IJIE

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 5 (2026) 118-127
https://publisher.uthm.edu.my/ojs/index.php/ijie

# Parallel Bending Strength Characterization of Malaysian *Bambusa Vulgaris* Bamboo Culms

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DOI: https://doi.org/10.30880/ijie.2026.18.05.011

**Article Info**

Received: 24 August 2025
Accepted: 15 June 2026
Available online: 15 July 2026

**Keywords**

Flexural test, bending strength, Bambusa vulgaris, physical bamboo culms, correlation analysis

**Abstract**

Bamboo has been utilized for decades due to its versatility and environmental benefits, making it increasingly significant in addressing modern sustainability challenges. Despite Bambusa vulgaris being one of the best bamboo species globally, limited research has been conducted on its natural form, particularly regarding its physical and mechanical properties. Most studies focus on engineered bamboo products, while natural bamboo's characteristics remain underexplored. This study focuses on analysing Bambusa vulgaris sourced from the northern and middle regions of Malaysia and assessing its suitability for structural use through 4-point bending tests conducted on 85 treated samples in accordance with ISO 22157. Specimens were tested across three sections along the culm length (top, middle, bottom) to investigate variations in mechanical and physical properties. The study found that Bambusa vulgaris exhibits significant variations in physical and mechanical properties across regions and culm sections. The bottom section had the largest diameter and thickest walls, while the top was the smallest, with both regions showing moisture content below 12%. Mechanical testing indicated that BVB outperformed BVK in bending moment, strength, and stiffness, with both showing similar failure modes of longitudinal and transverse cracks. Positive correlations between diameter and ultimate strength, as well as bending stiffness and linear mass, highlight its potential as a sustainable structural material in Malaysia.

## 1. Introduction

For thousands of years, bamboo has been utilised in human history and industry due to its great versatility. In a world where environmental issues are being addressed and the need for sustainable solutions is growing, the significance of these solutions has increased. It is now well known for its strength, rapid growth, and wide range of applications. *Bambusa vulgaris*, commonly referred to as "Buluh Minyak", is a prominent and widely recognised bamboo species within the *Poaceae* family. *Bambusa vulgaris* is found in Southeast Asia, particularly in Indonesia, Malaysia, the Philippines, and other Indo-Pacific countries. When it comes to construction, bamboo is well known for its strength, flexibility, and durability. It is lightweight, but it can hold heavy loads. Bamboo has high tensile strength, which makes it useful for building columns and beams. According to Adier et al. [1], unlike many other trees used in building, *Bambusa vulgaris* grows rapidly and reaches maturity in three to five years rather than decades. This makes bamboo a sustainable, easily accessible resource. Madhura et al. [2] stated that *Bambusa vulgaris* is an efficient load-bearing structure without being overly bulky, owing to its remarkable strength relative to its weight. The test methods and characterisation of physical and mechanical properties of Bambusa vulgaris are currently being set to follow the international standard ISO 22157 Bamboo structures - Determination of physical and mechanical properties of bamboo culms – Test methods and ISO 19624 Bamboo structures – Grading of bamboo culms – Basic principles and procedures. Using these essential elements, ISO 19624 defines grading procedures for mechanically and visually sorting round (pole) bamboo for structural applications. According to Meiling et al. [3], bamboo has mechanical and physical characteristics that are on par with or superior to those of wood, and it has significant potential for use in composite materials. Awalluddin et al. [4] investigated the tensile and shear strengths of four species of treated bamboo that are available in Malaysia, namely *Bambusa vulgaris, Dendrocalamus asper, Gigantochloa scortechinii, and Shizostachyum grande*. The results indicate that *Gigantochloa scortechinii* exhibits the highest shear strength value when compared to the other species, while *Bambusa vulgaris* and *Dendrocalamus asper* have the highest tensile strengths. Further information is still needed to determine and compare the bending strength of *Bambusa vulgaris* with other bamboo species available in Malaysia.

