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Original Research Article

Evaluation of the Compressive Strength of Bamboo Culms under Node and Internode Conditions

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Abstract

Four samples of Guadua Angustifolia (Colombian Timber Bamboo) bamboo culms were investigated in this study in order to determine the effects of nodes and other physical properties on the compressive strength. The samples were categorized into two groups; samples with nodes (labeled 1M and 1G) and samples between nodes (internode) which were labelled 1J and 1B. The mechanical properties such as moisture content, density, modulus of elasticity and compressive strength of the samples were studied in the laboratory. From the results obtained, it was observed that the density of all the bamboo samples was directly proportional to their respective compressive strengths. Bamboo culm samples from the internode part had a compressive strength that is lower than that of those from the node part (1M and 1G). The culm sample from the node part (1M) had the highest compressive strength of 80.5379 N/mm^2 while the culm sample from the internode part (1B) had the lowest compressive strength of 60.8930 N/mm^2. The culm diameter, wall thickness and length influenced the cross-sectional area over which the stress was determined. Therefore, the mechanical properties of bamboo are dependent on its physical properties to a reasonable extent.

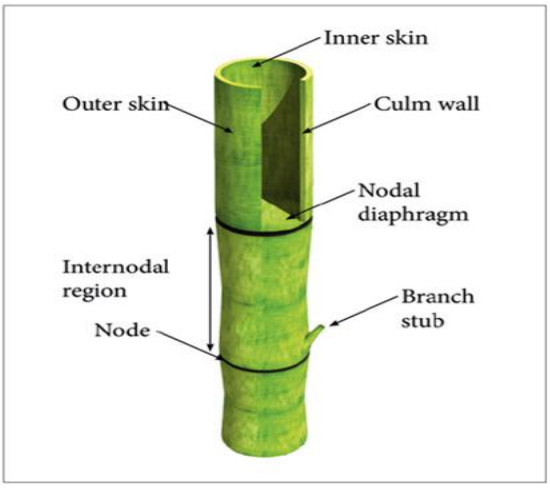
Keywords: Bamboo culms, Compressive strength, Moisture content, Density, Modulus of Elasticity, Axial Compression.

1. INTRODUCTION

Traditional building materials like cement, steel, and bricks are getting more expensive due to increase in demand and cost of raw materials/production. Furthermore, the greenhouse effects of construction materials such as cement have raised serious environmental concerns. Therefore, researchers are interested in alternative materials for construction that are environmentally friendly and sustainable. The use of natural fiber and waste materials as cost-effective and environmentally friendly construction materials has been extensively investigated by researchers. Bamboos are big woody grasses that may grow up to 25m in six months and are sustainable, eco-friendly, low weight, high strength, resilient, and renewable (Lu, 2006; Ray *et al*., 2004; Trujillo, 2007). Furthermore, they are very strong natural fiber material that is widely available and also economical among many other natural fiber materials such as sisal, wood, banana, coconut coir, and rice husk (Chaowana *et al*., 2021). Bamboo is classed as stalk fiber and is part of the *Plantae* kingdom's *Bambusoideae* sub-family. There are approximately 91 bamboo genera and over 1,450 bamboo species worldwide (Lee *et al*., 1994; Lo *et al*., 2008).

Bamboo stems are divided into segments called internodes and nodes as shown in Figure 1. When bamboos are subjected to compressive stresses, these nodes aid to keep the bamboos from buckling (Amada *et al.*, 1997; Huang *et al.*, 2015). The culms of the bamboo are invariably, but not always, hollow. Each culm rises from the ground at its final diameter (i.e., its girth does not extend during its life), tapering as it grows in height, and growing vertically through cell division "telescopically" between the nodes (i.e., the distance between nodes develops as it grows) (Kaminski *et al.*, 2016). Culms normally take three to five years to mature to full vigor once completely grown, during which time they undergo silicification and lignification (Daud *et al.*, 2018).

