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ORIGINAL ARTICLE

Assessment of physical and mechanical properties of juvenile and matured *Bambusa vulgaris* glue-laminated bamboo for structural applications in Ghana

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Abstract: This study assessed the properties of juvenile and matured glue-laminated bamboo for structural applications. Glue-laminated bamboo was produced from 2-year-old and 4-year-old culms of *Bambusa vulgaris* with a fast-curing polyurethane adhesive (Rapid Lion). The composites produced were assessed for their physical (moisture content, basic density, radial, longitudinal, tangential and volumetric shrinkage) and mechanical (modulus of rupture, modulus of elasticity and compressive strength parallel to grain) properties. The results show that the juvenile glue-laminated bamboo significantly shrinks about twice that of the matured glue-laminated bamboo with values of 6.32% for radial, 6.51% for tangential and 0.22% for longitudinal. It was further observed that the basic density of the matured glue-laminated bamboo was 810.56 kg/m ^{3}which is 14.56% higher than that of the juvenile glue-laminated bamboo. The juvenile glue-laminated bamboo had MOE of 5876 MPa; MOR of 43.42 MPa and compressive strength of 37.58 MPa whilst that of the matured glue-laminated bamboo recorded MOE of 13379 MPa; MOR of 82.48 MPa and compressive strength of 62.78 MPa. The matured bamboo laminates had better physical and mechanical properties than that of the juvenile bamboo laminates. It is recommended that matured *Bambusa vulgaris* can be used as an engineered composite material for structural applications.

Keywords: Glue-laminated bamboo; juvenile bamboo; matured bamboo; physical properties; mechanical properties

1 Introduction

The growing need for timber and timber products has increased significantly as a result of the increasing world population. This has necessitated the call for researchers to intensify their quest for finding alternative raw materials suitable to replace timber in order to reduce the over-dependence on timber and thereby help to preserve the forest cover. One such alternative material that is currently gaining attention globally is bamboo. Bamboo is widely recognized as an alternative material for replacing wood due to its excellent strength properties. Additionally, it is available, inexpensive to acquire, environmentally friendly, meets existing processing technologies and possesses physical and mechanical properties that are comparable to wood [1]. Furthermore, bamboo is a fast-growing and can attain its maximum height in about 5-6 months, and matures in 3 to 5 years compared to most timber species that mature in 10 - 50 years [2-5]. Bamboo is a woody plant that has a history of being versatile and widely utilized resource in the world [6-8]. About 2.5 billion people are estimated to be using bamboo in one form or other worldwide for their basic needs [9-11]. Technology advancement has

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further enhanced bamboo utilization potential and it has been established that nearly 4,000 commercial products manufactured from bamboo are in daily use across the world [12]. Commercial products produced from bamboo include containers, chopsticks, woven mats, handicrafts, fishing rods and traps, walking sticks, flutes, packing cases for teas and fruits, pipes for water supply and irrigation, cages for poultry, cart yokes, cradles, ladders, winnows and sieving for cleaning grains and bullock carts [13].

The efficient utilization of the full bamboo culm is usually confronted with challenges, especially where flat surfaces are required for building and furniture applications. Additionally, its hollow and cylindrical nature makes it difficult in constructing suitable joints for structural applications. These limitations have further affected its acceptability as raw material for construction especially in developing countries as it is used as props in construction sites to support form works [14-15]. However, technological advancement has helped to transform the full culm bamboo into engineered bamboo composites (EBC) to meet the demand for sustainable construction and furniture production. There are several engineered bamboo products such as bamboo scrimber, strand woven bamboo, bamboo ply and glue-laminated bamboo which have been studied and proven to have properties comparable to other materials such as timber [16]. The two most preferred engineered bamboo composites are scrimber and glue-laminated bamboo [17]. According to Sharma et al. [17], engineered bamboo composites are of particular interest due to the standardization of size and shape, and the relatively low variability in the properties of the material. Glue-laminated bamboo is made of bamboo strips glued and pressed together into beams or panels. Glue-laminated bamboo is the modern method of improving the durability of bamboo for structural purposes. Xiao and Li [18] reported that glued laminated and bamboo-based panels are two types that can be utilized in modern bamboo construction. Sharma et al. [19] also reported that glue-laminated bamboo possessed mechanical properties that are suitable for structural applications. Furthermore, their study concluded that the glue-laminated bamboo properties could be compared with or surpassed that of timber.