Physically, *Bambusa vulgaris* ranges in density from 500 to 860 kg/m$^3$, which is lower than that of traditional timber [5]. Its low weight makes it an effective material where weight reduction is crucial, like in building and furniture manufacturing. According to Awalluddin et al. [6], *Bambusa vulgaris* exhibits an exceptional strength-to-weight ratio, surpassing that of certain steel varieties. This feature allows it to be applied in situations where structures must have a high strength and minimal dead load. Depending on their native habitat, *Bambusa vulgaris* can have remarkably distinct mechanical and physical properties. Even though the species is the same, its characteristics may vary because it originates from different regions with distinct rainfall patterns. These variations in rainfall can lead to different soil compositions, which may affect the bamboo's growth. Sá Ribeiro et al. [7] inferred that location does not significantly affect the average density of bamboo culms; nonetheless, they determined that the bottom culm was more effective at supporting greater loads, as it sustains more weight than both the middle and top culms. Apparently, this finding was contradicted by Adam & Jusoh [8], who reported that the top culm has a greater Modulus of Rupture (MOR) than the middle and lower culms, indicating that culm strength increases with elevation. Therefore, further investigation at various locations along the culm length is necessary to ascertain the impact of bamboo strength. Another study conducted by Sulaiman et al. [9] has demonstrated the different quality of mature (more than three years) and young bamboo (less than three years) culms of *Bambusa vulgaris* and *Schizostachyum brachycladum*, in which the mature culms exhibit high strength as they are less hygroscopic. However, the former species had a lower strength bound than the latter.

Gumbe [10] investigated the tensile, bending, and compressive strengths of *Bambusa vulgaris.* The research found that the presence of nodes significantly reduced tensile and bending strengths but had minimal effect on compressive strength. The study concluded that *Bambusa vulgaris* exhibits promising mechanical properties for engineering applications. Additionally, Onche et al. [11] examined the compressive deformation of *Bambusa vulgaris* in the middle section. The research elucidated deformation mechanisms through in situ observations, revealing that compressive deformation leads to progressive micro-buckling and kink band formation. The onset of micro-buckling was well predicted by the Euler buckling model, and the critical loads for failure in the transverse orientation were consistent with conditions for shear yielding in the ply with fibres oriented orthogonally to the loading axis. Although studies on Bambusa Vulgaris characterisation have been on the rise, limited knowledge was found to infer the characteristics of Bambusa Vulgaris in terms of its physical and bending strength, and the correlation between these parameters across different locations along the culm length, as well as across resources from different regions. Hence, the objectives of this study are to determine the physical characteristics and the bending strength of *Bambusa vulgaris* and to define the correlation of the physical and mechanical strength of *Bambusa vulgaris*. The discussion was centred on the effect of different locations along the culm length and the different regions. This study, which focused on the physical and bending strength of *Bambusa vulgaris,* was limited to a specific bamboo species from two regions in Malaysia. Ideally, this study, with significant economic and environmental implications, is essential for understanding the characteristics and structure of bamboo species, especially for their potential use in designed constructions in rapidly developing countries.

## 2. Methods

The method for testing bending strength parallel to the bamboo fibre was carried out in accordance with ISO 22157:2019, which stipulated estimating the bending modulus of elasticity parallel to the bamboo fibre and determining the moisture content of the bamboo sample using the oven-dry method. A total of 44 *Bambusa vulgaris* samples from the middle region (Sungai Tua - BVK) and 41 *Bambusa vulgaris* samples from the north

(Teluk Bakong - BVB) were utilised in this study to assess the physical and mechanical properties of *Bambusa vulgaris* parallel to the bamboo fibre using a 4-point bending test machine, as shown in Fig. 1. The treated bamboo samples were stored in a container and kept free from contact with the soil in the laboratory. During the regrading process, the sections of the bamboo were marked and cut to length from the support to support of the bamboo specimen, with a minimum of 30 diameters (30D) and an additional 500 mm. The bamboo specimens were cut to obtain 15 culms from the top, middle, and bottom sections. Each bamboo sample was measured for its diameter and wall thickness at both the bottom and top parts of the bamboo culm. The mass of the bamboo was measured and recorded. The bamboo was then inserted into the flexural apparatus, a 4-point bending test machine, with a load application time of (300 ± 120) seconds and a loading rate of 0.5 mm/s. The bending test was conducted until the bamboo sample reached the failure point, after which the bending test output data were recorded before discarding the sample. The disturbed bamboo samples were then subjected to a moisture content process. The acquired samples were measured with a moisture meter and by the oven-dry method to determine the bamboo's moisture content. For the oven-dry method, the bamboo sample that had undergone the bending test was cut into 25 mm x 25 mm sections, weighed to determine its initial mass, and then placed in a 105°C oven for 24 hours. After 24 hours of drying in the oven, the specimen was removed and weighed again to determine its mass.

