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The Geometrical Properties of Round Bamboo of *Gigantochloa levis* and Their Effects on Construction Design

(Sifat Geometri Batang Buluh *Gigantochloa levis* dan Kesannya terhadap Reka Bentuk Pembinaan)

Mohd Jamil Abdul Wahab* & Nor Marzuina F.K. Naysir

Forest Products Division, Forest Research Institute Malaysia, 52109 Kepong, Selangor, Malaysia

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ABSTRACT

Round bamboo is reviewed as a highly potential material for building components. However, the assessable data of the geometrical variability of Malaysian bamboos proposed as structural members are greatly lacking. A study was conducted to establish the geometric properties of *Gigantochloa levis* culms and to derive the important parameters that will affect engineering design. The evaluations were based on the internode length, culm diameter, wall thickness, and the second moment of area with respect to the height of the culm. Most internode sections measured between 35 and 50 cm. An internodal crack could severely change the cross-sectional geometry of the culm. Two major factors concerning culm diameter that need to be considered in the design are diameter shrinkage and taper rate. The diameter of a culm was fairly equal within the height of 1 to 5 m and decreased from 5 m onwards. Upon drying, the culm of the larger diameter tended to shrink more than the smaller one. Thickness irregularity around the circumference of the internode wall was minor. The shrinkage of the internode wall was within 20%. The selection of culms for construction is best between the height of 1 and 5 m whereby the internodal length is more consistent.

Keywords: Beam; column; dimensional measurements; second moment of area; structure

ABSTRAK

Buluh bulat dikaji sebagai suatu bahan yang amat berpotensi untuk komponen bangunan. Walau bagaimanapun, data keragaman geometri untuk jenis buluh di Malaysia yang dicadangkan untuk kegunaan struktur adalah sangat kurang. Satu kajian telah dijalankan untuk menubuhkan sifat geometri batang buluh *Gigantochloa levis* dan seterusnya menerbitkan parameter penting yang akan mempengaruhi reka bentuk kejuruteraan. Penilaian dijalankan berdasarkan panjang ruas, diameter batang, tebal dinding dan momen luas kedua, dengan merujuk kepada ketinggian batang. Kebanyakan bahagian ruas berukuran antara 35 hingga 50 cm panjang. Keretakan ruas boleh mengubah geometri keratan rentas batang. Dua faktor utama berkaitan diameter batang buluh yang perlu dititik beratkan dalam reka bentuk adalah pengecutan dan kadar tirus. Diameter batang buluh adalah hampir seragam pada ketinggian 1 hingga 5 m dan berkurang daripada 5 m ke atas. Sewaktu pengeringan, batang buluh yang berdiameter lebih besar mempunyai kecenderungan untuk mengecut dengan peratusan yang lebih tinggi berbanding yang lebih kecil. Kadar ketidakteraturan tebal di sekeliling dinding ruas pula adalah rendah. Kadar pengecutan dinding ruas adalah di bawah 20%. Pemilihan batang buluh untuk tujuan pembinaan adalah paling sesuai pada ketinggian antara 1 hingga 5 meter yang panjang ruasnya adalah lebih seragam.

Kata kunci: Momen luas kedua; pengukuran dimensi; rasuk; struktur; tiang

Introduction

Lately, bamboo in its original round form has been widely reviewed and discussed as a material for building components (Esti 2016; Muhammad Fahim et al. 2022). There are 70 species of bamboo found in Malaysia, comprising 50 species (7 genera) in Peninsular Malaysia, 30 species (8 genera) in Sabah, and 20 species (7 genera) in Sarawak. The total area of the country covered with bamboo is approximately 421,722 hectares with a standing stock of about 207.66 million clumps (Asniza, Mohd

Fahmi & Mohd Khairun Anwar 2022). To improve the durability of bamboo against deterioration agents, various preservatives such as chromated copper arsenate (CCA), alkaline copper quaternary (ACQ), borax, light organic solvent preservative (LOSP), and tributyltin oxide (TBTO) were experimented. Although commercial products made of bamboo are mostly traditional at present, research and technological advancements have greatly encouraged the application of bamboo as engineered composites and building components (Asniza et al. 2022). Currently, the price of bamboo poles in domestic trade is not regulated, but the local bamboo industry is certainly vigorous and flourishing. Until the end of 2021, the country's total export of bamboo and bamboo-based products has been recorded up to RM8.43 million (MTIB 2022).

Unlike typical beams or columns of solid timber and glulam, the dimensions along the span of bamboo culms are not uniform. The main geometrical variability of bamboo is due to a) tapering, b) irregular internodal length, c) variable cross-sectional properties along its axis, and d) out-of-straightness (Lorenzo & Mimendi 2019). Hence, builders and engineers have to impose an asymmetric geometry along the axial and perpendicular axes of bamboo poles in designing for structural members.

Investigators have described the structural effects of the culm geometry on the magnitude of deflection and the position at which it occurs (Lorenzo, Mimendi & Li 2019). Based on the principle which is already well established in engineering mechanics, the flexural formula:

$$\sigma_b = {}^{My}/_{I}$$

is used to compute the value of bending stress, σ_b developed in a loaded beam, where M is the bending moment (N mm), y is the perpendicular distance from the neutral axis (mm), and I is the second moment of area (mm^4). For a structural member that is symmetrical with respect to axes, the computation of stress distribution is fairly straightforward since I is a constant. On the contrary, bamboo culms are naturally tapered. A bamboo culm is an orthotropic hollow cylinder divided into chambers by stiff diaphragms positioned at the sequential nodes and the length of the internodal sections differs between species (Shima, Sato & Inoue 2016). Besides, the diameter and wall thickness of a species vary greatly within- and between culms (Asniza, Mohd Fahmi & Mohd Khairun Anwar 2022; Azmy et al. 2011; Razak et al. 2010). Therefore, comprehensive geometrical data of bamboo culms is greatly required to determine the stress behaviour under bending load, especially for space frame structures such as the Luum Temple in Tulum.

