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Principal Indicator for Compressive Load Capacity of Phyllostachys Pubescens Bamboo

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Abstract: In construction, materials of various kinds such as steel, concrete, and timber have consistently been pertinent. Yet the ambition to provide a more sustainable, effective and cost-efficient solution, in a world where the environment is becoming a growing consideration, is at the forefront of many minds. With bamboo being the fastest-growing plant in the world and having many structurally desirable qualities, it may have the potential to become part of Australia's primary construction materials due to its ability to thrive in Australia's tropical and sub-tropical climates. With the growing popularity of bamboo in structural applications, this study aims to identify the primary indicator of compressive load capacity of Phyllostachys pubescens, which may facilitate the use of intact whole culms in the Australian construction industry. To investigate the potential of bamboo culms for construction, an indicator for the ultimate load capacity in compression (B_u) parallel with the grain of 5-year-old construction-ready Phyllostachys pubescens (Moso bamboo) culms was examined. This was achieved by testing the load capacity of culm representatives with consideration to the number and location of nodes, culm diameter, wall thickness, moisture content, and density of the bamboo culm. Bamboo representatives from the top and bottom of the culm were cut to an aspect ratio of 1:2 (diameter to length) and compressed in a Universal Testing Machine at a rate of 0.1 mm/min. Diameters of 60 mm, 80 mm, 100 mm, and 120 mm were tested. From the investigation results, the principal indicator for the compressive load capacity of a bamboo culm is deduced. As an anisotropic material, it is important to note any relevant trends in an attempt to categorise bamboo, for the development of guidelines for bamboo usage in construction. Key findings indicate a positive correlation with diameter and wall thickness to compression load capacity; however, wall thickness was a more accurate indicator with a higher coefficient of determination, while diameter exhibited more anomalies. The top of the culm representatives provided very high accuracy for determining compressive load capacity through wall thickness and were shown to provide lower load capacity relative to their bottom counterparts. This suggests that using the wall thickness at the top of the culm as an indicator for compressive load capacity to be the most accurate, and a safe and conservative approach. Density and moisture content as independent indicators had a negative correlation with load capacity; however, it was observed to be a poor indicator of load capacity providing very low accuracy. The number of nodes affected load capacity in relation to wall thickness, with two nodes showing slightly lower and 0 nodes slightly higher capacity; however, the effect was insignificant, as representatives with one node showed greater deviation. The location of nodes impacted perceived load capacity, with centrally located nodes observed to provide larger load capacities in comparison to representatives with top or bottom located nodes. All failures occurred in a controlled manner, exhibiting primarily ductile failure. Given the B_u for the tested segments is relatively high, Moso bamboo has the potential to be an applicable construction material provided appropriate guidelines are developed.

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1. Introduction

As global efforts to enhance sustainability intensify, construction materials such as concrete, steel, and masonry are being critically examined for their negative environmental impacts. These materials are associated with high energy consumption during production and a lack of renewability, which contribute to the environmental challenges posed by construction demands [1–8]. Timber has traditionally been the primary renewable construction material; however, due to increasing demand, its renewability is compromised by insufficient supply. As a result, there is a need to incorporate alternative materials to address the gap in sustainable and renewable construction [1,3,6–9]. Bamboo is a versatile material that has been used for millennia for diverse applications ranging from simple furniture to temporary structures for disaster relief. Due to the growing need to construct with the environment and economy in mind, materials such as bamboo-based composite-covered particle board [9–12], bamboo strand board [13–16], and bamboo-bundle laminated veneer lumber, similar to timber [17–20], are being tested and developed for their structural capabilities. Bamboo in its natural form; however, is often overlooked in the construction industry [1,3,6,8,11,21].

In comparison to timber, bamboo exhibits a shorter growth cycle and a more rapid recovery after harvesting, thereby reducing its environmental footprint [1,2]. As the fastest-growing plant in the world [22], bamboo can grow at a rate of 30 to 100 mm per day, reaching approximately 36 m in height with a potential diameter of 300 mm within six months [6,8,23,24]. There are over 1000 species of bamboo [1,8,25], with Phyllostachys pubescens (Moso bamboo) being one of the most widely used commercial bamboos because of its rapid growth, high tensile strength and high flexural strength [1,5,13,16]. In its native country of China, Moso bamboo predominantly grows in the subtropical regions of Fujian, Hunan, Zhejiang, and Jiangxi [26]. These regions are highlighted in red in Figure 1a [27], while the tropical and subtropical regions in Australia, illustrated in green and light green in Figure 1b [28], are comparably ample in size. This provides opportunity for viable growing and production of construction bamboo within Australia.

Bamboo as a natural fibrous grassy material, provides advantages in terms of sustainability and structural properties; however, it presents challenges regarding its fire resistance and degradation in various contexts and applications [29–32]. A mixture of sodium hydroxide solution and magnesium layered double hydroxides coating bamboo culms has been observed to both provide “excellent” fire resistance and smoke suppression properties [33], with hyperbranched polymers with polyether backbone and phenylboronic acid as binding groups capable of “good” fire resistance [34]. Bio-deteriorators of bamboo, such as insects or Fungi, classified as brown, white, or soft rot [30,35], can have an adverse effect on the short- and long-term durability and overall strength [35–37]. Typical treatments of these issues traditionally included boron, zinc chloride, arsenic, chromium, and copper, which have adverse environmental impacts through leaching into and polluting waterways [30,38,39]. In some cases, thermal heating of bamboo has proven to be an effective deterrent while preserving structural integrity of the bamboo sample; however, this process still results in the emission of CO_2, albeit at lower levels [30,40–42]. This has led to the development of environmentally friendly treatments in the form of borax, boric acid, and acetic acid, which have proven to combat bio-deteriorators “completely” while also proving to strengthen bamboo specimens when tested [30,35]. Fungi and insects can infiltrate during storage, processing, and transportation, especially in areas prone to high humidity (above 70%), particularly if culms crack or split. Therefore, early correct processing and treatment is necessary [35,40,43–46]. If treated early and correctly, bamboo increase the degradation expectancy of 1 to 5 years, to potentially a 40-year degradation expectancy [5,7,30,39,47,48]. Despite its renewability, cultivation suitability, and ability to be treated for fire and degradation resistance, Moso bamboo is not commercially grown, treated, and used in Australia as a construction material due to the lack of guidelines [49,50].