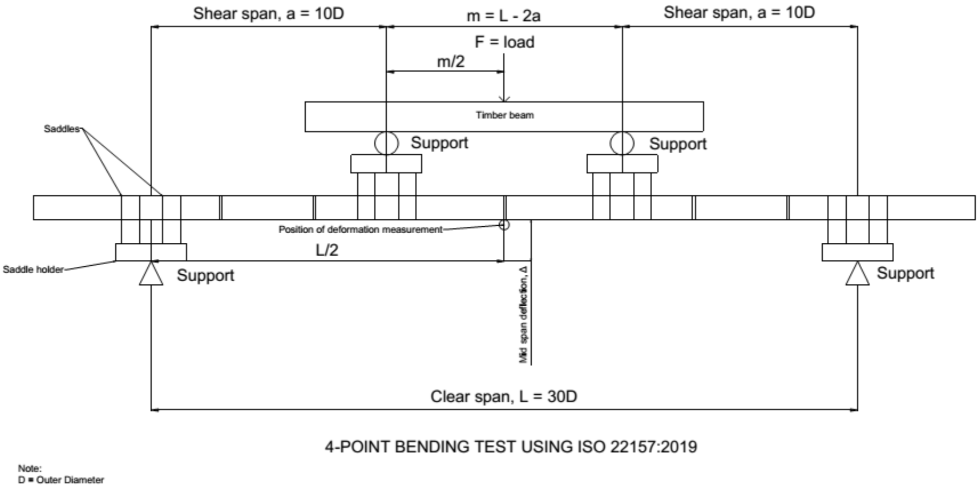



**Fig. 1** *Four-point bending test schematic diagram*

Equations and expressions to determine the mechanical properties of *Bambusa vulgaris* for both regions in accordance with ISO 22157:2019 are as follows:

$$M_{ult} = \frac{F_{ult} \times a}{2} \tag{1}$$

where $M_{ult}$ is the ultimate bending moment, $F_{ult}$ is the maximum applied load (the total load applied to both load points, in N), and a is the shear span, in mm.

$$F_{m,0} = \frac{(M_{ult} \times D)}{(2 \times I_b)} \tag{2}$$

where $F_{m,0}$ is the bending strength parallel to fibres, $M_{ult}$ is the ultimate bending moment, in Nmm, $D$ is the outer diameter nearest point of failure, in mm, and $I_b$ is the second moment of area, in mm$^4$.

$$E_{m,0} = \frac{[(F_{60} - F_{20}) \times a(3L^2 - 4a^2)]}{[48(d_{60} - d_{20})] \times I_b} \tag{3}$$

where $E_{m,0}$ is the modulus of elasticity, $F_{20}$ and $F_{60}$ are the applied loads in N at 20% and 60% of $F_{ult}$, $d_{20}$ and $d_{60}$ are the deflections at mid-span, in mm at 20% and 60% of $F_{ult}$, $L$ is the the overall length, in mm, $A$ is the shear span length, in mm, and $I_b$ is the second moment of area, in mm$^4$.

$$MC = \frac{(m - m_0)}{m_0}\ x\ 100 \tag{4}$$

where $MC$ is the moisture content, m is the mass of the specimen before drying (Initial weight), in g, and $m_0$ is the mass of the specimen after drying (final weight), in g.

$$\rho = \frac{m_0}{V_0} \tag{5}$$

where $\rho$ is the basic density, $m_0$ is the mass of the specimen after drying (final weight), in g, and $V_0$ is the volume of the specimen, in $mm^3$.

## 3. Results and Discussions

The *Bambusa vulgaris* specimens were collected from the northern and central regions of Malaysia. The samples of *Bambusa vulgaris* from the middle region of Sungai Tua and the north region of Teluk Bakong will now be referred to as BVK and BVB, respectively. Despite the samples being of the same species, the results indicate considerable differences in diameter, wall thickness, moisture content, density, ultimate bending moment, bending strength, and Modulus of Elasticity (MOE) between the two regions.