Bamboo grows swiftly and is quite efficient when compared to other building materials. Bamboo is stronger than hardwood, and its strength-to-weight ratio is higher than that of aluminium composite, regular wood and steel. According to Shao *et al.* (2010), most of the investigations on the mechanical properties of bamboo are conducted in the culm segments without nodes, despite the fact that it is well known that nodes have an effect on mechanical strength of bamboo. In the case of tensile strength parallel to the fibers, the node decreases mechanical strength because, at the node, the fibres produce transverse stresses due to discontinuities in the fibers when they link at the nodes.



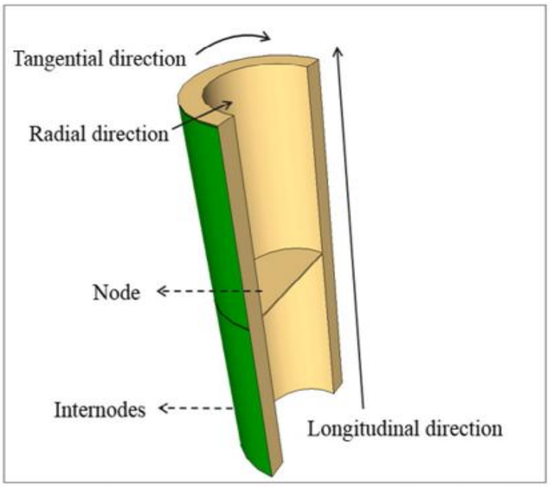


Fig-1: Structure and cross-section of a typical bamboo (Amada *et al*., 1997; Huang *et al*., 2015)

Bamboo is used in the construction industry to construct bridges, frames, scaffolding, flooring, cabinetry, furniture, and fencing (Figure 2). It can also be used as a decorative material in fountains, grates, and gutters (Ahmad *et al*., 2005). There are various advantages of using bamboo as a structural material, including the fact that maximal mechanical strength is achieved in a few years, often between three and six years (Ghavami, 2005), and it is generally available and abundant in tropical and subtropical regions (Wakchaure and Kute, 2012).

The specific resistance of bamboo (the material tensile strength divided by the material density) can be six times that of steel (Ghavami, 1995, 2005, and 2008). Furthermore, bamboo also has an edge over steel in terms of mechanical strength to cost ratio (Mahzuz *et al.*, 2013). Although bamboo has a lower mechanical strength than steel, its tensile strength parallel to the fibers can surpass 350 Mpa (Ghavami, 1995 and 2005; Beraldo, 2003; Mahzuz *et al.*, 2013; Wakchaure and Kute, 2012). However, because bamboo is an organic material that is susceptible to a variety of factors such as moisture content, thickness, soil conditions, density, climate conditions, and developing space, it is possible for its mechanical properties to vary greatly even in standardized and clear culm samples (Low *et al*., 2006; Zhao *et al*., 2017). As a result, it is important to investigate the mechanical properties of bamboo to ensure that it is suitable for various construction applications.


Fig-2: Some of the applications of bamboo in construction (Kaminski *et al*., 2016; Lynch, 2016)

One of the most essential properties required for the design and strength calculations of structural components produced from bamboo and wood composites is the compressive strength along the fiber of bamboo. Most members in two or three-dimensional frames, such as columns, piles, and struts, are subjected to compressive stresses, and their design is based on buckling load due to the slenderness effect. Hence, determining the allowable compressive stress for bamboo under axial compressive forces is necessary.

Gyansah *et al*. (2010) studied the crushing strength of fresh bamboo samples (*Bambusa vulgaris*) in an attempt to explore the mechanical properties of fresh bamboo. The moisture content of bamboo samples was evaluated in order to determine the influence of moisture on crushing strength. The results revealed that increasing the length of the bamboo reduces its strength and vice versa; increasing the moisture content enhances the bamboo's strength; and the effect of thickness depends not only on the crushing stress but also on the level of moisture in the bamboo. Furthermore, Lo *et al.* (2004) discovered that the compressive strength of *Moso* bamboo improves with height along the culm, increasing from 45 MPa to 65 MPa. According to Lee *et al*. (1994), the flexural strength of air-dried bamboo improves from 70 MPa in the green condition to 103 MPa.