Ghana has about 400,000 hectares of bamboo cover and is made up of seven (7) indigenous species and of which *Bambusa vulgaris* forms about 90-95% of the total bamboo resources in Ghana [20]. *Bambusa vulgaris* is an important material for the construction industry in Ghana due to its availability, low cost, and ease of transport. Additionally, the high cost of building materials and the non-availability of timber have further increased the demand for bamboo. This has resulted in both juvenile and matured culms being used in the construction industry. The danger of this phenomenon has created a lot of anxiety among the industry players due to the lack of adequate information about the differences in properties between the matured and juvenile *Bambusa vulgaris.* Studies have shown that there are gaps in knowledge of bamboo properties [21-22]. Liese [23] reported that a thorough understanding of the relations between structures, properties, behaviour in processing and product qualities is necessary for promoting bamboo and its utilization. Wang et al. [24] also reported that the promotion of widespread use of bamboo in construction and other engineering applications, depends largely on knowledge and understanding of its properties. It is against this backdrop that this study seeks to determine the differences between the physical and mechanical properties of juvenile and matured glue-laminated bamboo composites and evaluate their utilization potentials in structural applications. In this study, glue-laminated bamboo was made using *Bambusa vulgaris*.

2 Materials and Methods

2.1 Materials

2.1.1 *Bambusa vulgaris* culms

Bambusa vulgaris were used to produce the laminated bamboo boards. The *Bambusa vulgaris* culms used for this study were obtained from clumps in Bibiani in the Western North Region of Ghana. Bibiani is located between latitude 6 ° N, 3 ° N and longitude 2 ° W, 3 ° W. Bibiani falls within the Equatorial Rain Forest Zone and the natural vegetation is moist-deciduous forest with an annual rainfall averaging between 1200 mm and 1500 mm. The pattern of the rainfall is bimodal, falling between March-August and September-October. Humidity is relatively high averaging between 75 percent in the afternoon and 95 percent in the nights and early mornings. The culm age was determined based on the culm sheath features, the external colour of the culm and the development of branches and leaves.

Bambusa vulgaris culms of 2-years and 4-years old were randomly selected based on its straightness and culm diameter before harvesting for the study. Ten (10) culms each were selected from two (2) clumps. In all, twenty (20) *Bambusa vulgaris* culms were harvested for the study of which ten (10) were juvenile culms and the other ten (10) were matured culms. The culms were cut 30 cm above the ground level and were coated with wax immediately to reduce sap evaporation and to prevent insect and fungal attacks. The culms were sent to Alhaji Wood Workshop at Bibiani for further processing into strips. Each culm for both juvenile and matured was cut to a twenty-one internodes height. The culms were later sub-divided into three equal lengths of bottom, middle and top portions of 7 internodes each. The study only focused on the bottom portion of the culms which were grouped according to their age before processing into strips. In all, 8-10 strips were produced per each culm totalling approximately between 90-100 strips on average for both juvenile and matured culms respectively. The strips were air-dried at room temperature for 14 days.

2.1.2 Production of Glue-Laminated Bamboo

Sixteen (16) strips of the bamboo were randomly selected and were prepared for the production of the glue-laminated bamboo. The strips were edged and trimmed to 93 cm × 3 cm × culm thickness (length x width x thickness) before the inner and outer surfaces (wax and cortex) of the strips were removed through sanding. A Hitachi SP 18 VA portable sanding machine with Velcro paper grit: P80 was used.

The sanded strips were glued together using the “Rapid Lion Express” wood adhesive. Two strips were glued and clamped together at a time before glueing them together to achieve the required dimension. The pressing pressure was 10 MPa with a pressing time of 30 minutes. The glue-laminated bamboo produced measured 90 cm × 7.5 cm × 7.5 cm (length × width × thickness). Each of the glue-laminated bamboo produced was clamped together using a cold-press method to ensure proper penetration of the adhesive and a strong bonding formation as well. Six (6) replicates were produced in all, 3 for juvenile and the other 3 for matured. **Fig.1** shows the glue-laminated bamboo manufacturing process.

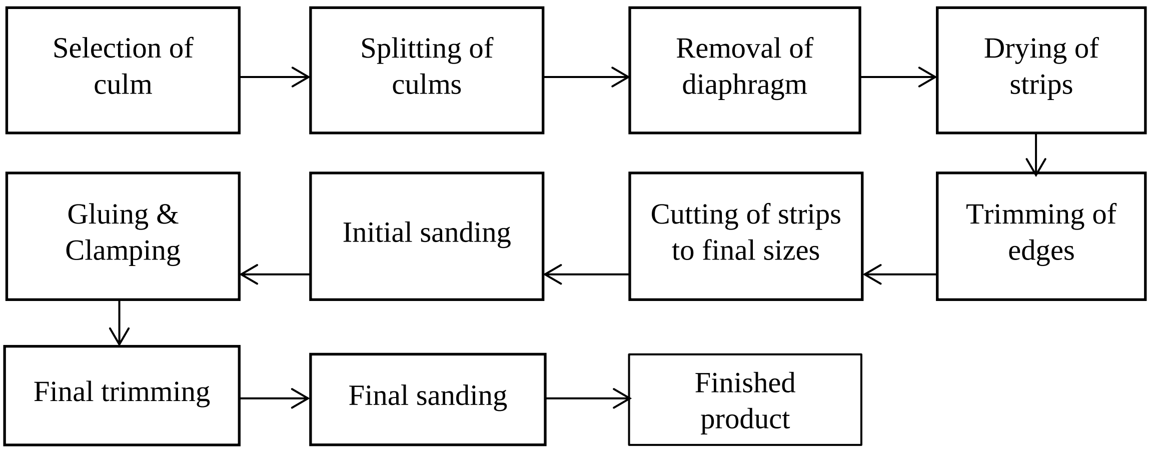


Fig. 1 Manufacturing flow chart of glue-laminated bamboo

2.1.3 Polyurethane adhesive

A fast-curing liquid polyurethane adhesive with the trade name “Rapid Lion Express Marine adhesive” was used for the lamination. It conformed to D4 according to DIN EN 204 [25] with a density of 1.10 g/mL, a viscosity of 3000 cp, and an application rate of approximately 150 mL/m^2.