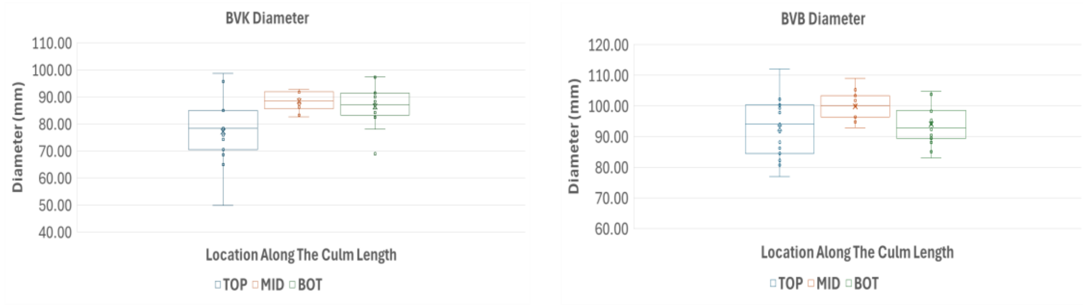
### 3.1 Physical Properties

A total of 44 BVK and 41 BVB samples were regraded for their physical properties in accordance with ISO 19624:2018. The geometric and physical properties, including the mean, standard deviation, and coefficient of variation (COV), are summarised in Table 1. For BVK, the average diameters at the top, middle, and bottom sections were 77.20 mm, 88.44 mm, and 86.44 mm, respectively. In contrast, the BVB had average diameters of 92.84 mm, 99.85 mm, and 94.04 mm for the top, middle, and bottom sections, respectively. A noticeable tapering pattern is observed between the bottom and middle sections, while the difference in diameter between the top and middle sections is more pronounced. However, because the variation is too small to produce a significant taper in alignment, the bamboo's straightness is primarily perceived in the transition from the middle to the bottom section. This observation holds even though, for both regions, the bottom section, as expected, exhibits a greater diameter than the top section. Regarding wall thickness, the average values for the top, middle, and bottom sections of BVK were 7.11 mm, 8.97 mm, and 10.55 mm, respectively. For BVB, the corresponding wall thicknesses were 8.06 mm, 8.94 mm, and 8.53 mm. While the middle section of BVB was slightly thicker than the top and bottom sections, the difference between the middle and bottom sections is not substantial enough to create an effective tapered alignment in wall thickness.

**Table 1** *Geometric and physical properties of Bambusa vulgaris*

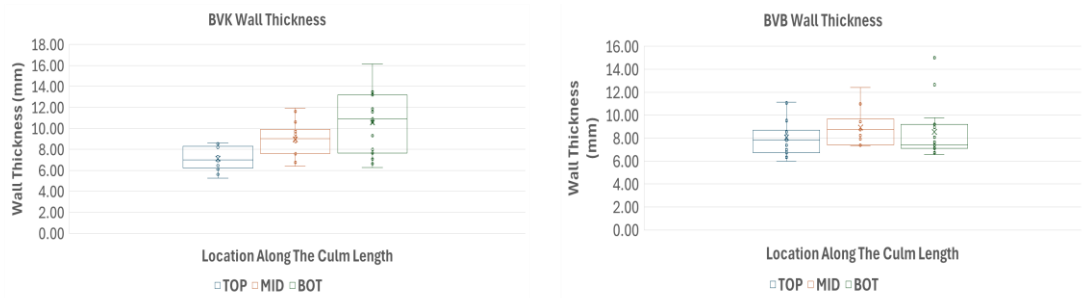
| Geometric/Physical properties | Species | Sample size (n) | Location along the culm length | Mean | Std. dev | COV (100%) |
|---|---|---|---|---|---|---|
| Diameter, D (mm) | BVK | 44 | Top | 77.20 | 11.90 | 15.42 |
| | | | Middle | 88.44 | 3.59 | 4.06 |
| | | | Bottom | 86.44 | 7.18 | 8.31 |
| | BVB | 41 | Top | 92.84 | 9.71 | 10.46 |
| | | | Middle | 99.85 | 4.81 | 4.82 |
| | | | Bottom | 94.04 | 6.72 | 7.14 |
| Wall thickness, t (mm) | BVK | 44 | Top | 7.11 | 1.08 | 15.26 |
| | | | Middle | 8.97 | 1.68 | 18.72 |
| | | | Bottom | 10.55 | 2.97 | 28.15 |
| | BVB | 41 | Top | 8.06 | 1.58 | 19.61 |
| | | | Middle | 8.94 | 1.61 | 18.01 |
| | | | Bottom | 8.53 | 2.39 | 27.97 |

Based on Fig. 2, the diameter of the bamboo varied along its length, with the top section having the smallest overall diameter and the bottom section the largest. The diameter of both bamboo regions gradually decreased from bottom to top, with no sudden changes. This gradual tapering allowed the strength and flexibility of the bamboo culm to transition smoothly along its length. Similarly, the wall thickness of the bamboo culm decreased progressively from the bottom to the top. In Fig. 3, the middle section of the BVB was nearly as thick as the bottom section of the bamboo's wall. However, the results for BVK indicated that the bottom section of the bamboo was thicker than both the top and middle sections.