Likewise, in order to avoid lateral deflection in columns, structural members subjected to an axially compressive force are designed based on Euler's formula. The critical buckling load, P_{cr} is determined using the formula:

$$P_{cr} = {}^{\pi^2 EI}/_{L^2}$$

where E is the elastic modulus (N mm^{-2}); I is the second moment of area (mm^4); and L is the unsupported length of the column (mm). Again, in designing asymmetric columns such as bamboo poles, accurate figures representing the geometric properties are necessary to determine the inconsistency of the second moment of area along the length. One example of modern bamboo design that requires detailed geometrical data is the gigantic columns of Kontum Indochine Café in Kontum City.

Nevertheless, our knowledge of the geometrical variability of Malaysian bamboos proposed as structural members is limited and obviously undetailed. In most studies, the dimensional measurements of bamboo were often documented as average values, simply to generate comparable figures between species and ages (Zakikhani et al. 2017). Besides, researchers preferred to explore the dimensional characteristics of bamboo in processed forms such as strips and laminated ply (Fadhlia et al. 2017). Fragmentary data as such are unworkable for engineering design.

In the actual harvesting, the selection of culms for building applications such as beams and pillars will certainly focus on the intended sizes, regardless of age and inherent properties. Thus far, evaluations of the properties and characterisation of bamboo material were strictly scientific, missing out on important information for engineering calculations. Most experimental works have left out the quantitative details of the geometrical variation within a culm. This paper aimed to establish comprehensive geometric properties of *Gigantochloa levis* culms and subsequently derive some important parameters affecting structural design. The findings are meant to assist builders and engineers in the technical decisions concerning round bamboo as building components.

Materials and Methods

FIELD SAMPLING

Gigantochloa levis (locally known as beting) is one of the most distributed bamboo species in Peninsular Malaysia. A total of thirty culms of *G. levis* from six different clumps on an undulating terrain of a secondary forest at Bukit Hari, Kepong (3º 13' N, 101º 36' E, 150 m above sea level) were selected for this study. The study focused on culms of a large diameter suitable for structural uses as poles. Reasonably straight culms were selected based on the measurement of diameter at the bottom-most internode of approximately 10 cm (Figure 1).

The selection of culms was based on the diameter measurement and physical characteristics, similar to sampling conducted by Azmy (1993). Mature culms of similar diameter were selected within the middle part of a clump, based on the absence of sheath, and the greyish tinge on the internode wall (Figure 2). Young culms were excluded based on the presence of sheath and shiny internode wall, while old culms were excluded based on the distinct brown colour. According to Nordahlia et al. (2012), mature culms of *G. levis* were estimated to be around 4 years old. The height of the first living branch and the total height were measured on all sample culms.

INTERNODE LENGTH, CULM DIAMETER, AND WALL THICKNESS

The length of the internodes, i.e., the distances between two nodes, *l* (cm) were measured on all culms. Subsequently, the culm diameter, D (cm) and wall thickness, t (mm) in green condition were measured at every mid-internode using parameters as described in Figure 1. The measurements were similar to Lorenzo and Mimendi (2019), following the guidelines in ISO 22157 (2019).