According to Yu and Yibiu (2007), the moisture content of bamboo affects its utilization in a similar way to that of wood. In their research, they observed that the compressive strength and shear strength of *Phyllostachys pubescens* bamboo were 56 N/mm^2 and 13.9 N/mm^2, respectively, while for *Guadua angustifolia* bamboo were 56 N/mm^2 and 9 N/mm^2. Sakaray *et al.* (2012) performed tensile and compression tests on *Moso* bamboo. Nodes were present in the tensile and compression specimens. According to the results, the ultimate tensile strength of *Moso* bamboo is around 115-128 MPa, and the modulus of elasticity is around 15 GPa. They attained an average ultimate compression test of 108.19 MPa.

Wakchaure and Kute (2012) studied the effect of moisture content on the physical and mechanical properties of the bamboo species *Dendrocalamus strictus*. The results showed that the moisture level of bamboo varies with the location of the height and seasoning duration, which affects its physical and mechanical qualities. At all phases of seasoning, the top regions exhibited consistently lower moisture content than the middle or basal portions. The study concluded that moisture content is directly proportional to compressive strength and is one of the main elements in determining the life of bamboo.

Lakkad and Pattel (1981) investigated the mechanical characteristics of bamboo. The species of bamboo utilized was not specified, but it was indicated that dry bamboo was used. The dimensions that were employed were 6 mm (T) x 12 mm (W) x 200 mm (L). The specimens had no nodes. The ultimate tensile strength and ultimate compressive strength of bamboo were determined to be 193 MPa and 68.4 MPa, respectively. The experiment also revealed that the specific modulus of elasticity of bamboo is similar to that of unidirectional glass-reinforced plastic (GRP), but lower than that of mild steel.

Compression tests were performed on two bamboo species, *Bambusa pervariabilis* and Phyllostachya pubescens, by Chung and Yu (2002). The average ultimate compressive strength measured for *Bambusa pervariabilis* is 103 MPa, whereas the average compressive modulus of elasticity obtained is 10.3 GPa. The average ultimate compressive strength achieved for *Phyllostachys pubescens* is 134 MPa, whereas the average compressive modulus of elasticity obtained is 9.4 GPa. They found that the mechanical qualities of bamboo were superior to ordinary structural lumber based on their findings.

According to Naik (2000), the tensile and compressive strength of raw bamboo are around 111-219 MPa and 53-100 MPa, respectively. Yap *et al*. (2016) discovered a similar range of compressive strength (124 MPa) on raw *Bambusa vulgaris vittata* bamboo. According to Mahzuz *et al*. (2013), the mechanical qualities of bamboo are superior to many beneficial timber products, but they are much lower than the tensile strength of steel. When compared to other investigations, Amada and Untao (2001) reported a different finding. They claim that the tensile strength of bamboo is nearly same to that of steel.

The aim of this study is to evaluate the response of bamboo under axial compression considering the effects of nodes and other properties. Moisture content, density, dynamic modulus of elasticity, and compressive strength tests will be performed to help reach this goal.

2. MATERIALS AND METHODS

2.1 Raw material sampling and preparation

The specimen used in this study was *Guadua angustifolia* (Colombian Timber Bamboo). Four bamboo culm samples were taken from the node (1M and 1G) and internode (1J and 1B) parts along the culm length as shown in Figure 3. Each culm was sampled, labelled, measured and prepared in accordance with ISO 22157-2: 2004. The physical properties of the bamboo culms are tabulated in Table 1.

2.2 Determination of mechanical properties of bamboo

The mechanical parameters of the four bamboo culm samples were assessed by testing their moisture content, density, dynamic modulus of elasticity, and compressive strength. Table 2 contains a summary of the outcomes of these tests.