**(a)** **(b)**

**Fig. 2** *(a) Diameter of the middle region Bambusa vulgaris (BVK); and (b) Diameter of the north region Bambusa vulgaris (BVB)*




**(a)** **(b)**

**Fig. 3** *(a) Wall thickness of the middle region Bambusa vulgaris (BVK); and (b) Wall thickness of the north region Bambusa vulgaris (BVB)*

According to Table 2, the average moisture content percentages for BVK and BVB, as determined by the moisture meter, were 19.71% and 16.30%, respectively. Using the oven-dry method, the average moisture content percentages for BVB and BVK were 11.38% and 11.35%, respectively. This showed that the moisture content percentage measured with a moisture meter was higher than that of the oven-dry method. Moisture meters often overestimate MC compared to the oven-dry method. A correction factor is usually needed when using electrical moisture meters. In contrast, the oven-dry method was highly accurate compared to the moisture meter, with values evidently close to MC 12%. Typically, dry bamboo is set to an MC of 12%, ensuring a controlled drying process and minimising internal stress and cracking [12]. Dry bamboo (≤12% MC) is less attractive to pests, reducing the risk of biological degradation.

**Table 2** *Moisture content for both Bambusa vulgaris regions*

| Species | Sample size (n) | Moisture content (moisture meter) | Moisture content (Oven-dry method) |
|---|---|---|---|
| BVK | 44 | 19.71% | 11.35% |
| BVB | 41 | 16.30% | 11.38% |

Table 3 showed that BVK had the highest average density, at 252.08 kg/m$^3$, compared to BVB, at 228.19 kg/m$^3$. Due to its thicker wall or diameter, denser bamboo was typically stronger and more resistant to bending, but it might not have been as flexible as it could have been. A potential reason for this was that the bamboo culm was not uniform throughout, and it might have concentrated on strengthening the lower sections that were most important for long-term stability and support. This resulted in a denser bottom section that served as the structural support for the entire bamboo structure.

**Table 3** *Density of both Bambusa vulgaris regions*

| Geometric/Physical properties | Species | Sample size (n) | Average |
|---|---|---|---|
| Density (kg/m$^3$) | BVK | 44 | 252.08 |
| | BVB | 41 | 228.19 |

## 3.2 Mechanical Properties

Table 4 provides a summary of the mechanical properties of Bambusa vulgaris based on the experimental results. It presented the average test conditions, including temperature and relative humidity, for both BVK and BVB species samples, along with the mean, standard deviation, and coefficient of variation (COV). When comparing BVK and BVB, the average ultimate bending moment was 2045.88 kNmm, with a standard deviation of 1032.86 kNmm and a COV of 50.48%, while BVB had an average ultimate bending moment of 2755.93 kNmm, with a standard deviation of 1031.42 kNmm and a COV of 37.43%. The average bending strength of BVK was 54.25 $N/mm^2$, with a standard deviation of 14.77 $N/mm^2$ and a COV of 27.23%, whereas the average bending strength of BVB was 59.12 $N/mm^2$, with a standard deviation of 13.53 $N/mm^2$ and a COV of 22.89%. However, these values were lower than those of Gigantochloa scortechinii [13]. BVK had an average tangent bending stiffness of 3.85 × $10^{10}$ $Nmm^2$, with a standard deviation of 2.06 × $10^{10}$ $Nmm^2$ and a COV of 53.37%, while BVB had an average tangent bending stiffness of 5.12 × $10^{10}$ $Nmm^2$, with a standard deviation of 1.93 × $10^{10}$ $Nmm^2$ and a COV of 37.84%. Lastly, the average Modulus of Elasticity for BVB was 23.06 $kN/mm^2$, with a standard deviation of 4.88 $kN/mm^2$ and a COV of 21.15%, compared to 24.05 $kN/mm^2$ for BVK, with a standard deviation of 5.65 $kN/mm^2$ and a COV of 23.51%. The test conditions for the Bambusa vulgaris samples averaged 27 ± 5°C in temperature and 65 ± 5% in relative humidity. Based on these reported results, it can be deduced that the consistent values of diameter and wall thickness in BVB do not necessarily indicate superior bending capacity. It is believed that the bending strength of both regions was comparable.

