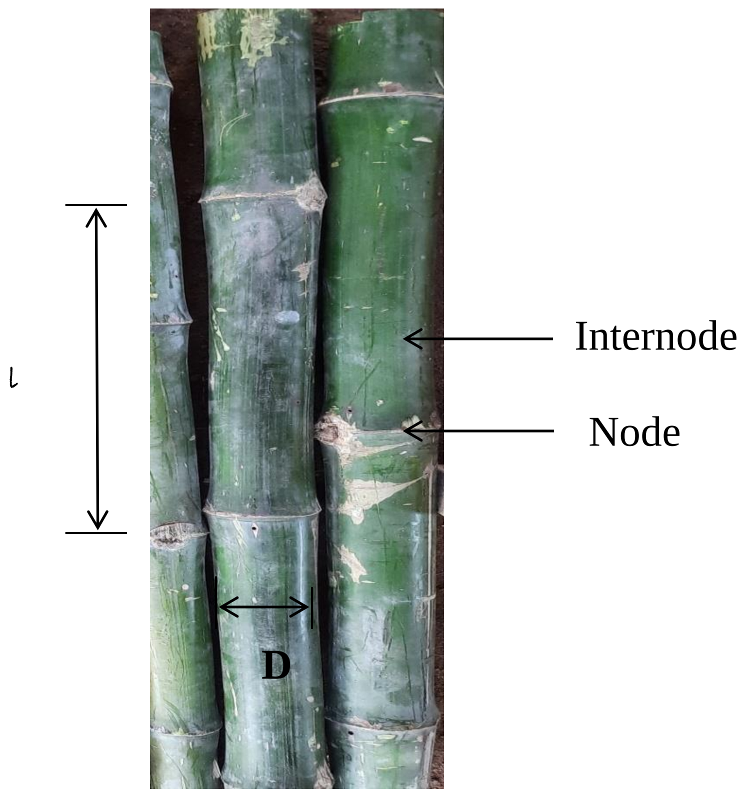

Figure 1. Typical Bamboo Culm

Determination of bamboo culm properties

The moisture content, density, compression, tension, and bending properties of bamboo were determined as per ISO22157-1:2004[13]. Bamboo culms were cut into lengths of 3m and maintained at a temperature of 27ºC ±2ºC and relative humidity of 70±5% before determining the properties.

The parameters were determined as follows

- Moisture content: Moisture content is an important parameter to be determined after every physical or mechanical test. Three numbers of 25mm x 25mm specimens were used for assessing the moisture content. The specimens were dried in the oven at 103±2ºC. The moisture content in the specimen is calculated as

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$$\text{Moisture content (\%)} = \frac{(m_2 - m_1)}{m_1} \times 100 \quad (1)$$

where,

m_1 – the initial mass of the specimen before drying

m_2 – the final mass of the specimen after drying

- The density of the specimen is calculated as

$$\rho = \frac{m}{V} \times 10^6 \quad (2)$$

where,

V - Volume of the sample in mm^3.

- Tensile strength test parallel to grain: The tensile test parallel to grains was conducted on wedge-shaped specimens with a node and internode as shown in Figure 2. The test was conducted on a 400kN capacity Universal Testing machine. The load was applied at a rate of 0.01mm/s. The ultimate tensile strength and failure stress was observed.

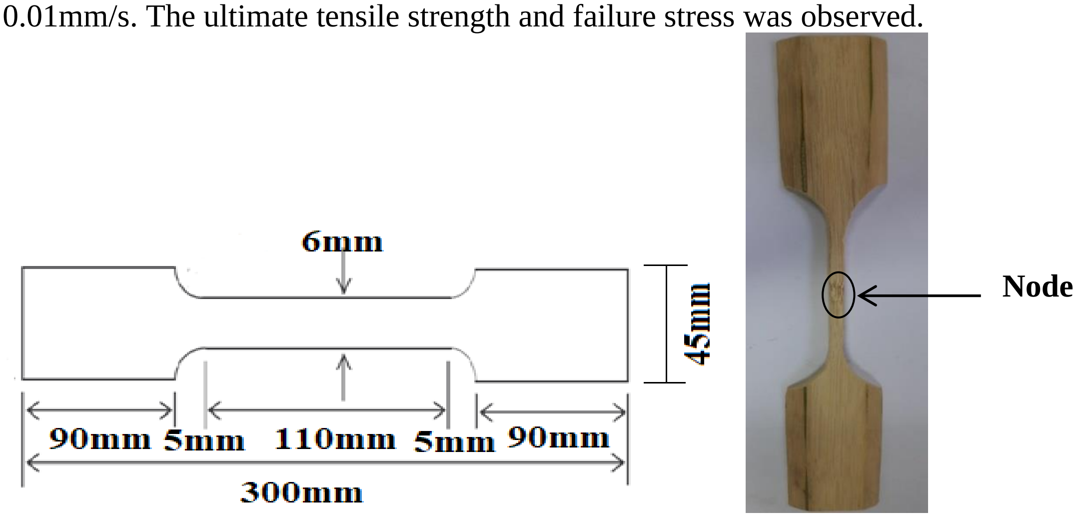

Figure 2. Typical Tension Coupon Specimens

- Compressive strength test: The test is performed by loading the culm parallel to the grains. The length of the specimen taken should be equal to the outer diameter or 10 times the culm thickness. The specimen without a node was selected. The test was carried out in a Computerised Universal Testing Machine (UTM) of 400kN capacity. The load was applied through the bearing plate at a constant rate of 0.01mm/s.