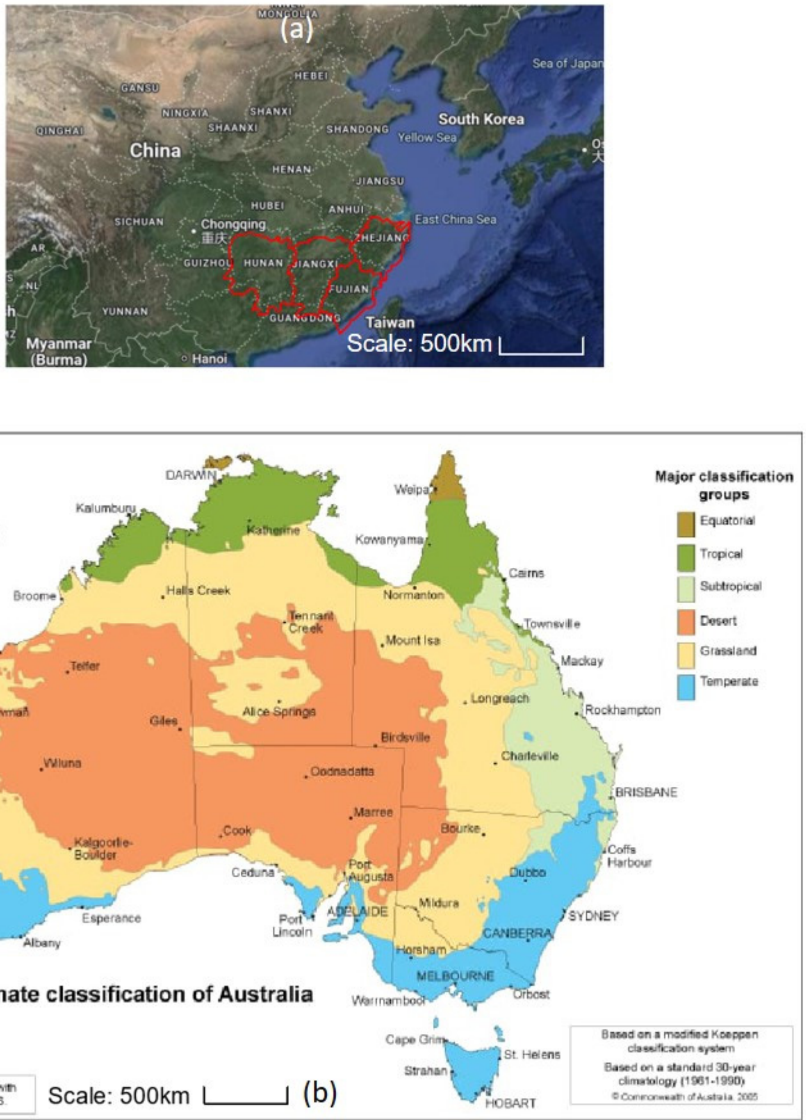


Figure 1. (**a**) Regions Fujian, Hunan, Zhejiang, Jiangxi of China [27] and (**b**) climate map of Australia presented with consistent scale [28].

Bamboo has been predominantly used in composite applications with other materials; however, its intrinsic structural qualities suggest it has significant potential as a construction material in its natural form [51]. Although the International Organisation for Standardisation (ISO) has test methods to determine bamboo performance [52], no established methods currently exist to quickly, reliably, and without destruction, predict the mechanical properties of bamboo based on its physical indicators [1,6]. Similarly to timber, the unaltered natural bamboo form needs to be considered for its construction potential. The physical structure of bamboo is hollow cylinders, formed by fibrous strands, separated by nodes [10,53]. These cylindrical canes are referred to as culms. Previous works which outlined the influences that physical properties of these culms may have on the mechanical properties of bamboo [54–59], investigated the influence of bamboo density on the mechanical properties detailing a connection between density and bending strength, while [60–62] investigated the effect of age, observing that the increase in density from the bottom of the culm to the top of the culm is linked to the samples increased compressive and tensile strength. The authors of [6,63–67] observed the influence of moisture content and noted similar reactionary behaviour to timber, noting that a lower moisture content reflects an increase in material strength. In addition, refs. [68–71] stated that diameter and wall thickness were imperative when considering a categorical grading process for bamboo due to variations in strength, while [72,73] investigated several influences of node versus internodal failures. Although construction bamboo research has recently increased in popularity due to environmental and sustainability concerns, the research is still limited, with few publications on the mechanical properties of bamboo, suggesting testing prior to detailed design is necessary [74]. The majority of studies investigating the properties of bamboo have been undertaken on segmented samples such as reconstituted/reconstructed or laminated sections, dog bone or cube samples focusing on material property [75–78], with few studies on intact culms investigating mechanical properties [79,80]. While the mechanical properties of bamboo have been studied through the test methods outlined in ISO 22157:2019 [52], grading for these properties are lacking in comparison to materials such as steel, concrete, and timber. To fully leverage bamboo's potential, the development of a grading system for its mechanical properties, supported by standardised indicators, could enable assessment without the necessity of conducting destructive testing.

To investigate the feasibility of using intact bamboo culms as a construction material, its mechanical properties must be considered similarly to other organic construction materials, such as timber, taking into account bamboo's anisotropic characteristics, geometric variations and biological features that may affect its mechanical properties. The objectives of this study were to investigate the principal indicator of compressive capacity parallel to the grain of 5-year-old, construction-ready Moso bamboo culms. Culm diameter, wall thickness, density, moisture content, number, and the location of nodes were considered as potential indicators, as each are intrinsic characteristics with perceived influence on bamboo mechanical properties.

2. Testing Materials and Methods

2.1. Material Preparation

The Moso Bamboo specimens were procured from Bamboo Australia, located in Belli Park, Queensland, and was available for retail in diameter increments of 60, 80, 100, and 120 mm. Consequently, the testing was conducted using these specific diameter sizes. Culms were harvested at 5 years of growth, air-dried, fumigated, with non-residual methyl bromide to meet Australian Quarantine and Inspection Service (AQIS) specifications, and imported from the Zhejiang province of China. Six, 2 m length samples, were acquired of each diameter, totalling in 24 samples. Each sample was labelled 1 to 24 respective of increasing diameter. Representative culm sections were taken from the top and bottom of each sample for mechanical properties testing. The 48 representatives were labelled according to their sample number in addition to T (top) and B (bottom), detailed in Table 1. Odd numbered representatives were selected for mechanical property testing in compression parallel to the grain whilst even number representatives were stored for future mechanical property testing. Wall thicknesses were measured via vernier calliper at eight equidistant locations at the top and bottom of each representative. The mean average of these 16 measurements was considered for the wall thickness for each representative (Table 1). Each representative was weighed, and the number of nodes was noted. The distance from the top of a representative to the node was measured similarly with a vernier calliper at four equidistant locations and the average was taken and recorded in Table 1.

Table 1. Moso bamboo physical characteristics.