Fig-3: Bamboo culm samples

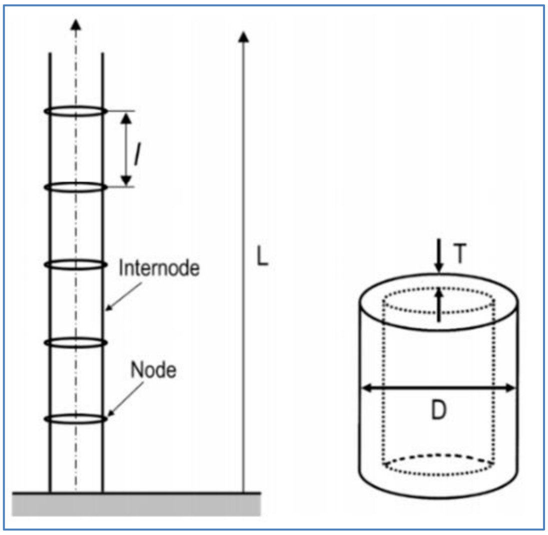


Fig-4: Simulation picture of the bamboo culm physical properties; L = Length of bamboo culm, *l* = Length of internode; D = Outer culm diameter, and T = Culm wall thickness

2.2.1 Moisture content

Bamboo's fibrous nature causes it to gain or lose moisture as the temperature and humidity of its surroundings fluctuate. These changes have been seen to have an impact on their weight, size, and strength. In this investigation, the moisture content of each sample was determined using an electrical moisture meter in accordance with ISO 22157 standards. To avoid any inaccuracy caused by the electrodes piercing an invisible defect, two measurements were taken in each measuring area, 10mm - 15mm apart.

2.2.2 Density

The density, ρ of each culm sample was determined from the mass (m) and volume (v) of the sample at the time of the test. However, the density of the sample was adjusted to the density at 12% moisture content, w according to Equation (2).

$$\rho = \frac{m}{v} \times 10^6 \quad (1)$$

Therefore;

$$\rho_{12} = \rho\left(\frac{1.12}{1 + w}\right) \quad (2)$$

2.2.3 Compressive test

A universal testing machine was used to conduct this test. Each specimen was placed in the machine and was subjected to a pre-load prior to the actual load in accordance with clause 6 of ISO 22157. The load was applied through a metal bearing plate, as illustrated in Figure 5, which was positioned across the upper surface of the culm wall thickness and at right angles to the specimen length. Using Equation (3), the compressive strength, $f_{c,0}$, was derived from the ultimate load.

$$f_{c,0} = \frac{\textit{Ultimate load}}{\textit{Area}} = \frac{F_{ult}}{A} \quad (3)$$

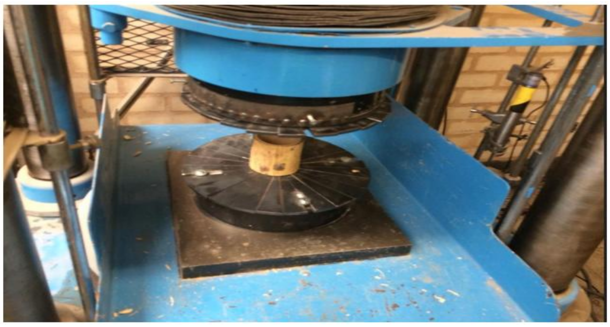


Fig-5: The setup of the compressive strength test

2.2.4 Dynamic modulus of elasticity in compression

The modulus of elasticity in compression, E_c, was calculated using Equation (4).

$$E_c = \frac{F_{60} - F_{20}}{A(\mathcal{E}_{60} - \mathcal{E}_{20})} \quad (4)$$

Where F_{60} and F_{20} are the applied load in Newton (N), at 60% and 20% of the maximum applied load, F_{ult}. While $\mathcal{E}_{20}$ and $\mathcal{E}_{60}$ are the mean of the strain readings obtained at 20% and 60% of F_{ult}.

3. RESULTS AND DISCUSSION

3.1 Physical properties of the specimens

The physical properties like length, mass, wall thickness and diameter of each bamboo sample were determined and reported in Table 1.

Table-1: Summary of the physical characteristics of the bamboo samples

Culm Specimen	Wall Thickness, t (mm)	Diameter, D (mm)	Length, L(mm)	Mass, m (g)
1M(Node)	6.92	79.12	80.77	99.80
1G (Node)	6.39	83.51	74.77	90.10
1J (Internode)	6.94	83.33	89.31	116.10
1B (Internode)	6.44	87.43	78.62	90.37

3.2 Mechanical properties of the specimens

The mechanical parameters of each bamboo sample, such as moisture content, density, dynamic modulus of elasticity, and compressive strength, were determined and given in Table 2.