Figure 3. shows the compressive strength test in progress

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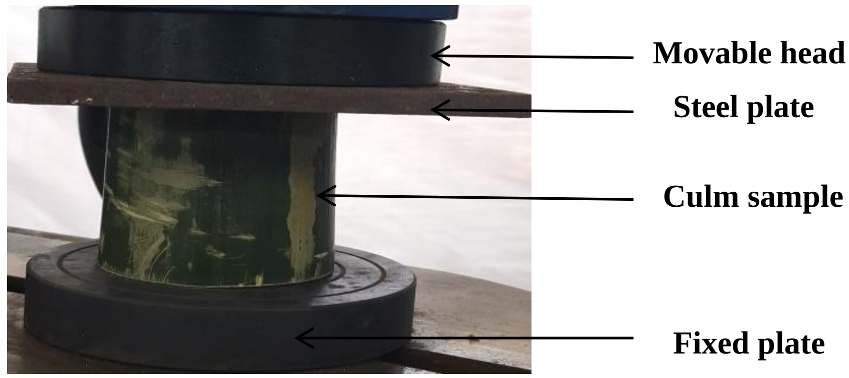

Figure 3. Typical Compressive strength test

- Four-point Bending test: The test was performed on a specimen of 3m length to study the elastic bending behaviour and 1m specimen was used to determine the failure load. The test setup is shown in figure 4.

Figure 4. Four-Point Bending Test setup

Modulus of Rupture and Modulus of elasticity were calculated using equations (3) and (4). The moisture content and specific gravity of the specimen were also determined near the regions of failure.

$$\text{Modulus of Rupture} = \frac{F \times L \times \frac{D}{2}}{6} \text{ X } I_B \quad (3)$$

$$\text{Modulus of Elasticity} = \frac{23 \times F \times L^3}{1296 \times \delta \times I_B} \quad (4)$$

where,

F is the maximum load, L is the free span, D is the outer diameter of the culm, I_B is the second moment of inertia and δ is the mid-span deflection.

- Pull–out test: The test was performed as per IS 2770(Part I)-2017 [14] to determine the interfacial bond between bamboo and concrete. Two types of bamboo viz. i) untreated bamboo and ii) treated bamboo (Epoxy coated) were studied. Epoxy adhesive (Cera bond EP) was used

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to enhance the bond. The load was applied using screw gear at a rate of 0.015”/min. The experimental setup for the pull-out test is shown in figure 5. The bond strength between bamboo and concrete is determined as.

$$\text{Shear bond stress } \tau_b = \frac{\mathbf{P}}{\mathbf{g.S}} \qquad (5)$$

where, P is the Maximum load, S is the perimeter of bamboo and g is the gauge length of bamboo [6].