Average Diameter (mm)	Representative	Number of Nodes	Average Wall Thickness (mm)	Node Distance from Sample Top (mm)	Area (mm^2)	Initial Length (mm)	Initial Mass, m_i (g)	Dry Mass, m_o (g)
60	**1T**	1	5.40	21.6	942.61	121.91	90	80.49
	1B	1	7.10	8.88	1280.39	129.23	118	105.39
	3T	1	5.35	103.8	972.73	126.37	98	86.93
	3B	1	7.30	124.45	1361.29	133.37	120.24	106.70
	5T	0	5.60	N/A	1060.95	131.78	110.9	99.19
	5B	1	7.00	125.0	1315.28	133.69	143.97	128.18
80	**7T**	1	6.59	31.1	1427.07	151.20	170.01	150.86
	7B	1	7.90	25.4	1992.85	176.34	266.53	237.11
	9T	1	6.86	110.64	1405.85	144.19	154.74	138.92
	9B	1	8.32	153.51	2029.81	171.89	246.6	221.35
	11T	0	6.07	N/A	1443.35	163.61	159.39	143.27
	11B	1	7.45	93.9	1810.63	169.66	214.09	191.96
100	**13T**	1	7.29	7.6	1862.83	177.30	264.24	236.99
	13B	1	8.10	99.38	2275.60	195.12	387.76	349.62
	15T	1	7.90	10.77	1872.78	166.79	226.23	202.09
	15B	1	9.22	93.8	2503.48	191.30	347.14	310.68
	17T	0	8.99	N/A	2393.61	187.48	300.23	268.25
	17B	1	10.77	91.39	3038.04	201.17	418.53	375.59
120	**19T**	1	7.33	134.51	2116.98	174.00	260.29	235.06
	19B	1	10.14	143.77	3252.51	224.41	439.71	396.84
	21T	0	9.77	N/A	2916.59	209.77	380.70	342.79
	21B	2	14.29	91.41, 201.02	4543.71	230.77	650.38	584.56
	23T	1	7.70	101.02	2196.50	197.03	290.39	262.40
	23B	1	9.21	87.0	2915.39	219.95	418.79	377.58

2.2. Methods and Measurements

Mechanical property tests were conducted in accordance with ISO 22157:2019 [52]. Experiments conducted focus on the bamboo diameter, number of nodes, culm wall thickness, distance to the node from the top of the culm, comparisons between top and bottom of bamboo poles, moisture content and density. These characteristics were considered to ascertain the most effective indicator for compressive load capacity parallel to the grain, as they are intrinsic to the composition of a bamboo culm.

2.3. Compression Test Parallel-to-Grain

Representatives were measured for average diameter and volume as per ISO 22157:2019 [52] and cut to the required length with an aspect ratio 1:2, shown in Figure 2. Nodal placement deviated from the standard central positioning in order to compare the variance in results with altered node locations.

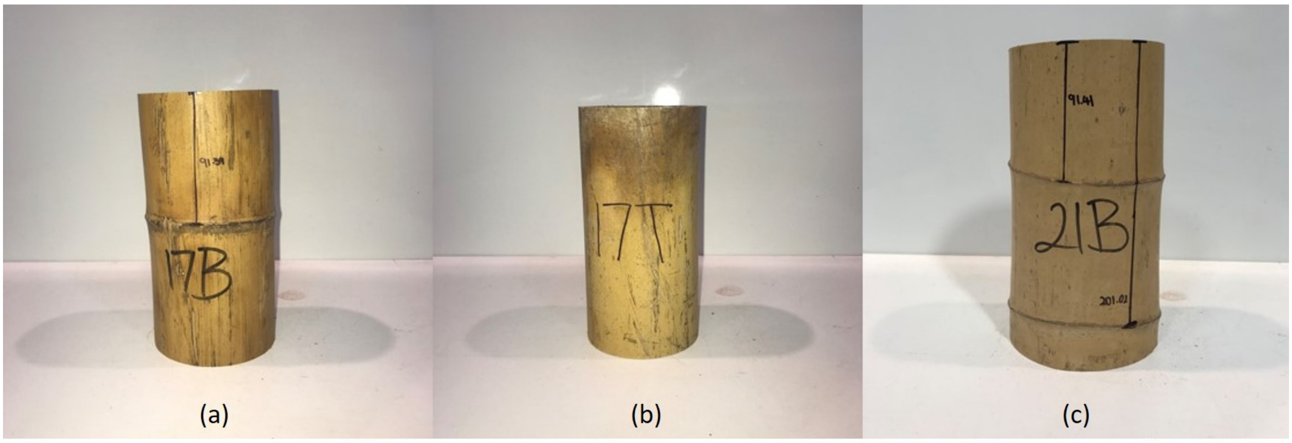


Figure 2. Examples of representatives prior to compression testing with a distance of a node from the top (**a**) 17B—one node (**b**) 17T—no node (**c**) 21B—two nodes.

Compression tests were conducted parallel-to-grain in the ultimate testing machine (UTM) at a rate of 0.1 mm/min, as bamboo is anisotropic and failure modes are relatively uncertain, particularly with varying node placements and lengths and therefore deemed safer [11]. The platens were locked to simulate construction applications, as most structural members would not involve load distribution, which is concentrically applied throughout the entirety of its service span. The forces applied to each representative were logged by the UTM at intervals of 0.5 s, with displacement being the controlled variable. Tests were loaded to the bamboo representative ultimate load capacity B_u and then continued until 50% of the ultimate capacity was reached. All representatives failed in a controlled style, generally in the manner shown in Figure 3. Values for ultimate compressive load capacity were taken to be the maximum load that each representative could withstand and are detailed in Table 2.

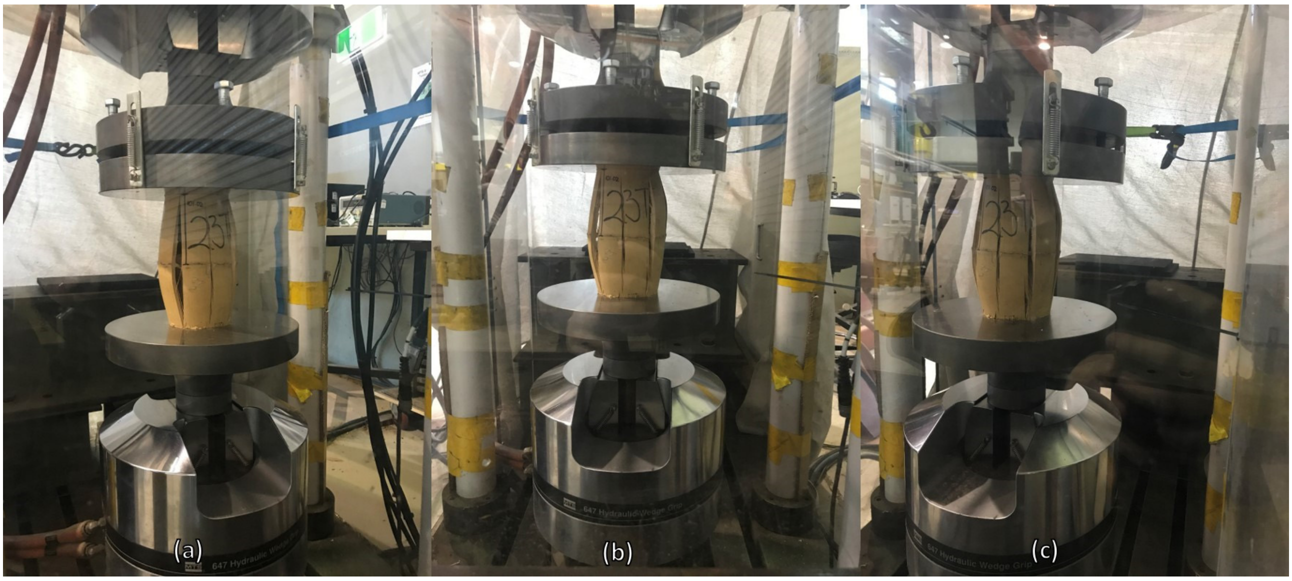


Figure 3. UTM testing final deformation of representative 23T (**a**) left side profile (**b**) front profile (**c**) right side profile (Note: protective sheeting and Plexiglas around testing setup to allow for safer controlled failure).