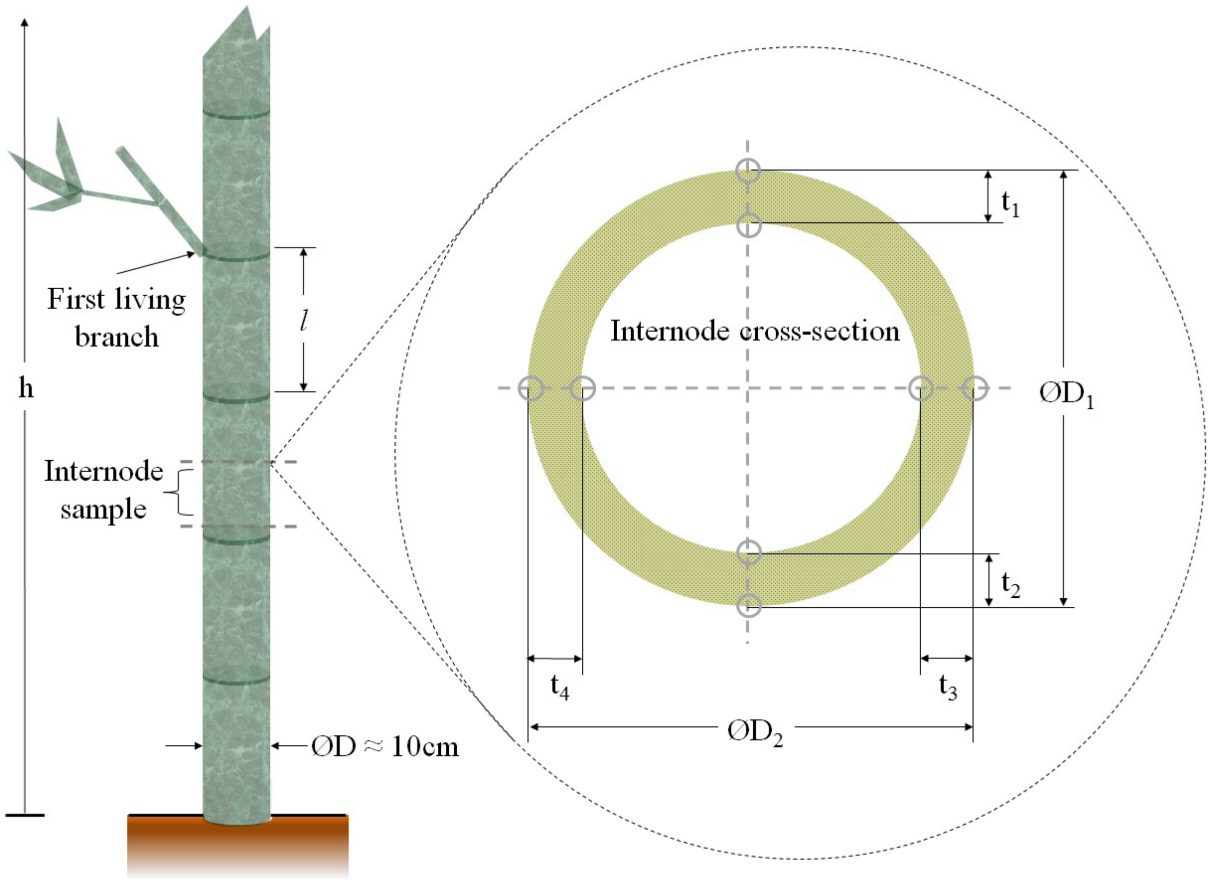

FIGURE 1. Measurements of the height of the first living branch, internode length, culm diameter and wall thickness

FIGURE 2. The visual appearance of young, mature, and old bamboo culms (left to right)

Culm diameter, D (cm) and wall thickness, t (mm) of each sample were calculated using the following formulae:

$$D = \frac{ØD_1 + ØD_2}{2} \quad (1)$$

$$t = \frac{t_1 + t_2 + t_3 + t_4}{4} \quad (2)$$

The same measurements were made on air-dried samples once they attained a constant weight. A total of 714 samples of internodes were measured.

TAPER RATE

The taper rate, T (cm m^{-1}) was measured as the difference between the bottom-end diameter and top-end diameter per meter length using the formula:

$$T = \frac{D_h - D_{h+L}}{L} \quad (3)$$

where D_h is the diameter (cm) at h meter in height of the bottom-end; D_{h+L} is the diameter (cm) at h+L meter in height of the top-end; and L is the length (m) between D_h and D_{h+L}.

SHRINKAGE

The drying shrinkage of the culm diameter and wall thickness was calculated based on the percentage of dimensional change. Diameter shrinkage, S_D (%) and thickness shrinkage, S_t (%) were determined using the equivalent formulae by Kamruzzaman et al. (2008):

$$S_D = \frac{D_G - D_{AD}}{D_G} \times 100 \quad (4)$$

$$S_t = \frac{t_G - t_{AD}}{t_G} \times 100 \quad (5)$$

where D_G is the culm diameter (cm) in green condition; D_{AD} is the culm diameter (cm) in air-dry condition; t_G is the wall thickness (mm) in green condition; and t_{AD} is the wall thickness (mm) in air-dry condition.

SECOND MOMENT OF AREA

Assuming that the cross-sectional area of bamboo culms is ideally round and hollow, the second moment of area at h meter in height, I_h (mm^4) was calculated using the formula (Lorenzo & Mimendi 2019):

$$I_h = \frac{\pi}{64}\left[(D_h)^4 - (D_h - 2t_h)^4\right] \quad (6)$$

where D_h is the diameter (mm) at h meter in height; and t_h is the internode wall thickness (mm) at h meter in height.

RESULTS AND DISCUSSION

The average height of 30 culms was 16.7 m within the minimum and maximum values of 10.4 m and 22.5 m, respectively. The height measurements of the first branch ranged from 3.8 to 8.4 m with an average of 6.4 m, though the heavy branching is mostly at the topmost nodes. Pruning the branches using a chainsaw was generally easy. The subsequent analyses were restricted up to 9 m of the culm height due to the size factor. The diameter of the culms at the height of 9 m ranged from 4.67 to 10.66 cm, thus, the material below the sizing was considered small and inappropriate for the intended evaluation. The analyses were conducted based on the green (moisture content of >100%) and air-dry (average moisture content of 14%) samples.

INTERNODE LENGTH/DISTANCE BETWEEN NODES

The number of the internode sections of each culm counted from the bottom to the height of 9 m varied from 20 to 33 with an average of 24. The shortest internode measured 10 cm and the longest measured 54 cm. The rate of the longitudinal drying shrinkage relative to the functional length is minor hence the evaluation of green samples was reckoned adequate and reasonable (Anokye et al. 2014). The relationship between the internodal length and culm height was generally erratic (Figure 3). Most internode sections measured between 35 and 50 cm. Only a few internodes (2%) measured >50 cm, distributed above the height of 4 m. Shorter internodes (<30 cm) were largely at heights of below 1 m and some were randomly scattered above 5 m. In short, it is unlikely to estimate the length and the number of the internodes in a culm of *G. levis*. However, by restricting the analysis below the height of 5 m, a moderately consistent exponential correlation was observed (R^2 = 0.761). At below 5 m, the length of an internode can be expressed as a function of the height based on the equation:

$$l = 9.4429 \ln \frac{\mathrm{h}}{0.0366}$$

where l is the internode length (cm) and h is the height (m) of the culm.

Based on the mechanical tests of moso bamboo, Shao et al. (2010) concluded that nodes do not impart any negative effects on bending strength, shear strength, and compressive strength parallel or transverse to grain. However, the negative effects of nodes on the tensile test parallel to the grain were significant, in which the strength decreased by 18 to 33%. Similarly, Taylor et al. (2014) concluded that under the exertion of tensile forces, a node may be a point of weakness of bamboo.