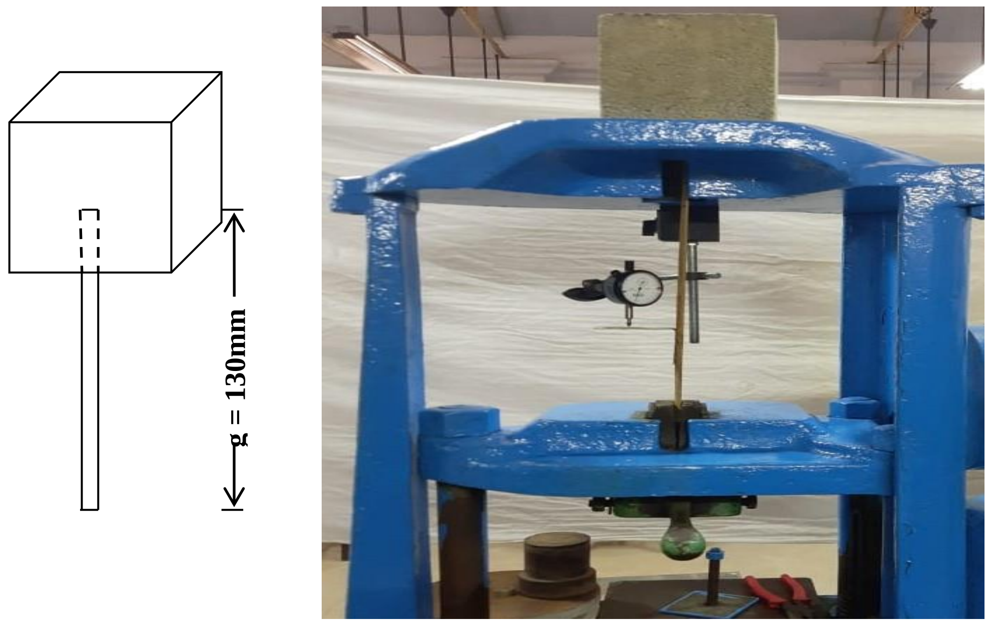

Figure 5. Pull-out Test in progress

- Microstructure Properties of Bamboo
  The microstructure of bamboo culm is composed of Parenchyma and Vascular bundles. The total culm comprises nearly 50% of parenchyma and 40% of fibres and 10% conducting a tissue which varies according to the species. Parenchyma cells are vertically elongated. The vascular bundles in the bamboo consist of the xylem with one or two protoxylem vessels [8]. The chemical composition of the bamboo culms is composed of cellulose, hemicelluloses, and lignin. Silica is deposited in the epidermis whereas the nodes contain little silica[1]. The moisture content and density get affected due to variation in the microstructural properties. Therefore the strength of bamboo gets decreased.
- Thermal Properties of Bamboo: The thermal property of bamboo was determined using a hot disk TPS 2500 S with Kapton insulated sensor as per ISO 22007-2[15]. The thermal analyzer was used to determine the thermal conductivity, thermal diffusivity, and specific heat capacity of bamboo as shown in figure 6.

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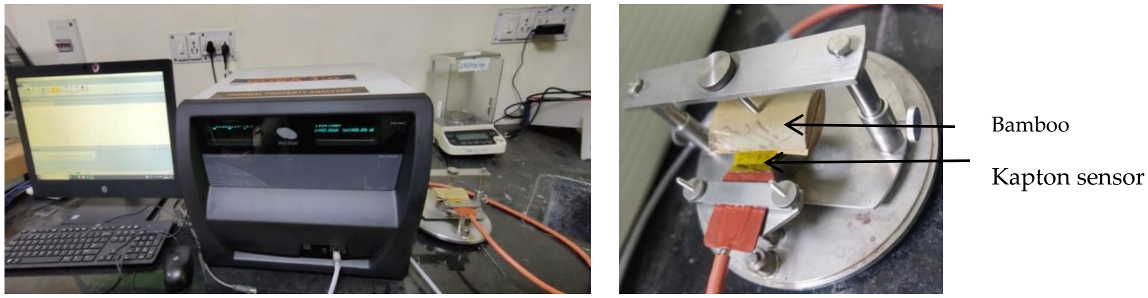

(a) Experimental setup (b) Enlarged view

Figure 6. Experimental setup to determine the thermal properties

Effusivity is defined as the measure of a material's ability to exchange heat with its surroundings

Thermal effusivity $e=\sqrt{(k\rho C_p)}$ (6)

Eqn 7 shows the relationship between thermal conductivity, thermal effusivity, density, and specific heat capacity

Thermal conductivity $k = e^2/\rho C_p$ (7)

where, k - thermal conductivity (W/mK); e - Thermal effusivity ($Ws^{0.5}/m^2K$); ρ - Density in (kg/m^3); C_p -Specific heat capacity (J/kgK)

Thermal diffusivity is defined as the measurement of heat transfer through a medium, usually, the heat transfer from the hot region to the cold region is measured. It is denoted by D or α

Thermal Diffusivity $\alpha = k/\rho C_p$ (8)

where α - thermal Diffusivity(m^2/s);

Results and Discussion

Culm properties

Bambusa bambos grows 30cm per day above the ground and is a straight, hollow, and cylindrical woody material. Initially, the colour of the culm is green later, the bamboo turns yellow after being sundried and stored in the shed. The bamboo consists of a node and internode in which the node is solid, whereas the internode is hollow along the culm. The strongest part of the bamboo is the culm which influences the strength.

The characteristics of the culm affect bamboo utilization. Short internodal length is for load-bearing members such as columns, posts, or beams. As the nodes act as connectors, a higher number of nodes give better strength. Bambusa bambos grows at a faster rate and possesses good strength so it can be used in load-bearing structures and scaffolding. The culm with a shorter internode is available in the bottom portion and internodal distance increases towards the top. Culms with a large internodal distance can be used in making baskets and ornamental products as it has a beautiful, uniform, and

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smooth surface. The lack of uniformity along the culm length is a drawback when two or more culms are tied together.

Physical and mechanical properties of bamboo culms

Moisture content

Moisture content is an important factor that greatly affects the mechanical property of bamboo and other timber materials. The moisture content of Bambusa bambos is 6.66% which is within the rate of 6 to 8% suggested by Chowana et.al (2021) for internal use such as reinforcement, and 9% to 14% for exterior building components.

Bamboo is a hygroscopic material that can gain or lose water from its environment. The moisture content in bamboo is determined after being conditioned at 27ºC and relative humidity of 70%. The moisture content of internodes is higher than the node. This property is due to the difference in chemical composition and microstructural arrangement of bamboo and their culm part. Yasin has found that microbial growth is possible if the moisture content is above 15%.[2]

Density

The density of Bambusa bambos ranges between 591-744.54 kg/m^3 depending on the type and culm portions. Internodes show a higher density than the nodal region. This phenomenon is due to the arrangement of vascular bundles which is less and short in the node region and more and long along the internodes. The density is slightly increased towards the top culm. Fiber content is directly proportional to bending strength and compressive strength. If density increases bending strength and compressive strength also increases. The comparison of density with other species is shown in figure 7.