Table 2. Moso Bamboo Strength and Mechanical Properties.

Representative	Ultimate Load Capacity B_u (kN)	Moisture Content (%)	Density, ρ (g/cm^3)	Density, at Time of Test, ρ_{test} (g/cm^3)	Density, at 12% Moisture Content, ρ_{12} (g/cm^3)
1T	52.44	10.57	0.70	0.78	1.013
1B	66.75	10.69	0.64	0.71	1.012
3T	49.73	11.30	0.71	0.80	1.006
3B	58.31	11.26	0.59	0.66	1.007
5T	70.78	10.56	0.71	0.79	1.013
5B	79.68	10.97	0.73	0.82	1.009
7T	67.70	11.26	0.70	0.79	1.007
7B	84.23	11.04	0.67	0.76	1.009
9T	71.81	10.22	0.68	0.76	1.016
9B	89.15	10.24	0.63	0.71	1.016
11T	72.18	10.11	0.61	0.67	1.017
11B	67.27	10.34	0.62	0.71	1.015
13T	86.14	10.31	0.72	0.80	1.015
13B	121.82	9.84	0.79	0.87	1.020
15T	89.67	10.67	0.65	0.72	1.012
15B	110.02	10.50	0.65	0.72	1.013
17T	115.64	10.65	0.60	0.67	1.012
17B	140.88	10.26	0.61	0.68	1.016
19T	98.08	9.69	0.64	0.71	1.021
19B	112.42	9.75	0.54	0.60	1.021
21T	122.14	9.96	0.56	0.62	1.019
21B	152.52	10.12	0.56	0.62	1.017
23T	89.52	9.64	0.61	0.67	1.021
23B	114.95	9.84	0.59	0.65	1.020

2.4. Moisture Content and Density Tests

Immediately following each mechanical test, representatives were weighed and placed into an oven at 105 °C for 48 h to ensure a change in mass of less than 0.5% at regular intervals, of no less than 2 h, confirming the drying process was complete. Moisture content, w, was determined using Equation (1),

$$w = \left[\frac{m_i - m_0}{m_0}\right] \times 100\% \tag{1}$$

where m_i is the initial mass of the test representative before drying (g) and m_0 is the mass of the test piece after drying (g). The values for moisture content are recorded in Table 2.

For density tests, representatives' dimensions were measured to a precision of 0.1 mm to determine the volume of the samples. The area (A) of each sample was determined using Equation (2),

$$A = \frac{\pi\left[D^2 - (D - 2t)^2\right]}{4} \tag{2}$$

where D is the outer diameter of the bamboo sample (mm), and t is the wall thickness (mm), as detailed in Table 1. The post-test oven-dried mass was also used to calculate the basic density, ρ, using Equation (3),

$$\rho = m_0 / V_0 \tag{3}$$

where V_0 is the volume of the green test piece in cubic millimetres (mm^3). The density at the time of the test, ρ_{test}, can also be determined using Equation (4),

$$\rho_{test} = m_e / V \tag{4}$$

where m_e is the mass of the test piece in grams (g) and V is the volume of the test piece in cubic millimetres (mm^3). Density at 12% moisture content, ρ_{12}, as calculated via Equation (5),

$$\rho_{12} = [\frac{1.12}{1 + w}] \tag{5}$$

where w is the moisture content calculated from Equation (1) at the time of test, expressed as a decimal. Values for density are provided in Table 2. Multiple constituents of density allow for a greater understanding of the test samples.

3. Results and Discussion

3.1. Moisture Content

The moisture content of all representatives was determined after each test was concluded, with values ranging between 9.64 and 11.30% with an observed average of 10.41%. This confirms that all mechanical testing was performed on samples that were not 'green' [52] and, therefore, mechanical properties observed adhere to a construction-ready standard. Figure 4 shows that moisture content had a negative correlation with load capacity; however, it did not provide strong correlations with compressive load capacity.

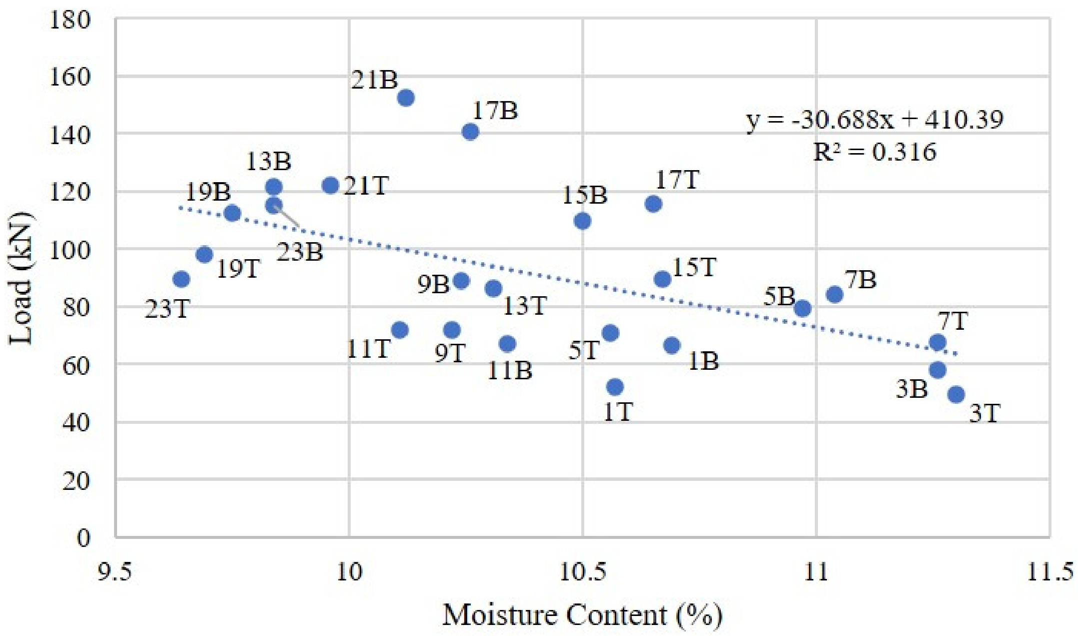


Figure 4. Moisture content vs. compressive load capacity.

3.2. Density

Figure 5 shows the effect that increasing density can have on the bamboo culm's ability to withstand compressive load. There was an apparent negative correlation with density; however, the coefficient of correlation of 0.1673 was very low. From Figure 5, density alone was not a suitable indicator for bamboo compressive load capacity. It was also notable that the top representatives provided less compressive load capacity while generally having a higher density compared to their bottom counterparts. The literature [57,72] suggests that the density of the vascular bundles increases up the shaft of the bamboo sample. As the quantity of fibrous strands within the entire culm remain consistent, while the culm decreases cross-sectional area, the density increases at the top of the culm and the load capacity decreases. This correlates with the notion that a higher density may yield lower compressive load capacity provided it considers other variables. Representative 13B was observed as an anomaly when interpreting load capacity through density; however, density is shown to be an unreliable indicator.