Table-2: Summary of the mechanical properties of the bamboo samples

Culm Specimen	Moisture Content, *w* (100%)	Peak load (kN)	Max. Displacement (mm)	Density (kg/m^3) (x 10^{-4})	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
1M (Node)	10.23	126.4	31.903	7.9970	80.5379	0.2
1G (Node)	10.23	105.8	26.668	7.9107	68.3583	0.2
1J (Internode)	10.41	119.4	20.530	7.4420	67.2659	0.6
1B(Internode)	10.41	99.79	22.046	7.1284	60.8930	0.2

3.2.1 Moisture content

After conditioning under relative humidity, the moisture content or equilibrium moisture content of the bamboo culms was determined. Table 2 shows the moisture content of the four bamboo specimens, which ranged from 10.23 to 10.41 percent. The samples from the internode section were observed to have higher moisture content than those from the node section. This phenomenon can be explained by the considerable differences in the chemical composition and microstructure of the culm sections (Rautkari, 2013; Zhang, 2019).

3.2.2 Density

The density of the bamboo specimens ranged between 7.1284 and 7.9970 kg/m^3. The density of the node section is slightly higher than that of the internode section, as seen in Figure 6. This is consistent with the findings of Huang *et al.* (2015), who observed that the density of specimens with and without nodes differed. This difference is driven by the particular feature of vascular bundles in nodes, which display less content of a vascular bundle, shorter fibre length, and greater lumen width of parenchyma cells than internodes (Huang *et al*., 2018).

Figure 7 shows that the compressive strength of bamboo increased as the density increased. This relationship between the density and compressive strength of bamboo has been reported by Akinbade (2019), Chaowana (2015) and Malanit (2009). They found that the positive correlation between density and compressive strength is due to the uneven distribution of specific gravity across the bamboo culm's heights and position.