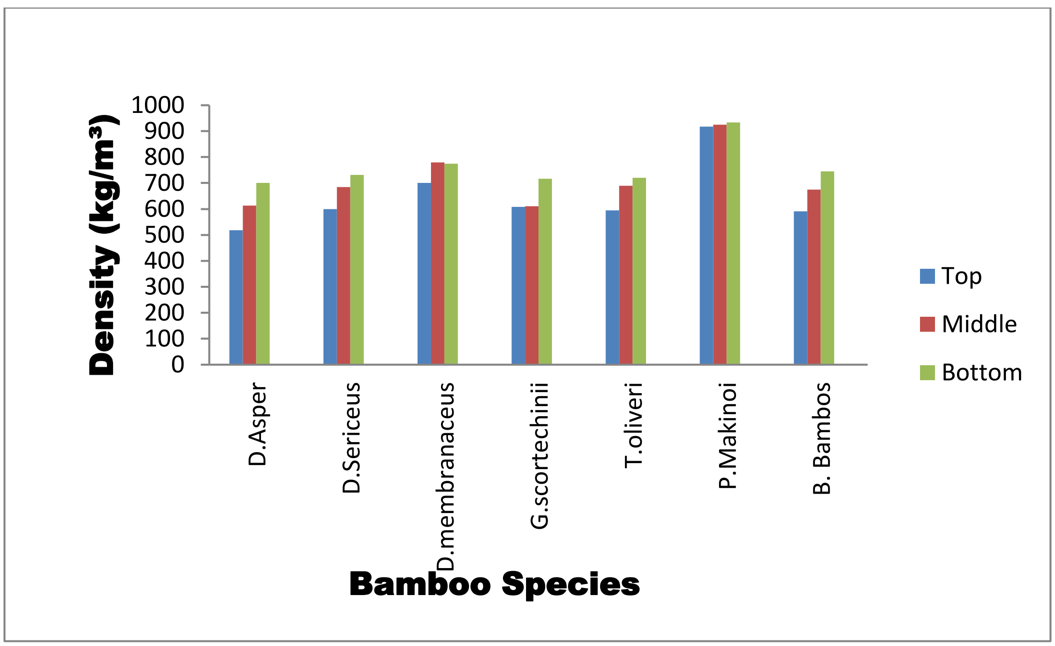

Figure 7. Comparison of density of various species of bamboo [4, 16]

Tensile Strength Test

The tensile strength of bamboo with nodes is greater than bamboo without nodes [4] and the failure occurs at the node. A node in the specimen affects the tensile strength parallel to the grain. Table 2 gives the results of the tensile test. It is seen that

Table.2 Details of Tensile test results

Sample	Ultimate load(kN)	Tensile strength(MPa)	Failure Stress(MPa)	Elongation(%)
Sample 1	27.52	97.30	77.842	3.08
Sample 2	30.34	97.12	90.225	1.20
Sample 3	29.20	63.50	59.23	5.06
Average	**29.02**	**85.97**	**75.76**	**3.11**

The linear relationship between load and deflection before failure is shown in figure 8.

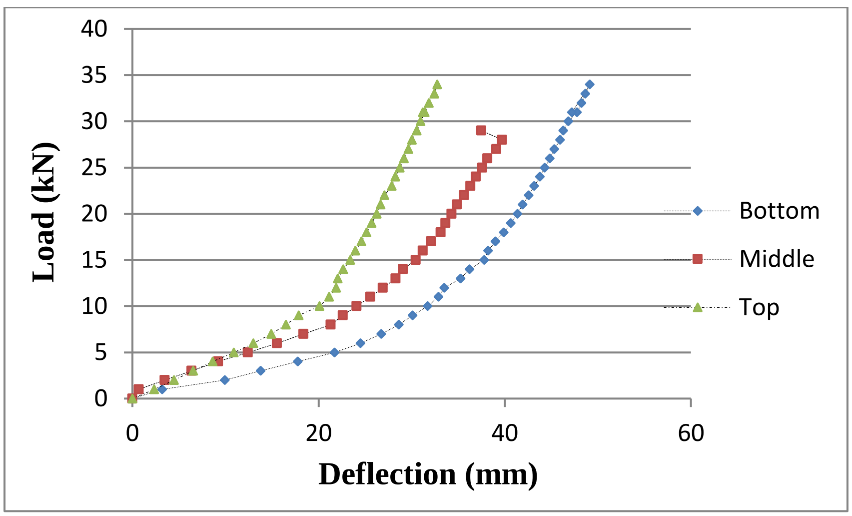

Figure 8. Load Vs Deflection

Figure 9. Typical snapping of specimen observed from tensile test

Figure 9. shows the failure pattern obtained from the tensile strength test. The tensile test is presented in figure 10.