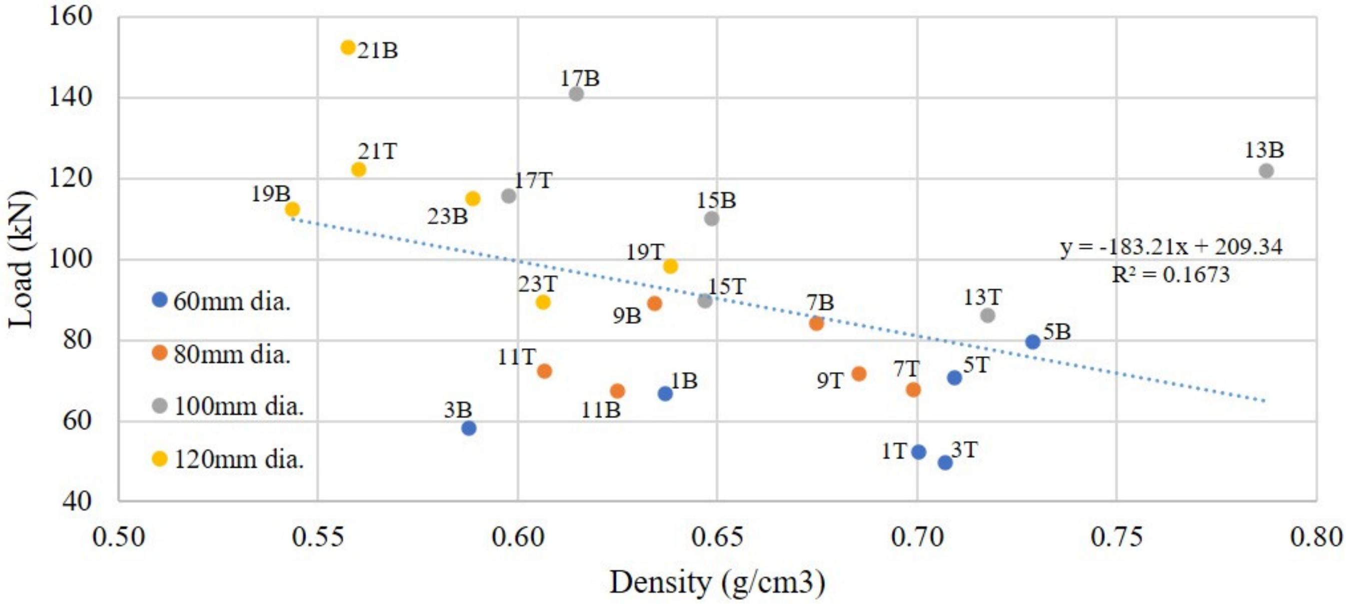


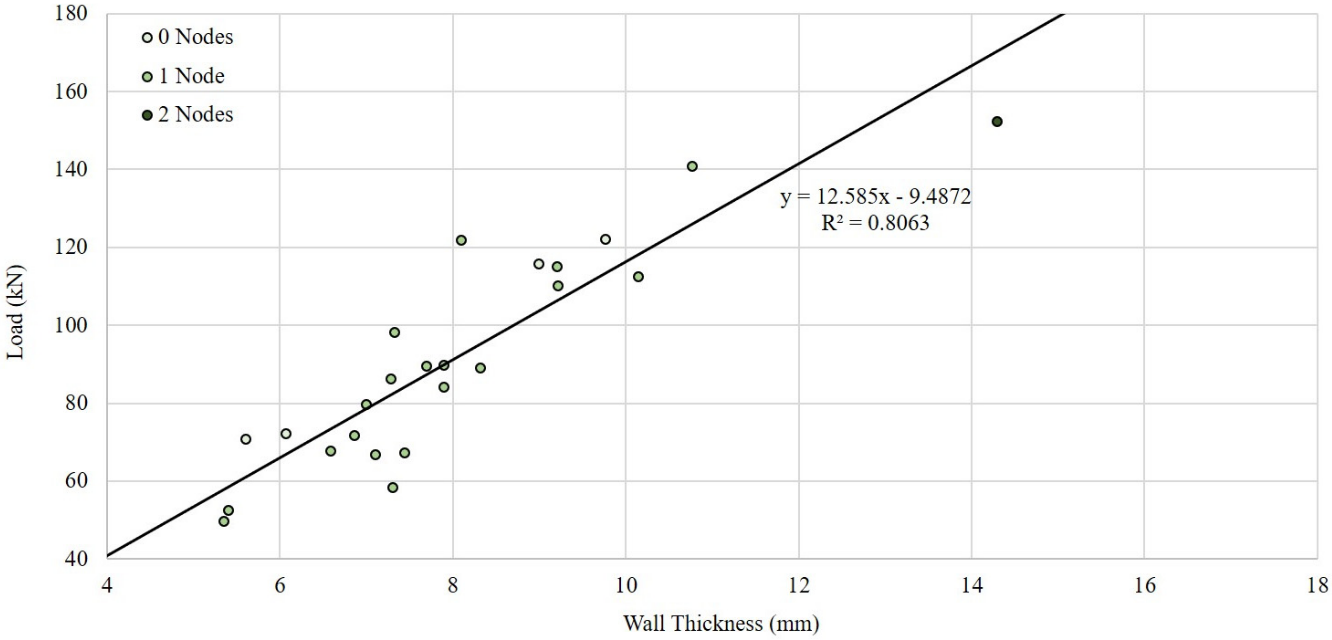
Figure 5. Density vs. the compressive load capacity with respect to culm diameter.