One possible mechanical disadvantage caused by long internodes is the tendency to collapse when a strong bending force is applied. A node is a combination of an external ridge at the outer surface and an internal diaphragm embedded in the hollow cavity which acts as a ring stiffener. Thus, the sequential insertion of many diaphragms improves the mechanical stiffness of the culm (Shima, Sato & Inoue 2016). Besides, nodes were claimed to effectively reduce the outer diameter compression of moso bamboo. The more nodes there were the smaller the outer diameter compression (Meng & Sun 2018).

Previous investigators have witnessed that bamboo culms frequently show cracks/splits at the internodal section which often stop at or near nodes (Taylor et al. 2014). They concluded that a possible role for the nodes is to prevent cracks from propagating along the entire length of the culm. In the present work, 3.0% of the samples (21 of a total of 705) were split and unfolded due to drying. Several samples (2.4%) were cracked in a shrivelling form. Evidently, an internodal crack could severely change the cross-sectional geometry of the culm. Thus, other than preventing the propagation of the longitudinal cracks, the nodes also mitigate the geometrical changes of the cross-sectional area in the event of cracking or due to drying shrinkage.

Depending on the proportion and severity, a crack might affect the strength properties of a culm. However, the hypothesis needs to be validated and quantified through actual mechanical tests. Additionally, crack creates a relatively vulnerable zone for deterioration agents and allows for access to water which enhances the degradation effect. During harvesting, lengthy cracks on some internode sections of standing culms were also observed. Either in live culm or cut samples, the occurrences of cracks were not restricted to any specific height. Clearly, the 'culm cracking' and how it relates to other parameters is an important subject to ponder for the effective utilisation of bamboo culm as a structural component.

In short, the selection of culms of *G. levis* for structural uses is best between the height of 1 to 5 m whereby the internodal length is much more consistent. The nodes in a bamboo culm adversely affect the tensile strength which is critical for sustaining bending load. At the same time, nodes have a special biomechanical function to restrain the longitudinal cracking of the internode walls. Nevertheless, the necessary data to establish the optimum number of nodes in a bamboo pole targeted as a structural component is lacking. A similar issue regarding the optimal spacing of nodes for adapting to bending was mentioned by Shima, Sato and Inoue (2016). Therefore, it is recommended that future tests should emphasise the loading stress limitations of a bamboo pole as a function of internode length.

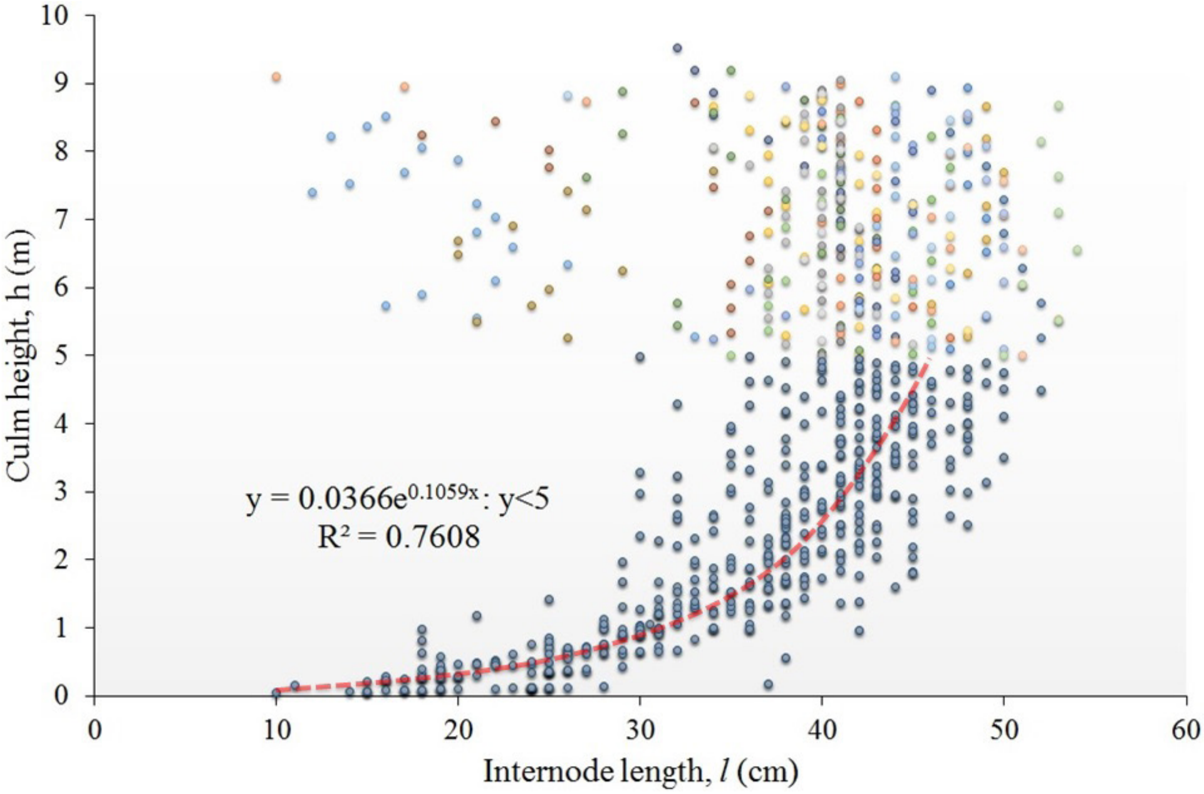

FIGURE 3. Culm height versus internode length

CULM DIAMETER

The diameter variation along the height of 30 *G. levis* culms is shown in Figure 4(A). The diameter of bottom-most internodes in green condition, D_G varied from 9.69 to 13.50 cm with an average value of 11.25 cm. The mean diameters of mid-internodes (around at the height of 5 m) and topmost internodes (around at the height of 9 m) were 9.88 cm (ranging from 8.19 to 12.23 cm) and 7.35 cm (ranging from 4.66 to 10.50 cm), respectively. The consistency of the diameter pattern along the height was fairly high. The diameter was highest at the bottom and gradually decreased towards the top. However, the tapering rates relative to heights were varied. There was a sudden change in diameter below 1 m height. The diameter of a culm was comparatively equal within the height of 1 to 5 m with measurement differences of roughly less than 1 cm. The diameter noticeably decreased from 5 m onwards.