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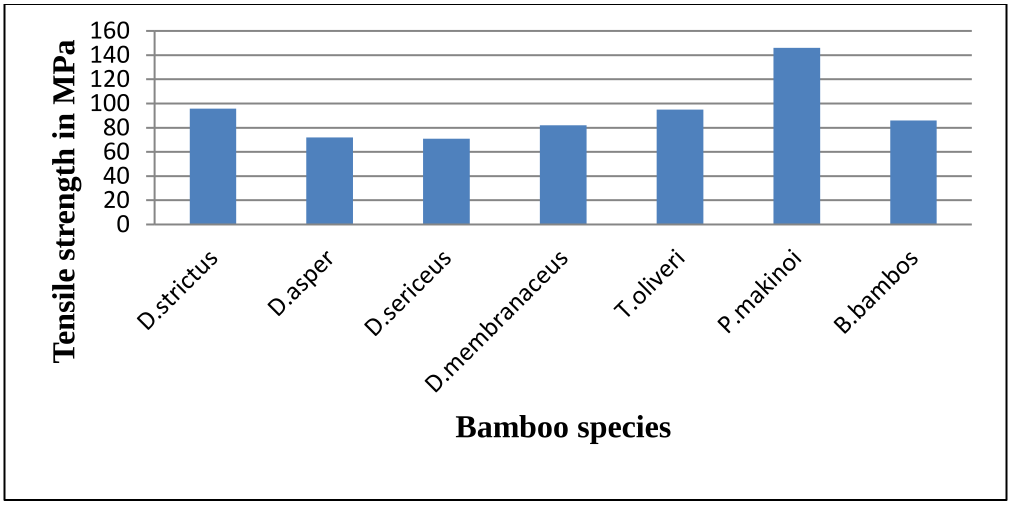

Fig. 10 Tensile strength Vs Bamboo species [4, 17]

Bamboo is a lightweight material and has a higher strength-to-weight ratio compared to steel. The ratio between tensile strength and specific weight is six times greater than steel [4]. Due to this property, bamboo strips can be used as a substitute for steel as reinforcement, beams, floors, or columns. The drawback of using bamboo as reinforcement is the moisture being absorbed by bamboo fibers; then, during the hardening process, the concrete dries and hardens, and the bamboo inside also shrinks, which leads to the development of cracks. To eradicate the problems of shrinking many researchers suggest a layer of coating bamboo strips with bitumen, wax, epoxy, or polyvinyl to improve the bonding between concrete and bamboo.

Compressive strength test

Compressive strength parallel to the grain of Bambusa bambos is compared with the values of other bamboo types taken from a study conducted by Chaowana et. al [4], and Dinesh Bhonde et.al [17]. The results are presented in figure 11.

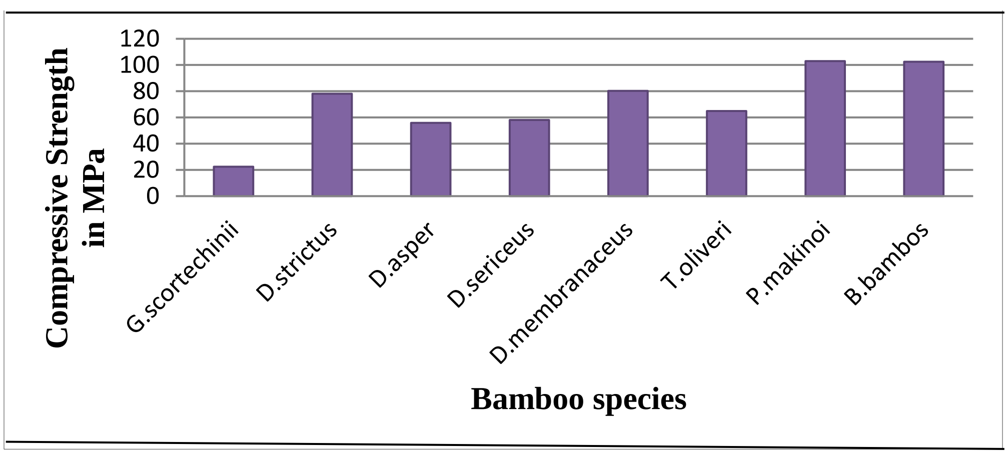

Figure 11. Compressive Strength vs. Bamboo Species [4,6]

As a result of the compression test, the peeling of the outer skin is visualized at both ends of the bamboo. Bambusa bambos behaves better compared to the other five species of bamboo but when compared with P.makinoi, its strength is a little lower i.e. less than 1%. Bambusa bambos compared with D.strictus, D.asper, D.sericeus, D.membranaceus, T.oliveri and P.makinoi, shows an increase in strength by 1.31%, 1.83%, 1.76%, 1.28%, and 1.58% respectively. In other words, the strength can be related in terms of density. When the density of bamboo increases strength also increases. The bottom portion of bamboo possesses greater density than the middle and top portions of bamboo.