3.3. Wall Thickness

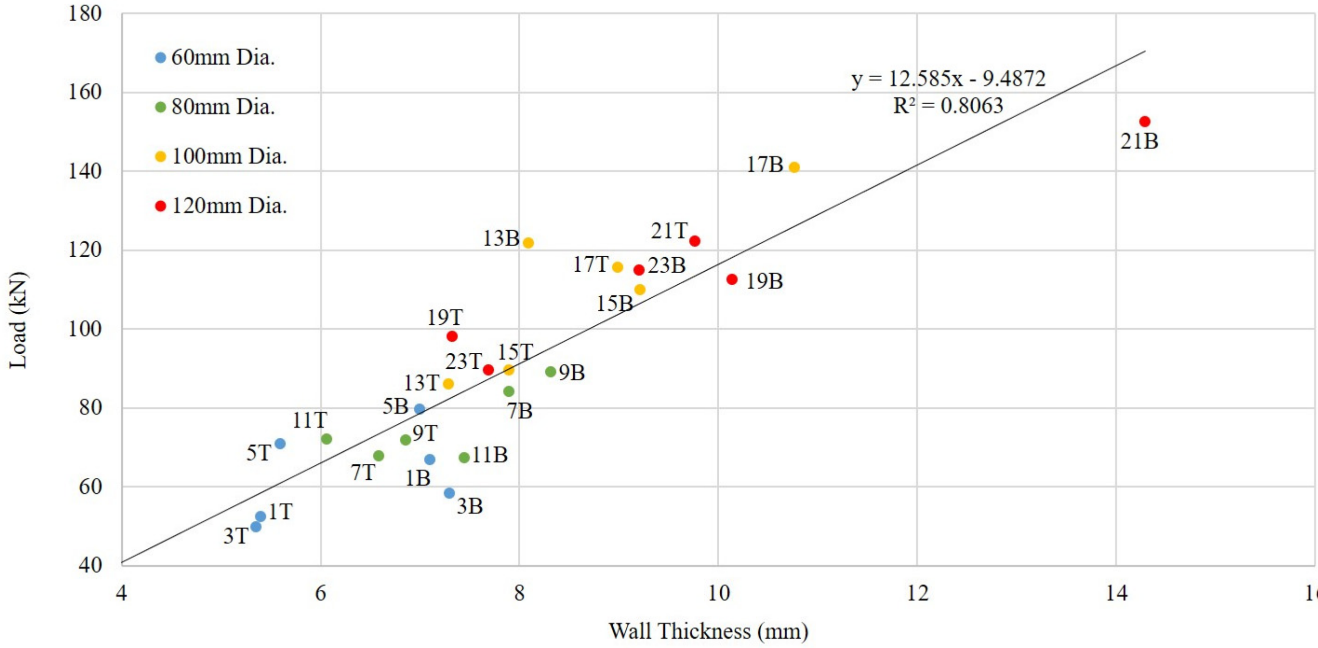
Figure 6a,b show a correlation between wall thickness and compressive load capacity, with regard to number of nodes and diameter, respectively. They illustrate a positive correlation between wall thickness and maximum compressive load. Figure 6a showed the number of nodes within the culm to have a minor influence. Representatives with 0 nodes were consistently above the trendline, whereas the representative with two nodes exhibited a lower compressive load capacity. This trend does suggest that the number of nodes negatively affects load capacity; however, representatives with one node were shown to have variation in load capacity exceeding the influence that the number of nodes imparted. Further testing with a wider variety of nodes would be required to make comprehensive observations regarding the effects of the nodes relating to compressive capacity.

Figure 6b shows wall thickness as an independent indicator provided a strong correlation with compressive load capacity for a natural material, as it has provided a linear relationship with a coefficient of correlation of 0.8063. An increase in diameter and wall thickness correlated with an increase in compressive load capacity; however, there was a tenuous increase in capacity between 100 mm diameter to 120 mm diameter representatives. All of the 100 mm representatives outperformed the trendline with some displaying the most significant positive deviations in load capacities within this dataset. The maximum positive deviation was viewed in 17B, which surpassed the expected load capacity for its wall thickness by 37.23 kN. This suggests that a 100 mm diameter may be an optimal diameter for compressive load capacity in Moso bamboo within the tested sample size.

Figure 7 shows the correlation between average wall thickness and average maximum compressive load derived from Figure 6b for the varying diameter sizes, considering top and bottom representatives. From this figure, the top of the culm presents very accurate results and is shown to have a lower compressive capacity than its respective bottom counterpart. Consequently, it is considered the most conservative and safest approach to use the top of the culm as the compressive capacity for the entire culm. Additionally, utilising the wall thickness to estimate compressive capacity, as shown in Figure 7, yields the most accurate results within this dataset, as evidenced by the coefficient of determination (R^2 = 0.9908).



(**a**)



(**b**)

Figure 6. (**a**) Ultimate compressive load capacity by wall thickness with respect to number of nodes. (**b**) Ultimate load capacity by wall thickness with respect to diameter.

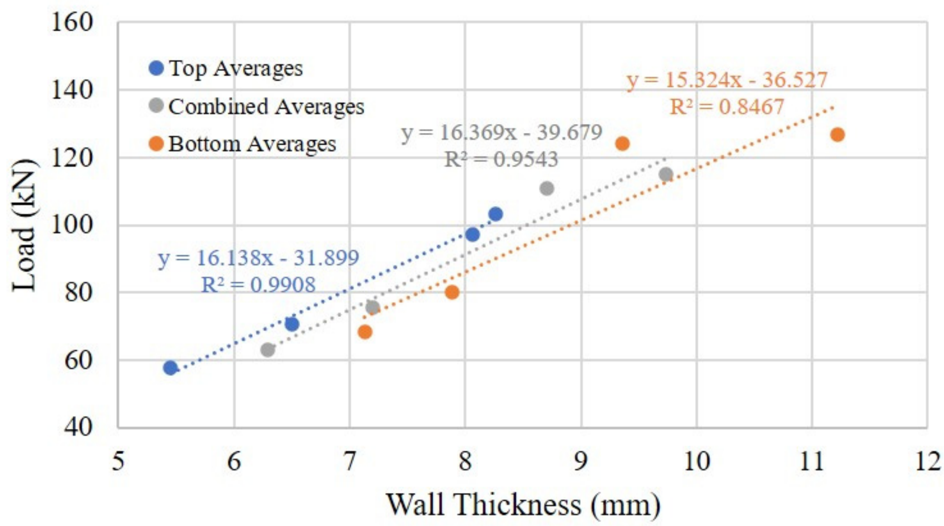


Figure 7. Average wall thickness vs. average maximum compressive parallel-to-grain load, with respect to bamboo culm diameter and consideration to top and bottom representatives.

3.4. Diameter

Figure 8 depicts the increase in loading capabilities as the diameter of the bamboo increases with relation to number of nodes. Two nodes were located on 21B, which was observed to have a significantly higher load capacity when compared with other 120 mm diameter representatives. This depicts having a larger quantity of nodes to increase the load capacity; however, when considering the wall thickness of 21B rather than diameter, it presents itself as having a lower load capacity. Provided with these findings, nodes with respect to diameter and wall thickness pose minimal effect. These findings are consistent with [57] who details nodes having little to no effect in compressive loading parallel-to-grain. Further testing with a larger sample size is recommended.