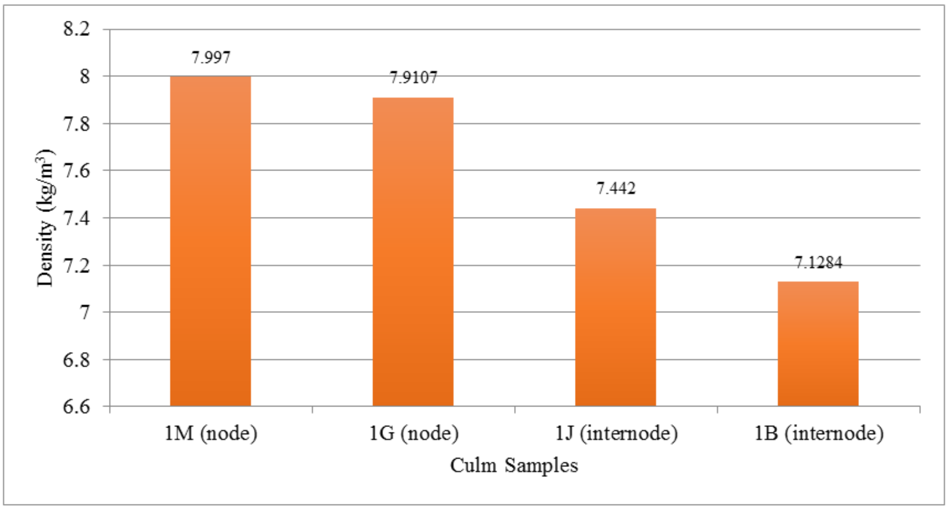


Fig-6: The variation in density of the four bamboo culm samples

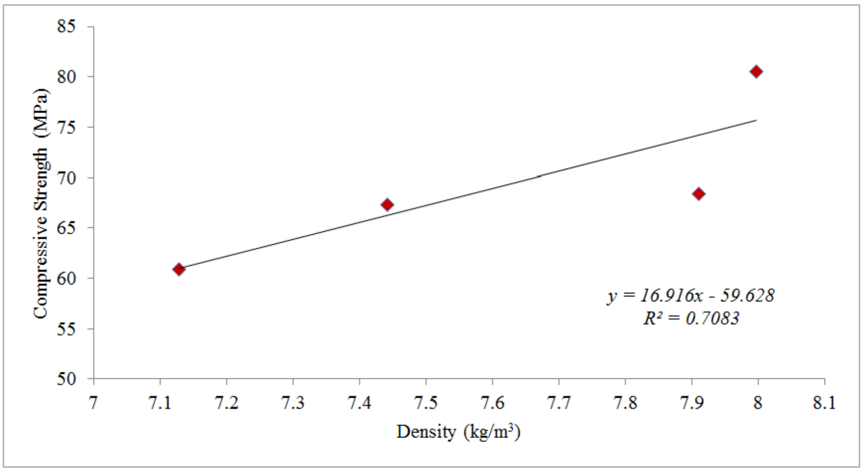


Fig-7: Relationship between the density and compressive strength of the four bamboo culm samples

From the compressive strength test results, it was observed that bamboo samples with node (1M and 1G) have a higher compressive strength than those without node (1J and 1B) as shown in Table 2. This is due to the widely spaced fibers and the stiff behavior at node points. The load-displacement plot of all the tested samples are shown in Figure 8, while a typical sample that failed in compression is shown in Figure 9. From Table 1 also, it was observed that the culm sample with the greatest length (1M) had the maximum compressive strength compared to the other sample with node (1G). This same trend was observed in the node-free samples. Considering the bamboo culm characteristics illustrated in Figure 4, the culm diameter, culm wall thickness, and culm length influenced the cross-sectional area over which the stress was determined. Hence, it can be said that the strength of bamboo is dependent on its physical properties.

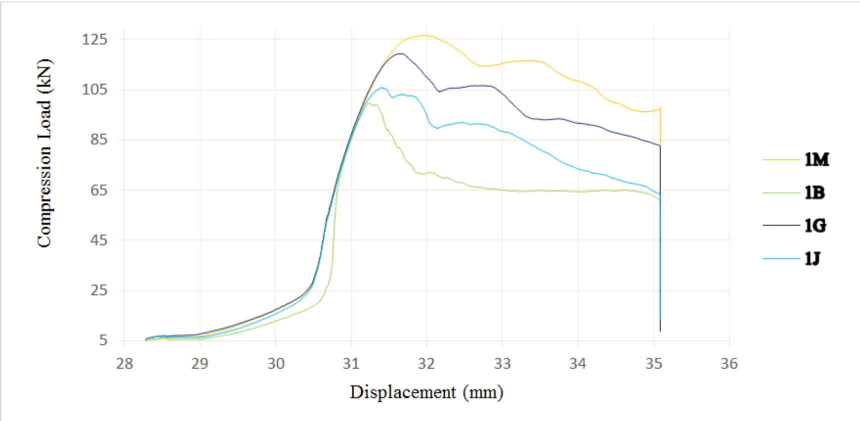


Fig-8: Load-displacement curves of the four culm samples

Fig-9: The splitting failure mode of a bamboo specimen after the compression strength test

The correlation matrix of the different properties evaluated in the study is shown the Table 3. From the correlation matrix, a strong positive relationship was observed between the moisture content, maximum displacement, density, and compressive strength. Furthermore, the thickness and diameter of the samples were also observed to affect the peak load of the sample. The density of the samples had a strong positive relationship with the compressive strength with a correlation coefficient of 0.841.

Table-3: Correlation matrix of the properties of the bamboo samples

	w	P	δ	ρ	σ_c	E_c	T	D	L
w	1								
P	-0.3077548	1							
δ	-0.8218999	0.0717115	1						
ρ	-0.9456242	0.5562256	0.6341208	1					
σ_c	-0.7295589	0.8501385	0.5753924	0.8416203	1				
E_c	0.5773503	0.3579595	-0.8992365	-0.2899003	-0.1623214	1			
T	0.0677761	0.9284098	-0.2433306	0.2132459	0.6074057	0.5981388	1		
D	0.6914178	-0.9001472	-0.4343672	-0.8540306	-0.9807366	-0.0034371	-0.6739232	1	
L	0.5814503	0.5609065	-0.7544777	-0.2929758	0.0420556	0.9149803	0.8141281	-0.1580762	1

w = moisture content; P = peak load; δ = maximum displacement; ρ = density; σ_c = compressive strength; E_c = modulus of elasticity; T = thickness of sample; D = Diameter of sample; L = Length of sample