Based on the post-drying measurements, a degree of diameter changes along the culms was observed. The average diameter comparison between green and dry conditions at different heights is demonstrated in Figure 4(B). The diameter of bottom-most internodes in air-dry condition, D_{AD} varied from 9.37 to 13.20 cm with an average of 10.94 cm. The mean diameters of mid-internodes (around at the height of 5 m) and top-most internodes (around at the height of 9 m) were 9.63 cm (ranging from 8.16 to 11.78 cm) and 7.27 cm (ranging from 4.55 to 10.40 cm), respectively. The diameter changes were greatest at the lower internodes and gradually lessen as the culms become smaller.

Culm diameter is a critical parameter in architectural design, especially when components are to be built in bundles. There were two important factors concerning culm diameter that need to be considered in the designing of bamboo poles, specifically 1) diameter changes due to drying shrinkage, and 2) culm taper rate.

Kamruzzaman et al. (2008) demonstrated that the shrinkage rate of culm diameter at different heights was not the same between species. Based on a total of 673 samples, the percentages of diameter shrinkage were somewhat random between 0 and 8.3% (Figure 5(A)). The mean shrinkage was 2.7% with a standard deviation of 1.9%. The larger diameter tended to shrink more than the

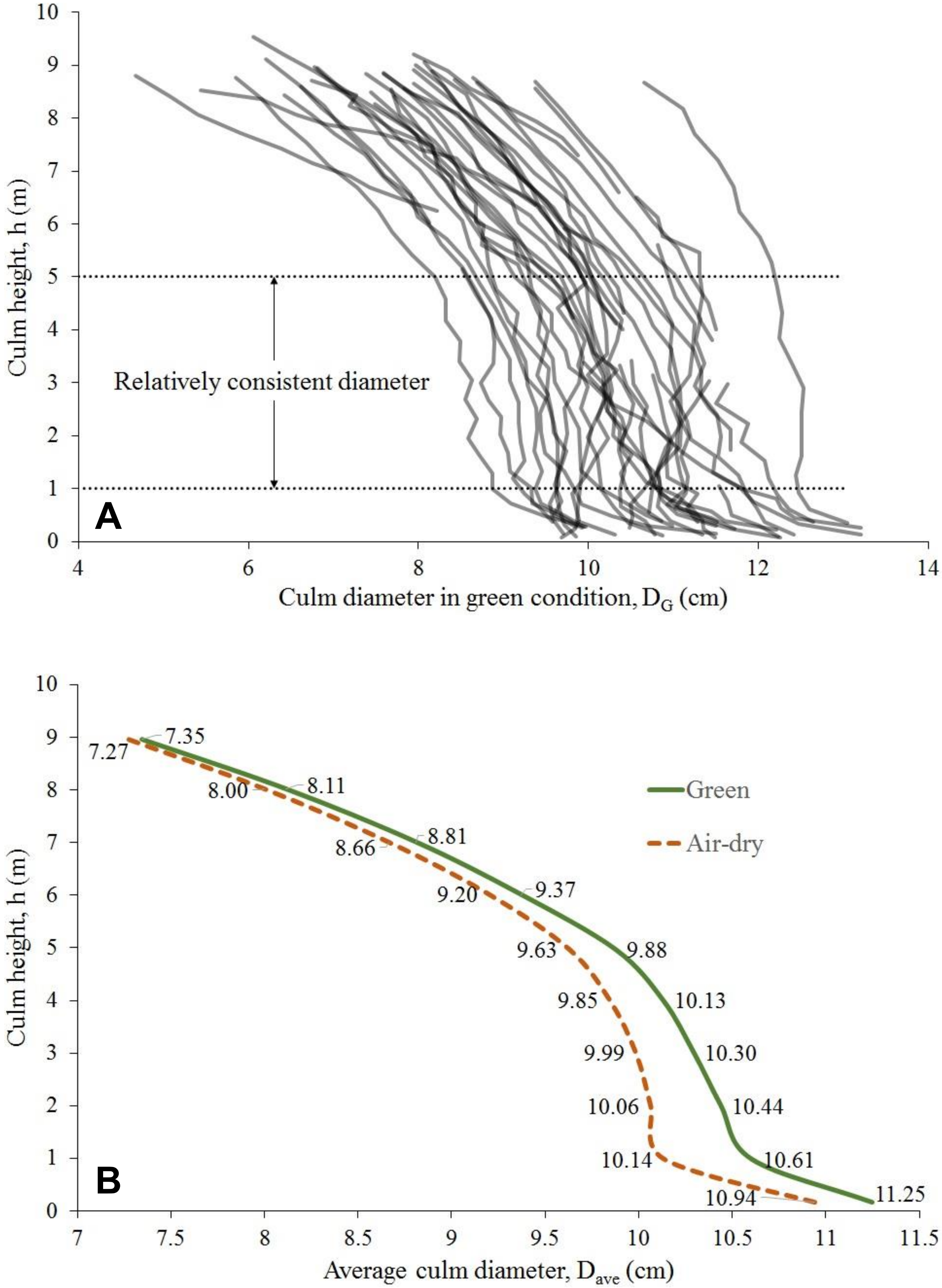

FIGURE 4. Culm height versus culm diameter. (A) Individual culm in green condition, and (B) Average values in green and air-dry conditions