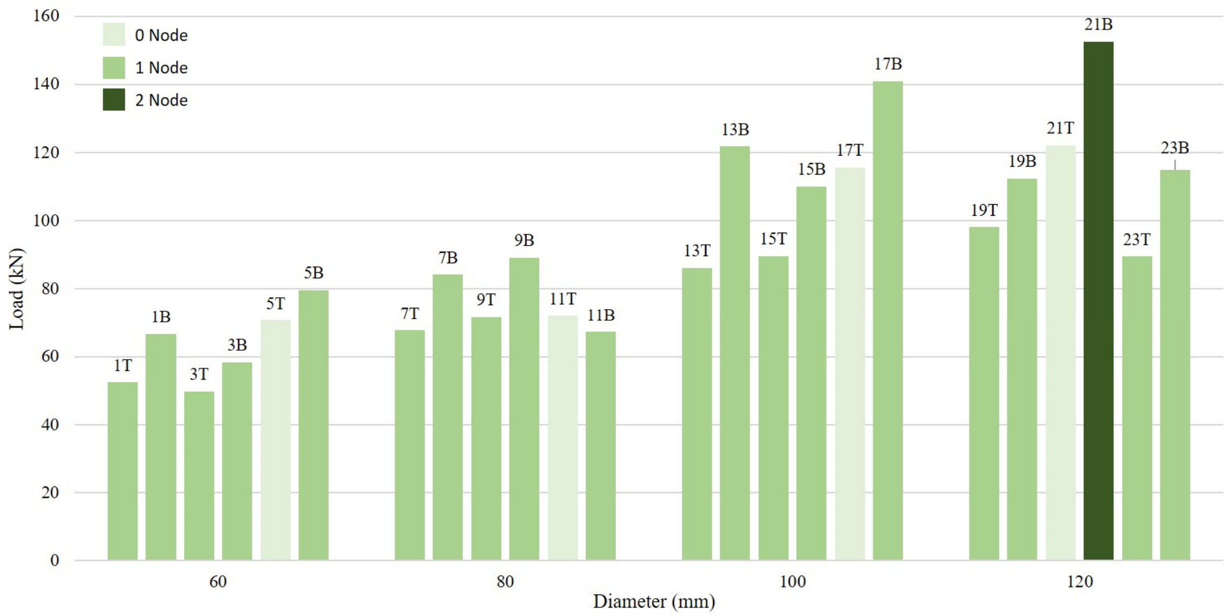


Figure 8. Ultimate load capacity by diameter with respect to the number of nodes.

Figure 9 shows the top samples consistently had a lower compressive load capacity. As the diameter and wall thickness decreases at the top of the culm the compressive load capacity subsequently decreases. Similarly to the observation from Figure 7, Figure 9 showed the average load capacity of 120 mm diameter representatives as marginally larger than those of 100 mm diameter, with an increase of merely 4.25 kN. This observation implies that an increase in diameter does not necessarily signify an increase in load capacity, or alternatively, that Moso bamboo may possess an optimal diameter for load-bearing performance.

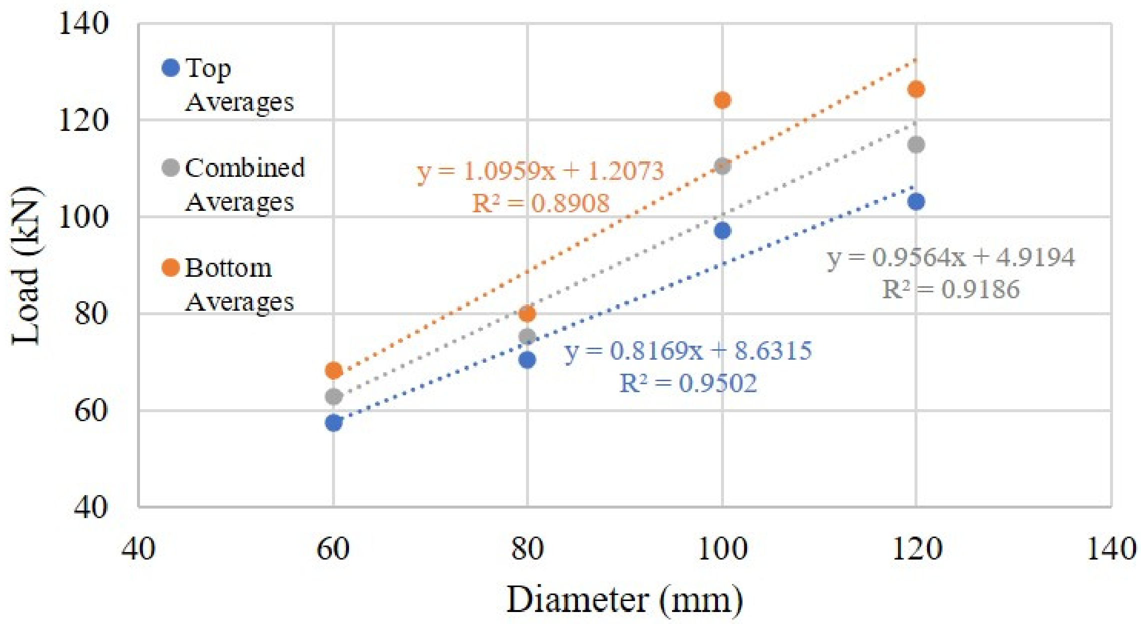


Figure 9. Diameter vs. average load capacity with consideration to top and bottom representatives.

3.5. Node Location

As detailed in Table 1, distances to the nodes from the top of the bamboo representative were recorded to understand how the locality of the node within the tested sample would affect its ability to withstand loading and in turn its failure mode. The distinction was made between node location in the top 25% of the representative and the bottom 25% of the representative, with the middle 50% pertaining to the central nodal position. This resulted in six representatives with top located nodes, seven representatives with centre located nodes, and six representatives with bottom located nodes. Representatives with 0 or two nodes were excluded from this part of the investigation. Table 3 details the description of nodal location.

Figure 10 focuses on representatives with a singular node and aims to identify the effects of node location on compressive capacity. The data demonstrate representatives with nodes placed centrally have the potential for higher maximum compressive loads, while representatives with nodes located at the top and bottom typically have similar lower compressive load capacities. Although centrally located nodes have higher than average load capacities for the dataset, they are larger in diameter and wall thickness. The ISO 22157:2019 [52] states that testing culms with nodes should have nodes centrally located; however, these data show that only considering central node placement may affect load capacity, potentially skewing the interpretation of a culm's collective capacity. This phenomenon may require further testing in the future.

Table 3. Node location within bamboo samples.

Average Diameter (mm)	Representative	Node Distance from Sample Top (mm)	Initial Length (mm)	Node Designation
60	**1T**	21.6	121.91	TOP
	1B	8.88	129.23	TOP
	3T	103.8	126.37	BOTTOM
	3B	124.45	133.37	BOTTOM
	5B	125.0	133.69	BOTTOM
80	**7T**	31.1	151.20	TOP
	7B	25.4	176.34	TOP
	9T	110.64	144.19	BOTTOM
	9B	153.51	171.89	BOTTOM
	11B	93.9	169.66	CENTRE
100	**13T**	7.6	177.30	TOP
	13B	99.38	195.12	CENTRE
	15T	10.77	166.79	TOP
	15B	93.8	191.30	CENTRE
	17B	91.39	201.17	CENTRE
120	**19T**	134.51	174.00	BOTTOM
	19B	143.77	224.41	CENTRE
	23T	101.02	197.03	CENTRE
	23B	87.0	219.95	CENTRE