4. CONCLUSION

The response of four bamboo specimens under axial compression was investigated in this study. From the study, the following conclusions were reached;

1) Bamboo density influences bamboo culm strength. The strength value increases in proportion to the density.
2) The node's constitutive relationship differs from that of inter-nodal sections. Those from the node section along the bamboo culm had better compressive strength than samples from the internodes. Therefore, it can be said that nodes along bamboo culm influence the compressive strength of bamboo positively.
3) The culm diameter, wall thickness and length influenced the cross-sectional area over which the stress was determined. Therefore, it is concluded that the mechanical properties of bamboo are to some part reliant on its physical attributes.

REFERENCES

1. Ahmad, M., Kamke, F. A. (2005). Analysis of calcuta bamboo for structural composite materials: physical and mechanical properties. *Wood Sci. Technol*, 39(6); 448–59.
2. Akinbade, Y., Harries, K.A., Flower, C.V., Nettleship, I., Papadopoulos, C., Platt, S. (2019). Through-culm wall mechanical behaviour of bamboo. *Constr. Build. Mater.* 216:485–495.
3. Amada, S., & Untao, S. (2001). Fracture properties of bamboo. *Composites Part B: Engineering*, 32(5); 451-459.
4. Amada, S., Ichikawa, Y., Munekata, T., Nagase, Y., & Shimizu, H. (1997). Fibre texture and mechanical graded structure of bamboo. *Composites Part B*, 28(1-2):13-20.
5. Chaowana, K., Wisadsatorn, S., & Chaowana, P. (2021). Bamboo as a sustainable building material-culm characteristics and properties. *Sustainability*, *13*(13); 7376
6. Chaowana, P., Barbu, M. C., & Frühwald, A. (2015). Bamboo-a functionally graded composite material. *For. Prod. J.*, 65:48-53
7. Chung, K. F., & Yu. W. K. (2002). Mechanical properties of structural bamboo for bamboo scaffoldings. *Eng Struct*, 24; :429–42.
8. Daud, N., Nor, N., Yosof, M. A., Bakhri, A. A. H., & Shaari, A. A. (2018). The physical and mechanical properties of treated and untreated *GigantochloaScortechinii* bamboo. *AIP Conference Proceedings*, *1930*(020016).
9. Ghavami K. (1995). Ultimate load behavior of bamboo reinforced lightweight concrete beams. *Cement and Concrete Composites*, *17*(4); 281-288.
10. Ghavami, K. (2005). Bamboo as reinforcement in structural concrete elements. *Cement and Concrete Composites*, 27(6); 637-649.
11. Ghavami K. (2008). Bamboo: low cost and energy saving construction materials. *Modern Bamboo Structures*, 1(1):5-21.
12. Gyansah L., Akinwonmi, A. S. and Affam M. (2010). The fracture behaviour of fresh bamboo under uniaxial compressive loading condition. *Res. J. Appl. Sci. Engg. & Technol.*, 2(8):720-726.
13. Huang, P., Chang, W., Ansell, M., Chew, Y., & Shea, A. (2015). Density distribution profile for internodes and nodes of *Phyllostachysedulis (Moso bamboo)* by computer tomography scanning. *Construction and Building Materials*, 93:197-204.
14. Huang, X., Li, F., De, Hoop C. F., Jiang Y., Xie, J., & Qi, J. (2018). Analysis of Bambusa rigida bamboo culms between internodes and nodes: Anatomical characteristics and physical–mechanical properties. *For. Prod. J.*, 68:157–162.
15. International Organization for Standardization. (2004). Bamboo—Determination of Physical and Mechanical Properties—Part II: Laboratory

Manual; ISO 22157-2; ISO: Geneva, Switzerland.