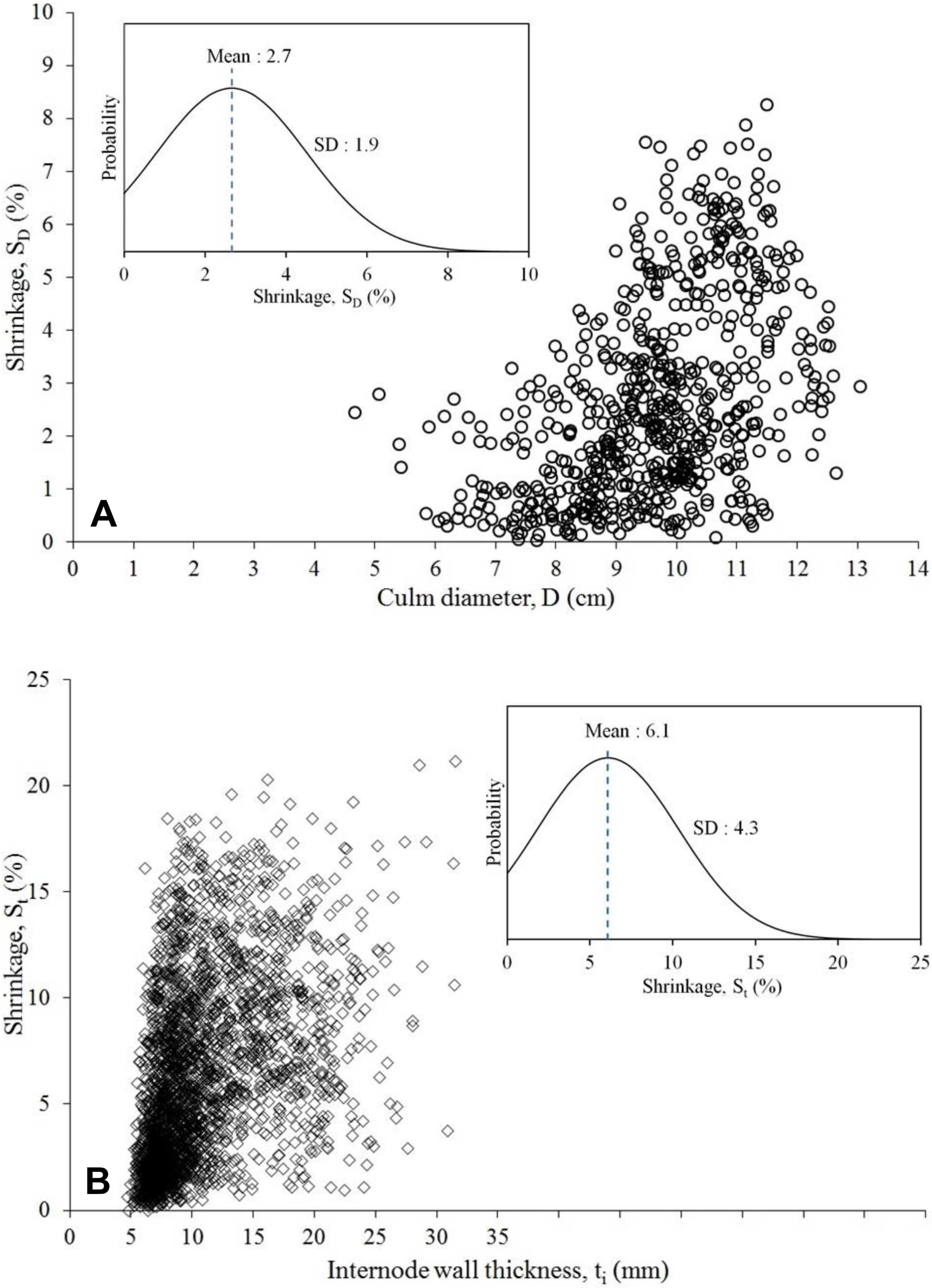

FIGURE 5. Percentage of shrinkage. (A) Culm diameter shrinkage, and (B) Internode wall thickness shrinkage

smaller one. The diameter shrinkage of culms affects the firmness of mechanical connections and ties. One direct approach to minimise the adverse effects in construction is by properly seasoning the culms before erection works. A study proved that additional treatments such as soaking and impregnation were capable of reducing the volumetric shrinkage of ply bamboo (Fadhlia et al. 2017). However, the effectiveness of such processes on round culms is uncertain.

Taper rate delimits the suitable length of poles for optimum design. Hence, the tabulated values of taper rates of *G. levis* in green and air-dry conditions, T_G and T_{AD} respectively, were developed and shown in Table 1. The rates were based on the mean diameter of 30 culms at 1 m intervals. Markedly, the culm diameter was fairly consistent from 1 to 2, 2 to 3, 3 to 4, and 4 to 5 m heights with T_G of 0.17, 0.14, 0.16, and 0.25 cm m^{-1}, respectively. The taper in air-dry condition, T_{AD} was slightly reduced by 0.07, 0.08, 0.14, and 0.22 cm m^{-1}, respectively.