**Table 4** *Mechanical properties of Bambusa vulgaris*

| Mechanical properties | Species | Sample size (n) | Mean | Std. dev | COV (100%) | Temperature (°C) | Relative humidity (%) |
|---|---|---|---|---|---|---|---|
| Ultimate bending moment (kNmm) | BVK | 44 | 2045.88 | 1032.86 | 50.48 | 27± 5 | 65± 5 |
| | BVB | 41 | 2755.93 | 1031.42 | 37.43 | | |
| Bending strength ($N/mm^2$) | BVK | 44 | 54.25 | 14.77 | 27.23 | 27± 5 | 65± 5 |
| | BVB | 41 | 59.12 | 13.53 | 22.89 | | |
| Tangent bending stiffness ($N/mm^2$) | BVK | 44 | 3.85E+10 | 2.06E+10 | 57.37 | 27± 5 | 65± 5 |
| | BVB | 41 | 5.12E+10 | 1.93E+10 | 37.84 | | |
| Modulus of elasticity ($kN/mm^2$) | BVK | 44 | 24.05 | 5.65 | 23.51 | 27± 5 | 65± 5 |
| | BVB | 41 | 23.06 | 4.88 | 21.15 | | |

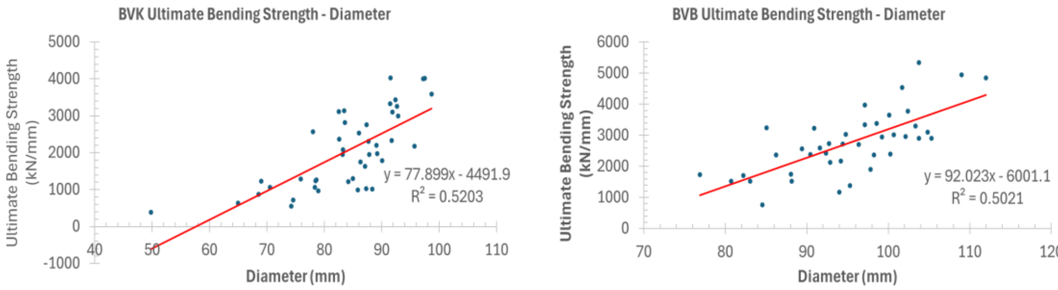
As shown in Fig. 4, the bamboo's failure modes were divided into two categories: longitudinal and transverse cracks. Bamboo fibres were extremely strong in tension along their length, but when bending forces were applied parallel to the bamboo fibres, they were more likely to split or crack. The lignin bonds that held the bamboo together may have been stressed by the load acting parallel to the fibres, causing longitudinal cracks to form and radiate along the length of the fibres. A crack's ability to propagate quickly along the bamboo's thin lignin layer between the fibres increased the extent of the split. The failure mode observed in both BVK and BVB appeared to be the same, with several transverse cracks interspersed among the predominant longitudinal cracks. Most of the longitudinal cracks developed beneath the two bending points where the bamboo was compressed when positioned parallel. In this test, transverse cracks were less common than longitudinal cracks, but they occurred when the bamboo reached its point of failure. While the longitudinal cracks travelled across the entire length of the culm, the transverse cracks spread throughout the bamboo fibres. The weak lignin layer between the fibres facilitated crack propagation, increasing splitting and reducing the bamboo's strength.

(a) (b) (c)