16. Kaminski, S., Lawrence, A., & Trujillo, D. (2016). Structural use of bamboo: Part 1: Introduction to bamboo. *The Structural Engineer*, *94*(8), 40-43.
17. Lakkad, S. C., & Patel, J.M. (1981). Mechanical properties of bamboo, a natural composite. *Fibre Science and Technology, 14*(4); 319-322.
18. Lee, A. W., Bai, X., & Peralta, P. N. (1994). Selected physical and mechanical properties of giant timber bamboo grown in South Carolina. *Forest Products Journal*, *44*(9), 40.
19. Lo, T. Y., Cui, H. Z., & Leung, H. C. (2004). The effect of fiber density on strength capacity of bamboo. *Materials letters*, *58*(21), 2595-2598.
20. Lo, Y. T., Cui H. Z., Tang P. W. C., & Leung H. C. (2008). Strength analysis of bamboo by microscopic investigation of bamboo fibre. *Journal of Construction and Building Material*, *22*(7); 1532-1535.
21. Low, I. M., Che Z.Y., Latella, B. A., & Sim K. S. (2006). Mechanical and fracture properties of bamboo. *Key Engineering Materials*, 312:15-20.
22. Lu, K. T. (2006). Effects of hydrogen peroxide treatment on the surface properties and adhesion of ma bamboo (Dendrocalamus latiflorus). *Journal of Wood Science*, *52*(2), 173-178.
23. Lynch, P. (2016). Watch How Bamboo Scaffolding Was Used to Build Hong Kong's Skyscrapers https. Retrieved from http://www.archdaily.com/793364/watch-how-bamboo-scaffolding-was-used-to-build-hong-kongsskyscrapers. (Accessed 20 August 2021).
24. Mahzuz H.M.A., Ahmed M., Dutta, J., & Rose, R. H. (2013). Determination of several properties of a bamboo of Bangladesh. *Journal of Civil Engineering Research*, *3*(1); 16-21.
25. Malanit, P., Barbu, M. C., & Frühwald, A. (2009). Mechanical properties of sweet Bamboo Dendrocalamusasper. *J. Bamboo Ratt*. 8:151–160.
26. Naik, N. K. (2000). Report on mechanical and physico-chemical properties of bamboo. IIT Bombay.
27. Rautkari, L., Hill, C. A., Curling, S., Jalaludin, Z., & Ormondroyd, G. (2013). What is the role of the accessibility of wood hydroxyl groups in controlling moisture content?. *Journal of Materials Science*, *48*(18), 6352-6356.
28. Ray, A. K., Das, S. K., Mondal, S., & Ramachandrarao, P. (2004). Microstructural characterization of bamboo. *Journal of Materials Science*, *39*(3), 1055-1060.
29. Sakaray, H., Togati, N. V. V. K., & Reddy, I. R. (2012). Investigation on properties of bamboo as reinforcing material in concrete. *International Journal of Engineering Research and Applications (IJERA)*, *2*(1), 077-083.
30. Shao, Z. P., Zhou L., Liu, Y. M., Wu, Z. M., & Arnaud, C. (2010). Differences in structure and strength between internode and node sections of Moso bamboo. *Journal of Tropical Forest Science*, *22*(2);130-138.
31. Trujillo, D. (2007). 'Bamboo structures in Colombia'. *The Structural Engineer*, 85(6):25-30
32. Wakchaure M. R. and Kute S. Y. (2012). Effect of moisture content on physical and mechanical properties of bamboo. *Asian J. Civil Engg. (Building and Housing)*, *13*(6); 753-763
33. Yap, C. T. M., Israr, H. A., Wong, K. J., & Yahya, M. Y. (2016). Compressive properties of Hawaiian Gold Timber Bamboo under different conditions. *Journal of Advanced Research in Applied Mechanics*, *25*, 10-18.
34. Yu, Xiaobing. (2007). Bamboo: Structure and culture. Utilizing bamboo in the industrial context with reference to its structural and cultural dimensions. PhD thesis submitted to the University of Duisburg-Esse, 19-21.
35. Zhang, Y., Yu, Y., & Yu, W. (2019). Effects of internal structure and chemical compositions on the hygroscopic property of bamboo fiber reinforced composites. *Applied Surface Science*, *492*, 936-943.
36. Zhao W., Chen, Z., & Yang, B. (2017). Axial compression performance of steel/bamboo composite column. *Procedia Engineering*, *210*;18-23.