Bending strength test

The ultimate load is affected mainly due to culm diameter and wall thickness. The bottom portion of the bamboo culm with larger diameter and increased thickness carries higher load compared to the middle and top portions where the diameter and thickness start decreasing towards the top of the culm as shown in figure 12.

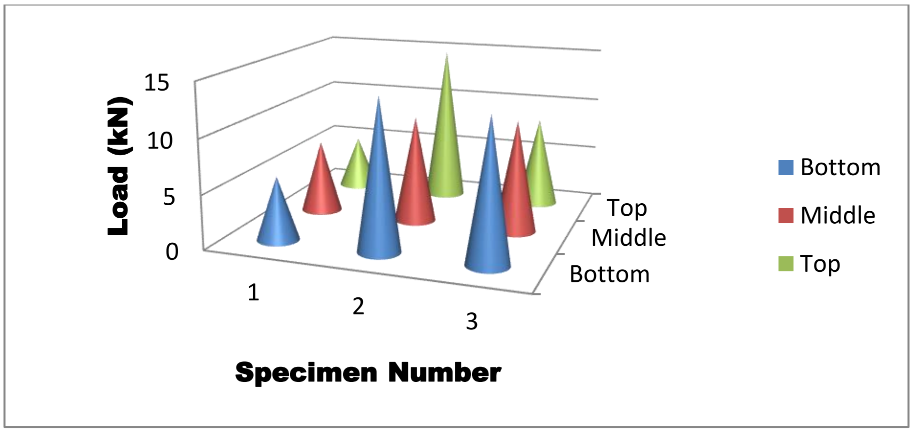

Figure 12. Comparison of Loads between Bottom, Middle, and Top Portions of Bamboo

The modulus of rupture(MOR) and modulus of elasticity(MOE) of Bambusa bambos are compared with other bamboo species[4] and tabulated in Table.3.

Table 3. Results from Four-point Bending Test

Properties	D.asper	D.sericeus	D.membranaceus	T.oliveri	P.makinoi	B.bambos
Modulus of rupture (MPa)	58.4	81.1	29.3	68.6	81.4	84.79
Modulus of elasticity(MPa)	1190	3985	1306	3749	4134	4024

In the case of specimen taken from the bottom culm, the failure occurred at the centre(Figure13b), whereas in the specimen taken from middle and top culms, the failure occur at the edges(Figure 13a). In some specimens, only deformation in the shape of culm takes place.

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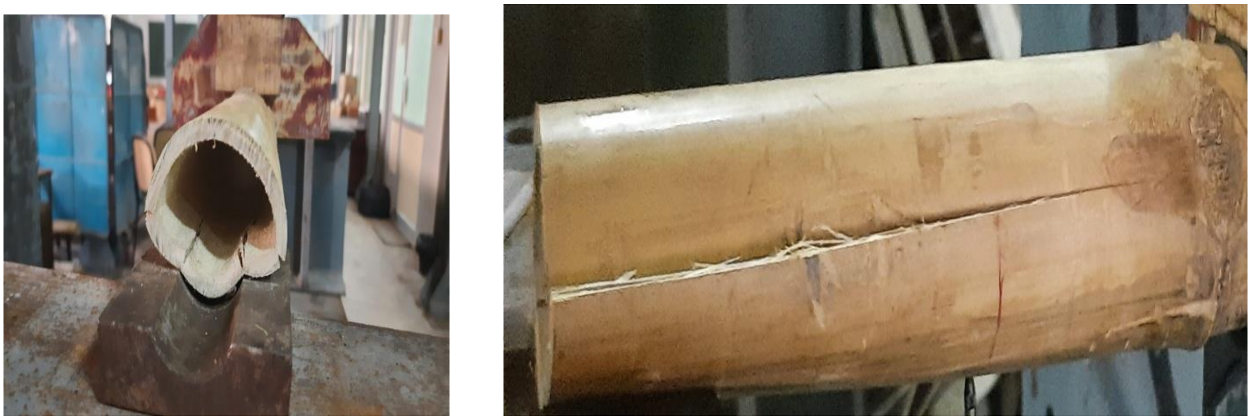

(a) Crushing at the ends of Bamboo Poles

(b)Bending failure at the centre

Figure 13. Failure patterns from Flexure Test

Bamboo can withstand heavy earthquakes or storms with minor damage to the structural elements of the building due to its flexibility. Notably, bending strength directly influences the behaviour of the structures. Before constructing, it is necessary to know the ultimate load and deflection of the material. A roof truss is one of the sensitive components that have to resist wind forces. In this aspect, bamboo culm is best suited for roof trusses because of its lightweight, and higher strength-to-weight ratio. The node is the strongest point in the culm to avoid crushing of internode [11].

Pull-out test

A comparison is made between uncoated bamboo and coated bamboo. The bond strength of uncoated bamboo is less compared with epoxy-coated bamboo. The coated bamboo shows improved shearing bond stress up by 400 %, as given in table 4. In some cases, the cracks are visible in bamboo strips due to slippage [1].