**Fig. 4** *Failure mode under compression (a); and (b) Longitudinal cracks; and (c) Transverse cracks*

## 3.3 Correlation of Physical and Mechanical Strength

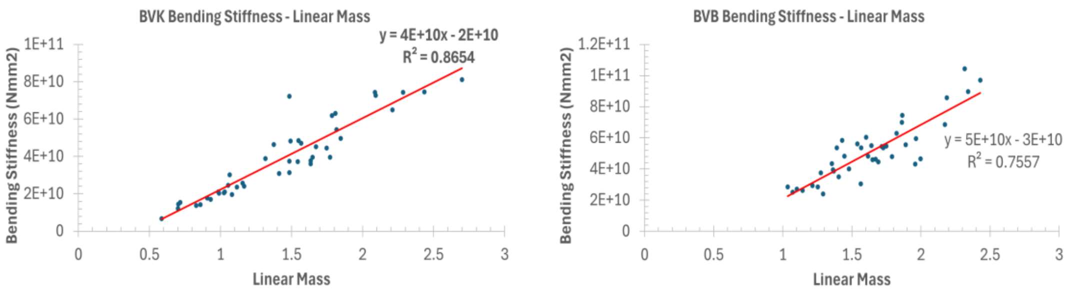
Fig. 5 illustrates the correlation between the external diameter and ultimate bending strength. It was found that BVK and BVB had a moderate relationship ($R^2$ = 0.5203 and $R^2$ = 0.5021, respectively), and that BVB had an acceptable coefficient of determination. Both bamboo species exhibit coefficients of determination greater than 0.5, making them suitable for acceptance in the explanation of bamboo behaviour in the current research's analysis. The ultimate bending strength and diameter were positively correlated, indicating that the ultimate bending strength increases with increasing bamboo culm diameter.




(a) (b)

**Fig. 5** *(a) Correlation of BVK between ultimate bending strength and diameter; and (b) Correlation of BVB between ultimate bending strength and diameter*

Fig. 6 illustrates the relationship between linear mass and bending stiffness for the two bamboo regions, establishing the correlation of determination. A very strong correlation was observed between bending stiffness and linear mass for both BVK ($R^2$ = 0.8654) and BVB ($R^2$ = 0.7557). This correlation can be accepted as a relationship because the coefficient of determination is greater than 0.5. As a result, the bending stiffness of the bamboo culm increases along with its linear mass. It gives a stronger indication of the close relationship between Bambusa vulgaris's mechanical and physical properties in Malaysia.




(a) (b)

**Fig. 6** *(a) Correlation of BVK between bending stiffness and linear mass; and (b) Correlation of BVB between bending stiffness and linear mass*

## 3.4 Effect of Location Along the Culm Length

Since the characteristics of the bamboo changed with height, the effect of a bending force applied parallel to the grain on a bamboo culm varied with its position along the culm. Compared with the thinner top section of the bamboo, the bottom section of Bambusa vulgaris had thicker walls, providing greater resistance to bending forces and requiring more force to initiate a crack. Cracks occasionally formed, and the larger diameter and thicker walls were usually the cause. In contrast to cracks that formed on the thinner sections of the bamboo, these cracks extended farther along the culm. The thickness of the walls in the bamboo's middle section most likely fell between the thicknesses of the bottom and top sections. The middle section had a slightly thinner wall than the bottom section, making it more likely for a crack to form under bending. However, the likelihood of crack formation in the middle section was lower than in the top section. Among the different sections of the bamboo, the top section had the thinnest wall thickness and provided the least resistance to bending forces applied parallel to the bamboo fibre. As a result, moderate bending stresses increased the probability of cracks forming in this section. The thinner wall thickness indicated that any cracks forming in the top section were smaller and shallower. Since the bottom section of the bamboo had thicker walls than the top, it may have served as a barrier, preventing moisture from entering or moving within the bamboo culm, resulting in a lower moisture content than in the top section. The moisture content of the middle section fell between that of the top and bottom sections, whereas the top section had a higher moisture content due to its thinner wall. Due to the increased number of fibres distributing the bending force along the culm's length, the bottom section of the bamboo culm was denser and more resistant to bending forces applied parallel to the bamboo fibre. Conversely, since the bamboo culm's top section had the lowest density, it was less resistant to bending forces due to the lower concentration of bamboo fibres along the length of the culm. According to the test analysis, the average bending strength of the middle section of the bamboo, for both BVK and BVB, was higher than that of the top and bottom sections. As a result, it suggested that the bamboo's middle section was more resilient to bending deformation than its top and bottom sections.