Although not quantified, a few culms with an obvious warp below 1 m height were observed. The occurrence is natural since sympodial bamboo such as *G. levis* generally grow at an upward-inclined angle. However, in terms of pole utilisation, excessive bowing of the culms affects the architectural design as well.

WALL THICKNESS

The correlation between the height, h and the internode wall thickness, t is demonstrated in Figure 6(A). The internode wall thickness in green condition, t_G varied from 4.7 to 31.6 mm. The walls were thickest at the bottom and gradually thinner towards the top. The average values of the bottom-most internodes, mid-internodes (approximately at the height of 5 m), and topmost internodes (approximately at the height of 9 m) in green condition were 21.9, 8.4, and 6.6 mm, respectively. The thickness variation of the wall diameter along the culm height was remarkably steady considering the number of sample culms and the different sources of clumps. The exponentially decreasing trend from the bottom towards the top was highly consistent with R^2 of 0.86 and 0.87 in green and air-dry conditions, respectively.

The thickness variation around the circumference of the internode wall was demonstrated by the graph of culm height versus standard deviation of t_i (Figure 6(B)). The standard deviation values were mostly lower than 1.5 mm except for a few culms below 1 m in height. Thus, thickness irregularity around the circumference of the internode wall was considered minor. Sympodial bamboo such as *G. levis* generally grow at an upward-inclined angle. The geometry of a bamboo culm is a consequence of self-adaptive control under natural conditions (Shima, Sato & Inoue 2016). Thus, the inclination resulted in the unbalance of wall thicknesses across the cross-sectional axis as a natural support to the vertical growth of the culm. Likewise, the same cause explained the slanted pattern of culm diameter at approximately 1 m height (Figure 4).

TABLE 1. Taper rates of *Gigantochloa levis*

Height interval	T_G	T_{AD}
m	cm m^{-1}	cm m^{-1}
0-1	0.64	0.80
1-2	0.17	0.07
2-3	0.14	0.08
3-4	0.16	0.14
4-5	0.25	0.22
5-6	0.51	0.43
6-7	0.56	0.54
7-8	0.70	0.67
8-9	0.77	0.72

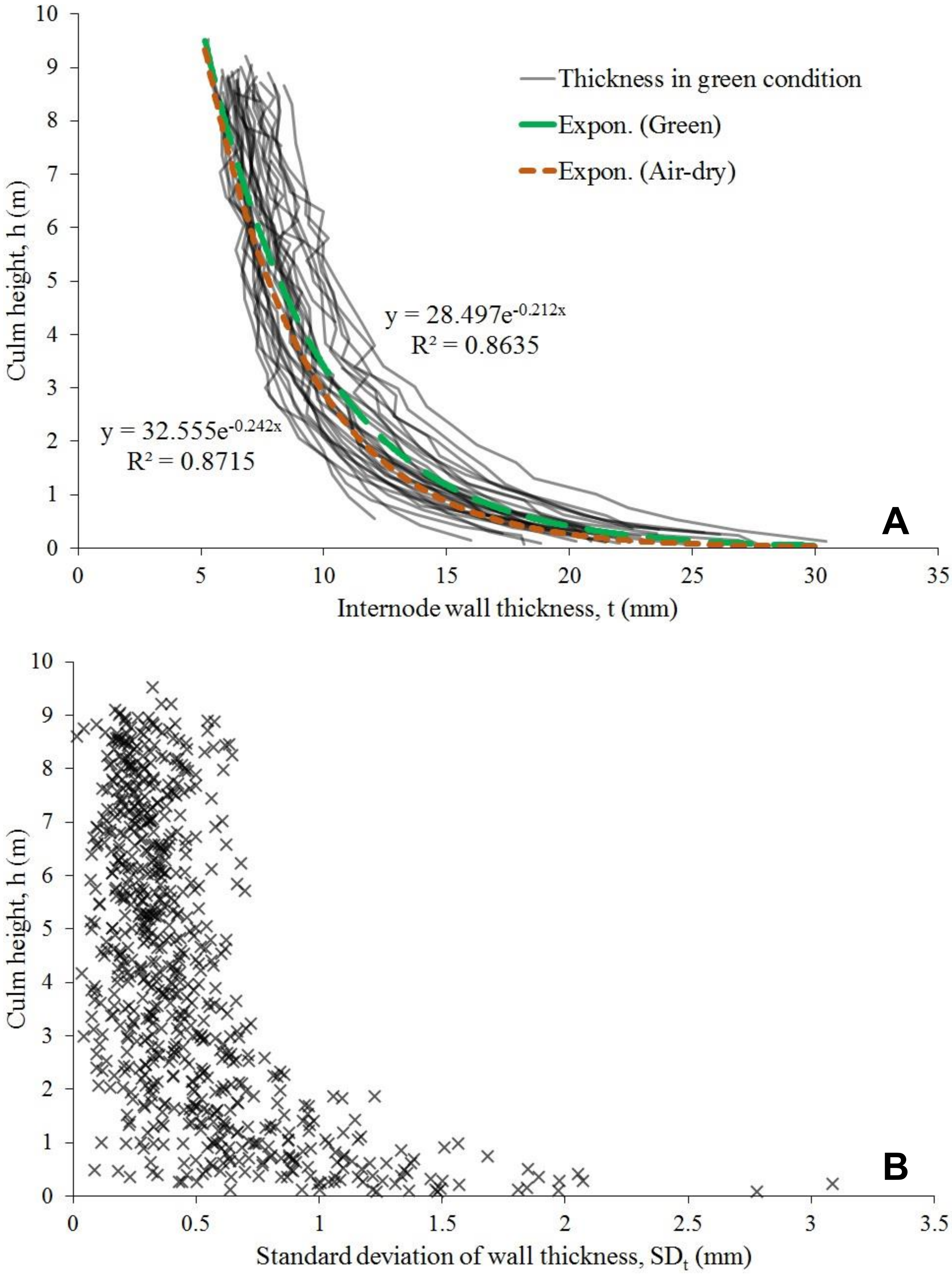

FIGURE 6. Graphs of internode wall thickness. (A) Culm height versus wall thickness, and (B) Culm height versus standard deviation in thickness measurements

Similar to the culm diameter, a degree of thickness change was observed in the post-drying measurements of the internode wall. The wall thickness in air-dry condition, t_{AD} varied from 4.7 to 29.7 mm. The average thicknesses of the bottom-most internodes, mid-internodes, and top-most internodes in air-dry condition were 20.3, 7.9, and 6.4 mm, respectively.