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Table 4. Pull out test results

Bamboo type	Width (mm)	Thickness (mm)	Contact area per unit height (mm)	Pull-out Load (kN)	Bond Stress(MPa)
Uncoated Bamboo	38	4.02	75.32	1.378	0.183
	38.5	3.97	74.68	1.601	0.214
	39	4.21	79.16	1.112	0.140
	Average Bond stress (Uncoated) = 0.179				
Coated Bamboo	38.2	2.95	82.71	5.338	0.645
	38.8	3.43	79.34	4.003	0.504
	40	4.09	81.65	8.229	1.008
	Average Bond stress (Coated) = 0.718				

Bambusa bambos exhibits 5.2% more bond stress compared with the bond stress of Melocanna bambusoides is 0.127MPa for plain bamboo. In the case of coated bamboo, the Bambusa bambos behaves better than coated Melocanna bambusoides [5]. The bond stress of Bambusa bambos with a coating is 0.718MPa which is better when compared with the bond stress of Melocanna bambusoides using different adhesives [5] as shown in Figure 14.

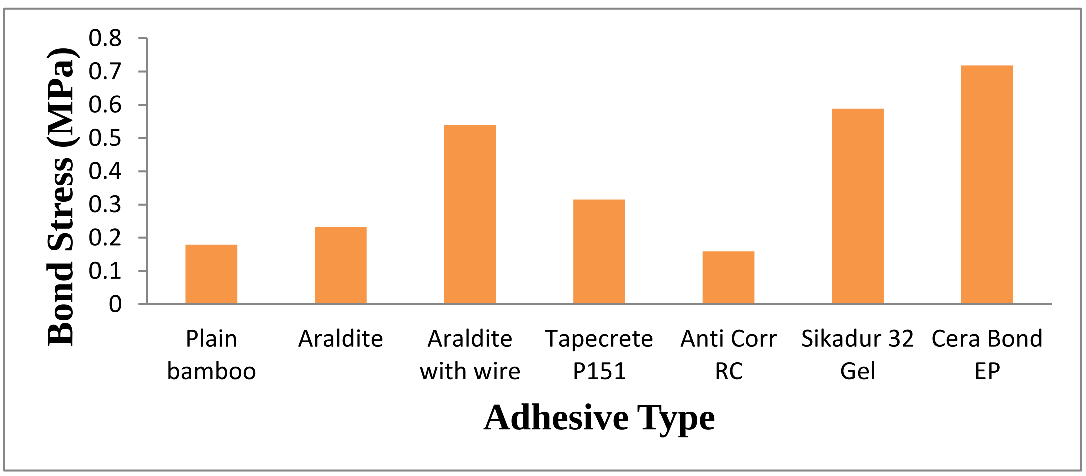

Figure 14. Comparison of bond stress with various adhesives [1]

Figure 15. shows the pull-out distance in coated and uncoated specimens. It is seen that in coated specimen the average pull-out distance is 5mm, whereas in uncoated specimen the average pull-out distance is 30mm.

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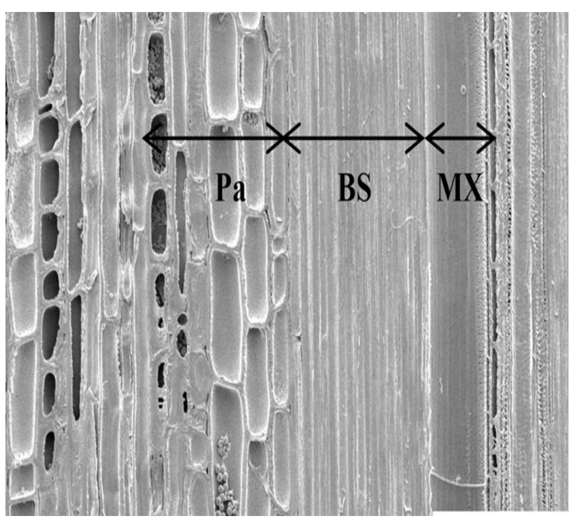
(a) Uncoated (b) Coated

Figure 15. Failure patterns of pull-out test

Micro-structure of bamboo

The Scanning Electron Microscopy (SEM) analysis is conducted to determine the fine structure of bamboo. Though the cell wall of bamboo species has a similar shape. The variation of cell wall arrangement can be noticed in different sections of the culms, such as at node, internodes, and outer, middle, and inner portions. The wall thickness varies from bottom to top. The micro structural layers of bamboo is shown in figure 16b,c. The presence of parenchyma cells, vascular bundles, and fibres affects the density and moisture content of bamboo. Liese [18]classified the bamboo species according to their anatomical structure, in which Bambusa bamboo is classified as type IV and consists of three parts, Central vascular strands with small sclerenchyma sheaths and two isolated fiber bundles, outside and inside the central strand [18,19]. Parenchyma cells occupy nearly 50%, bundle sheath with 40% so there is no variation in density and moisture content of Bambusa bambos.