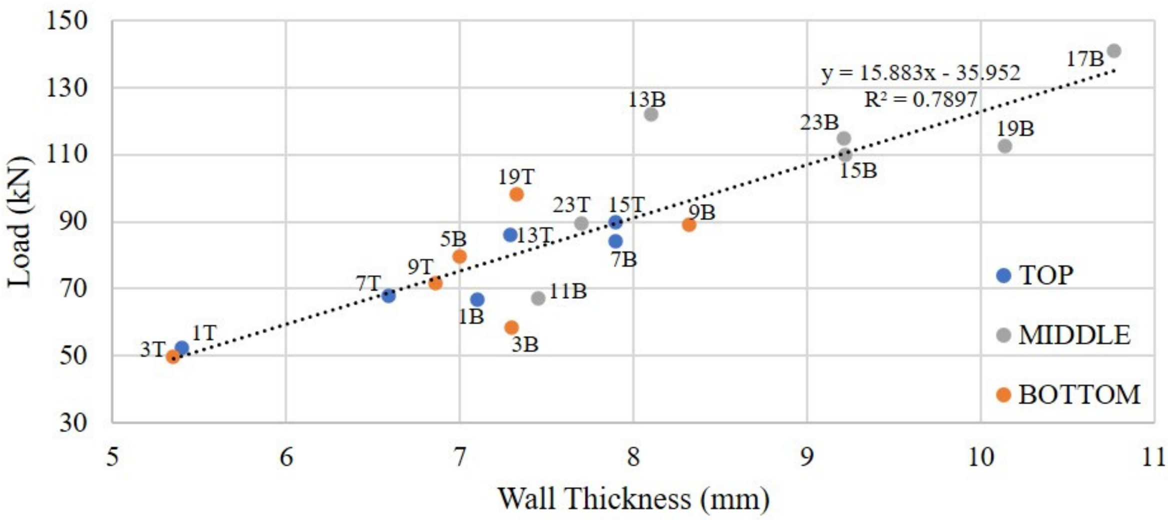


Figure 10. Influence of node location with respect to wall thickness (mm) and compressive load (kN).

Figure 11 illustrates that compression failure parallel-to-grain occurred in a splitting fashion with convex deformation within the culm walls. Failure was controlled and ductile with a gradual decline in load capacity. This failure mode is quite typical of the literature [72,76]. Splitting occurred within some nodes, while other nodes remained intact. There were no noticeable trends of failure initiating at node or internode locations regardless of node placement.

Figure 11. Post-compression failure of representatives (**a**) 5B (**b**) 9B (**c**) 9T.

4. Conclusions

Following Moso bamboo testing in compression parallel-to-grain, moisture and density testing, the primary conclusions reached can be summarised as follows:

- Failures occurred in a controlled manner, with all samples exhibiting a ductile failure. Compression failure occurred parallel to the grain, with splitting and convex deformation in the culm walls. Failure occurred in some nodes, but no consistent trend was observed regarding failure initiation at node or internode locations.
- Lower moisture content, to some extent, positively affected compressive load capacity. This is a key factor in the unsuitability of green bamboo for construction applications. The accuracy of determining compressive capacity based on moisture content was observed to be low.
- Although a negative correlation with density was observed, the low correlation coefficient (0.1673) suggested a weak relationship. Notably, top representatives, which had higher density, exhibited lower compressive load capacity, consistent with the existing literature.
- Wall thickness as an independent indicator was shown to be the most accurate out of the tested indicators within this dataset. 21B consisting of two nodes, demonstrated a relatively high compressive load capacity for its diameter, suggesting that a larger quantity of nodes increases the compressive load capacity; however, its capacity in terms of wall thickness was in keeping with the predicted value. This suggests that the increase in load capacity is due to wall thickness rather than the number of nodes, supporting wall thickness as a reliable indicator of load capacity.
- Determining compressive load capacity through wall thickness for top of culm representatives was very accurate. The tops of the culm representatives were shown to have lower compressive capacity than their respective bottom counterparts. Consequently, it is considered that the most conservative, safe, and reliable approach to use the top of the culm wall thickness as the indicator for compressive capacity for the entire culm. As a means of estimating bamboo culm compressive load capacity from measured wall thicknesses Equation (6) as follows may be applied;

$$B_u = 16.138t - 31.899 \quad (R^2 = 0.9908) \tag{6}$$

  * Note: Only suitable within the constraints outlined in this research

- Both wall thickness and diameter provided positive correlation with compressive load capacity; however, there was a tenuous increase in capacity between 100 mm diameter and 120 mm diameter representatives. The 100 mm representatives consistently outperformed the trendline with some displaying the most significant positive deviation of load capacities within this dataset. This observation implies that an increase in diameter does not necessarily signify an increase in load capacity or wall thickness, alternatively, that Moso bamboo may possess an optimal diameter for load-bearing performance. This may require further testing in the future.

- Representatives with 0 nodes consistently exhibited higher compressive capacity than predicted based on their wall thickness, while those with two nodes showed lower capacity. This trend appeared inconsequential; however, as representatives with one node demonstrated deviations in load capacity that surpassed the effect of the number of nodes. This may require further testing in the future.
- The ISO 22157:2019 [52] states that testing culms with nodes should have nodes centrally located; however, these data show that centrally located nodes may increase the perceived culm compressive load capacity. Only considering central node placement may potentially skew the interpretation of the collective capacity of the culm, which may present increased liability. This may require further testing in the future.

The limitations of this study are as follows:

- This investigation focused on representatives of the bamboo culm with an aspect ratio of 1:2 (diameter: length), which limited the number of nodes in each representative. Further investigation into the impact of the number of nodes on the compressive capacity of Moso bamboo culms would be valuable.
- The focus of this research was to identify a non-destructive indicator for determining the compressive capacity of Moso bamboo specimens. However, given that bamboo is an anisotropic material, further investigation into other applied forces, such as, but not limited to, tension, bending, shear, and compression perpendicular to the grain, is still necessary to utilise bamboo culms in construction.
- The experimental findings of this research are applicable only to Moso bamboo harvested from the Zhejiang province of China at 5 years of growth, air-dried, fumigated, with non-residual methyl bromide to meet Australian Quarantine and Inspection Service (AQIS) specifications, and imported to Australia. There is currently no commercially grown construction bamboo in Australia and Moso bamboo mechanical properties may vary with variation on growing conditions and processing.
- The sizing, treatment process, and growth of the Moso bamboo was dependent on the supplier in Australia. This study was limited to diameters of 60, 80, 100, 120. Further investigation not limited to these particular diameters would be valuable.
- As with experimenting on any natural material, anomalies were observed. These, however, were not excluded in this investigation. Including these anomalies highlights the necessity for a safety factor and a more conservative approach in determining compressive load capacity.
- This study focuses on finding an indicator for compressive capacity parallel to the grain of Moso bamboo for construction application; however, to enable its use in construction, a safety factor and appropriate design conditions must still be established.

Bamboo culm wall thickness is thus identified as the most suitable sole indicator of the compressive load capacity parallel-to-grain when compared with diameter, number of nodes and location, and culm density. This research provides an indicative method to determine the compressive load capacity of a Moso Bamboo culm and an understanding of the installation and compression integrity of Moso bamboo culm piles and their constraints. In the future, the information will be utilised for laboratory bamboo pile testing.

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