To evaluate the changes in wall thickness, the percentages of shrinkage with regard to the discrete measurement of t_i were plotted (Figure 5(B)). Based on a total of 2852 measurement points, the percentages of shrinkage were between 0 and 21.2% with a mean value of 6.1% and a standard deviation of 4.3%. Although a steady pattern was configured, the exact correlation between the two parameters was actually unclear. A previous study has confirmed that the shrinkage behaviour of bamboo is influenced by variations in moisture content (Anokye et al. 2014). Nevertheless, the distribution of the present chart showed that the wall shrinkage of *G. levis* was statistically within 20%, with a high probability of a lower percentage for below 10 mm thickness.

Overall, the wall thickness variation of *G. levis* over 5 m of height was minor. On the contrary, designers need to consider the difference in the wall thickness between 0 and 5 m, despite the consistency of culm diameter within that particular range. The dissimilarity of internode wall thickness between culms is significant since it determines the second moment of area and affects the material weight. Thus, in any intended design using bamboo culms, it is incorrect to assume that lengthy poles with a consistent diameter possess a comparable wall thickness. Likewise, based on the non-linear pattern of the culm height versus wall thickness graph (Figure 6(A)), the customary approach of taking an average thickness based on two ends measurements is technically inaccurate.

Another noteworthy observation was the consistency of the culm diameter and wall thickness with height despite the irregularity of the internodal distance. Although the length of the internodes is dissimilar (especially at the height of 5 m and above), the culm diameter and the wall thickness were clearly consistent. Thus, we can assume that the culm diameter and the internode wall thickness were not influenced by the internode length.

SECOND MOMENT OF AREA

The second moment of area of a cross-section, I_h at a specific height, h was developed from 30 culms of *G. levis* with a nominal diameter at the bottom-most internode of 10 cm. Since the wall thickness variation around an internode circumference is considered trivial (consistent with low SD), the mean value, t is used. The data are essential to establish the geometrical limits. The variation of the second moment of area of bamboo culms was extensive although we have restricted the analyses to one species of a similar size. The values of I_h ranged from 0.14×10^6 mm^4 at the height of 9 m to 14.83×10^6 mm^4 at the bottom. The variation was highest at the bottom-most section and reduced towards the top. The reference values of the second moment of area of *G. levis* in green and air-dry conditions are important tolerances to engineers and builders in designing round bamboo culms as structural components (Table 2). Based on the targeted diameter of 10 cm, the geometric properties of *G. levis* culms shall be established within these limits. Any value lower or higher is considered inappropriate.

TABLE 2. Second moment of area of *Gigantochloa levis* culms at different heights

I_h	Second moment of area, $I \times 10^6$ mm^4 (Internode wall of *Gigantochloa levis*)					
	Green			Air-dry		
	Min	Average	Max	Min	Average	Max
I_{0m}	3.45	6.80	14.83	2.76	5.94	12.71
I_{1m}	2.07	4.63	9.60	1.82	3.75	7.85
I_{2m}	1.63	3.76	8.41	1.55	3.14	6.85
I_{3m}	1.47	3.22	7.60	1.42	2.78	6.46
I_{4m}	1.24	2.81	6.46	1.18	2.44	5.36
I_{5m}	1.12	2.45	5.78	1.08	2.16	4.88
I_{6m}	0.92	1.96	5.02	0.84	1.79	4.58
I_{7m}	0.59	1.52	4.36	0.57	1.38	3.87
I_{8m}	0.30	1.12	3.73	0.24	1.03	3.44
I_{9m}	0.15	0.78	2.93	0.14	0.74	2.80

The values were based on the geometrical measurements of 30 culms of *Gigantochloa levis* of 100 mm nominal diameter at bottom-most internode

Conclusions

The study has generated tangible data concerning the geometric properties of *Gigantochloa levis* culms and has derived some important parameters for structural design. The average number of the internode sections within 9 m height was 24, with the shortest measured at 10 cm and the longest measured at 54 cm. The selection of culms for structural uses is best between the height of 1 to 5 m whereby the internodal length is more consistent. Plus, the diameter pattern along that specific height was remarkably steady. The taper rates were consistent from 1 to 5 m heights with values of 0.25 cm m^{-1} and below. The average percentage of diameter shrinkage was 2.7%, ranging from 0 to 8.3%.

The internode walls were thickest at the bottom and gradually thinner towards the top with an exponentially decreasing trend. Although there were some dissimilarities in the length of the internodal sections, the wall thickness was not influenced by the dimension. Also, the thickness irregularity around the circumference of the internode wall was minor. The average shrinkage of wall thickness was 6.1%. The percentages ranged from 0 to 21.2% with a very high probability of a lower shrinkage for below 10 mm thickness. Lastly, the reference values of the second moment of area were derived whereby the geometric properties of *G. levis* culms shall be validated.

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*Corresponding author; email: mohdjamil@frim.gov.my