(a) Culm section of Moso bamboo[19]

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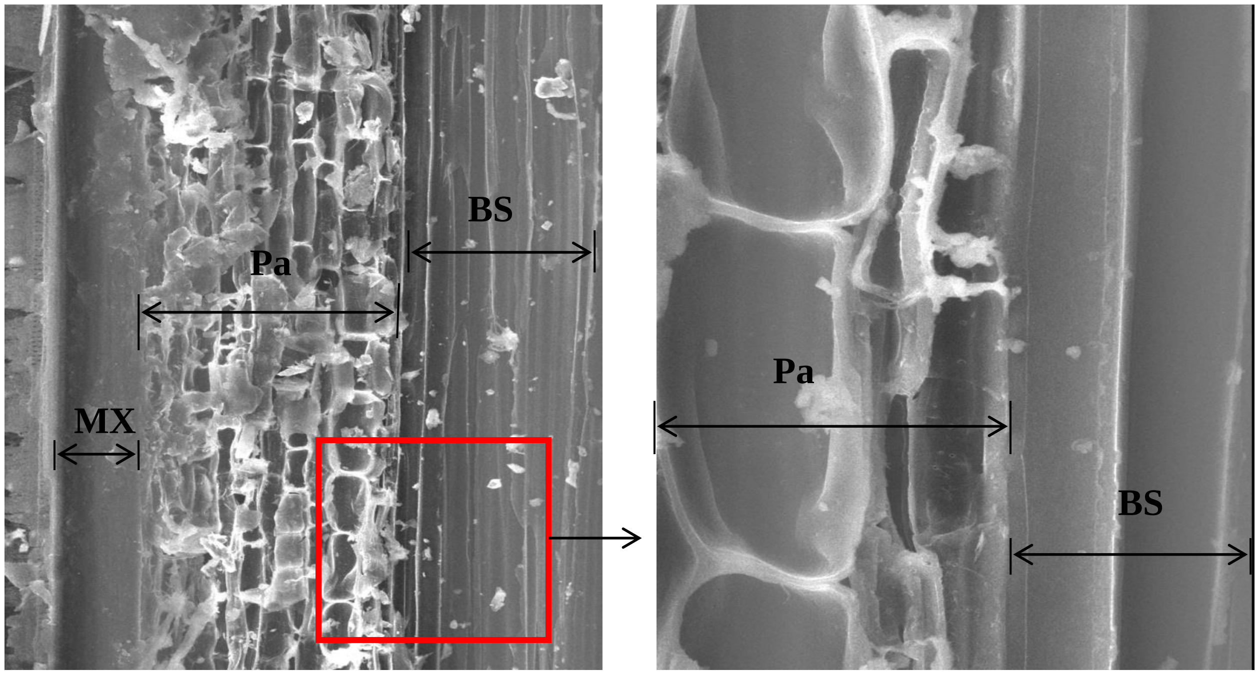

(b) Section of Culm in the radial direction (c) Enlarged image of a section

Figure 16. SEM image of a longitudinal section of culm *Pa*- Parenchyma, *BS*- Bundle Sheath, *MX*-Metaxylem

Thermal conductivity of Bambusa bamos

The thermal conductivity of Bambusa bambos is 0.1917W/mK whereas the thermal conductivity of Moso bamboo is 0.227W/mK. In terms of the heat transfer procedure through bamboo, the thermal parameters such as the density, thermal conductivity, thermal effusivity, and, thermal diffusivity are determined and listed in Table.5

Table 5. Thermal properties of Bamboo

Properties	Bambusa bambos	Phyllostachys edulis[8]
Thermal Conductivity, W/mK	0.1917	0.227
Thermal Effusivity, Ws/m^{2}K	2.595	2.779
Thermal Diffusivity, mm²/s	0.3818	0.618
Specific heat, MJ/m³K	0.5021	0.479

The thermal properties of Bambusa bambos are far better when compared with Phyllostachys edulis.

Conclusions

Understanding the culm properties of bamboo helps in assessing its suitability as a building material. The major aim of the study is to compare the properties of Bambusa bambos available in India and its advantage over other species of bamboo from other Asian countries. The following conclusions are made from this study:

1. The density of the Bamusa bambos varies between 591- 744.5 kg/m^3. Density increases from the bottom towards the top of the culm. Density is directly proportional to strength. With an increase in density strength also increases.
2. Based on the compressive strength test Bambusa bambos is found to perform better compared with all other species, except P.makinoi.

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3. Nodes are the strongest point of culm but in the case of tensile strength, presence of nodes is a disadvantage.
4. Bambusa bambos exhibit better bond strength compared to Melocanna bambusoides. Hence can be used as reinforcement with suitable epoxy coating.
5. Thermal conductivity of bamboo is 0.1917W/mK is less when compared with other building materials.
6. The thermal parameters such as thermal conductivity, thermal diffusivity, and thermal effusivity are determined which can be used in analytical modeling of the bamboo species.

Future Scope:

This work is a preliminary study to determine the physical and mechanical properties of bamboo to check the feasibility of bamboo being used in construction as load-bearing and thermally efficient structure.

Conflicts of interests: The authors declare no conflict of interests

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