## 3.5 Effect of Different Regions

The data obtained from testing the bending strength parallel to the bamboo fibre varied significantly due to the use of bamboo from different regions of Malaysia. Despite belonging to the same species, the results indicated that bamboo from different regions yielded different values. The variations in climate, rainfall, and geological conditions between the middle and northern regions might have contributed to these differences. Compared to Malaysia's middle region, the northern part of the country experienced slightly lower temperatures and more frequent rainfall. The colder temperatures in the north may have slowed the bamboo's growth rate, potentially resulting in a slightly denser culm. Additionally, since the northern region received more rainfall on average, bamboo from that region may have had a slightly higher moisture content than bamboo from the middle region. Each region had distinct soil types, which could have influenced bamboo characteristics. For example, some regions had more fertile soils, providing better overall growing conditions than those for bamboo grown in clayey or sandy coastal soils. Based on the test results, BVB outperformed BVK in average bending strength, indicating that BVB could withstand higher bending forces before failure. Although BVK and BVB originated from different regions and exhibited differences in strength, they shared the same failure mode: longitudinal and transverse cracks.

# 4. Conclusion

This study was conducted to determine the physical and mechanical properties of Bambusa vulgaris from two regions of Malaysia: the northern and middle regions. A total of 85 Bambusa vulgaris samples underwent bending tests using a 4-point bending test machine to achieve the objectives of this research study: determining the physical characteristics, determining the bending strength, and determining the correlation between the physical and mechanical characteristics of Bambusa vulgaris. The physical properties of Bambusa vulgaris revealed that the bottom section of the bamboo culm has the largest diameter and thickest wall, while the top section has the smallest diameter and thinnest wall, with the middle section falling between these extremes. Both BVK and BVB samples showed moisture content below 12%, classifying them as dry bamboo. The average densities of BVK and BVB were measured at 252.08 kg/m$^3$ and 228.19 kg/m$^3$, respectively. The average ultimate bending moment for BVK was 2045.88 kNmm (standard deviation: 1032.86 kNmm, COV: 50.48%), while BVB recorded 2755.93 kNmm (standard deviation: 1031.42 kNmm, COV: 37.43%). The average bending strength for BVK and BVB was 54.25 N/mm$^2$ (standard deviation: 14.77 N/mm$^2$, COV: 27.23%) and 59.12 N/mm$^2$ (standard deviation: 13.53 N/mm$^2$, COV: 22.89%), respectively. The tangent bending stiffness averaged $3.85\times10^{10}$ Nmm$^2$ for BVK (standard deviation: $2.06\times10^{10}$ Nmm$^2$, COV: 53.37%) and $5.12\times10^{10}$ Nmm$^2$ for BVB (standard deviation: $1.93\times10^{10}$ Nmm$^2$, COV: 37.84%). The Modulusof Elasticity was 24.05 kN/mm$^2$ for BVK (standard deviation: 5.65 kN/mm$^2$, COV: 23.51%) and 23.06 kN/mm$^2$ for BVB (standard deviation: 4.88 kN/mm$^2$, COV: 21.15%). Both BVK and BVB displayed similar failure modes, characterised by longitudinal and transverse cracks. The differences in bending strength between BVK and BVB could be attributed to the climatic and soil conditions of their respective growth regions rather than the controlled test environment. The northern region, where BVB originates, experiences lower temperatures and higher rainfall, which may have led to slower growth and denser bamboo culms. Denser bamboo generally has higher mechanical strength, explaining why BVB outperformed BVK in bending strength.

The correlation analysis of the physical and mechanical properties of Bambusa vulgaris revealed a significant positive relationship between diameter and ultimate strength for both BVK and BVB. Additionally, a strong positive correlation was observed between bending stiffness and linear mass for both regions. However, further analysis and work should be done to achieve impressive results, for example, the statistical comparison based on measured bending strength data at different sections along the culm length.

## Acknowledgement

Authors acknowledge the College of Engineering UiTM and Universiti Teknologi MARA for funding under the LESTARI SDGTriangle @ Triangle 2.0 Research Grant (600-RMC/LESTARI SDG-T5/3 (008/2021)) and AIDAQ for supplying research materials.

## Conflict of Interest

There is no conflict of interest regarding the publication of the paper.

## Author Contribution

*The authors confirm contribution to the paper as follows:* ***Study conception and design:*** *Mohd Khairul Kamarudin, Zakiah Ahmad;* ***Data collection:*** *Alvin Chin Hon Loong;* ***Analysis and interpretation of results:*** *Mohd Khairul Kamarudin, Yazmin Sahol Hamid, Hazrina Mansor;* ***Draft manuscript preparation:*** *Mohd Khairul Kamarudin, Alvin Chin Hon Loong, Khairul Anuar Shahid. All authors reviewed the results and approved the final version of the manuscript.*

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