2.2 Methods

2.2.1 Determination of Physical properties

Samples for determining the physical properties were prepared at the Wood and Furniture Testing Centre of the Forestry Research Institute of Ghana. The physical properties determined included moisture content, basic density and shrinkage (longitudinal, tangential, radial and volumetric).

1) Moisture Content

The moisture content (MC) of the matured and juvenile glue-laminated bamboo was determined in accordance with EN 13183-1 [26]. 10 samples for each group having a sample size of 20 mm × 20 mm × 20 mm. The initial weight (W_1) of each sample was determined using an electronic weighing balance before drying. The test samples were then oven-dried for 24 hours at a temperature of 103 ± 2 ℃. Further drying was done until the weight of the samples became constant after two successive weighings. The oven-dried weight or final weight (W_2) of each specimen was recorded and the MC was calculated using Eq. (1):

$$Moisture\ Content\ (\%) = \frac{W_1 - W_2}{W_2} \times 100 \quad (1)$$

2) Basic Density

The basic density of the matured and juvenile glue-laminated bamboo was determined in accordance with BS 373 [27]. 10 samples for each group having a dimension of 20 mm × 20 mm × 20 mm were used. The initial weight for each sample was determined using an electronic balance. The samples were oven-dried for 24 hours at a temperature of 103 ± 2 ℃ until a constant weight was attained. The test sample weight was determined using an electronics balance. The basic density was calculated using Eq. (2):

$$Basic\ density\ \left(\frac{kg}{m^3}\right) = Mass/Volume \quad (2)$$

3) Shrinkage

The Radial, Tangential and Longitudinal shrinkage of the matured and juvenile glue-laminated bamboo were determined using the procedure adopted by Dinwoodie [28]. Ten (10) samples for each group having a dimension of 20 mm x 20 mm x 20 mm were used. The samples were labelled as 'R', 'T' and 'L' for radial, tangential and longitudinal planes respectively. The initial dimensions (D_1) of the samples were measured using a digital caliper. They were then oven-dried at a temperature of 103 ± 2 ^{o}C until attaining constant weight, after which the final dimensions (D_2) in the radial, tangential and longitudinal directions were measured. The percentage shrinkage (S_h) for each dimension was calculated using Eq. (3):

$$Shrinkage\ (\%) = \frac{D_1 - D_2}{D_1} \times 100 \quad (3)$$

Where: D_1 is the initial dimension before oven-dried (mm); D_2 is the final dimension after oven-dried (mm).

Furthermore, the volumetric shrinkage (V_S) was estimated using the procedure adopted by Dinwoodie [28] as indicated in Eq. (4):

$$Volumetric\ Shrinkage\ (V_S) = SR + ST + SL \quad (4)$$

Where: *SR* is the radial shrinkage; *ST* is the tangential shrinkage; *SL* is the longitudinal shrinkage.

2.2.2 Determination of mechanical properties

The modulus of rupture, modulus of elasticity and compressive strength parallel to the grain of the glue-laminated bamboo were determined in accordance with BS 373 [27]. The bending and compression tests were conducted using an Instron universal testing machine (Instron Model 4482, Norwood, MA, USA) with a maximum load of 100 KN and an accuracy of 0.01%. All the samples were stored under controlled conditions of 65% relative humidity (RH) and a temperature of 20 ℃ for 24 hours before the testing.

1) Modulus of rupture and modulus of elasticity

Static bending test for both juvenile and matured glue-laminated bamboo was conducted. Ten (10) samples each measuring 20 mm×20 mm×300 mm were prepared for the bending test. The load was applied at the centre of a 250 mm span with a displacement rate of 6.6 mm/min.

2) Compressive Strength Parallel to Grain

From the juvenile and matured glue-laminated bamboo, 10 samples each measuring 20 mm × 20 mm × 60 mm were prepared for the compressive strength parallel to the grain. The continuous compression load with a displacement rate of 0.6 mm/min was applied until the deformation of the sample was reached.

3 Results and Discussions

3.1 Physical Properties

3.1.1 Moisture Content

Fig. 2 indicates the moisture content (MC) of the matured and juvenile *Bambusa vulgaris* glue-laminated bamboo. The juvenile glue-laminated bamboo comparatively had a higher MC (16.3%) than the matured glue-laminated bamboo which was 12.4%.

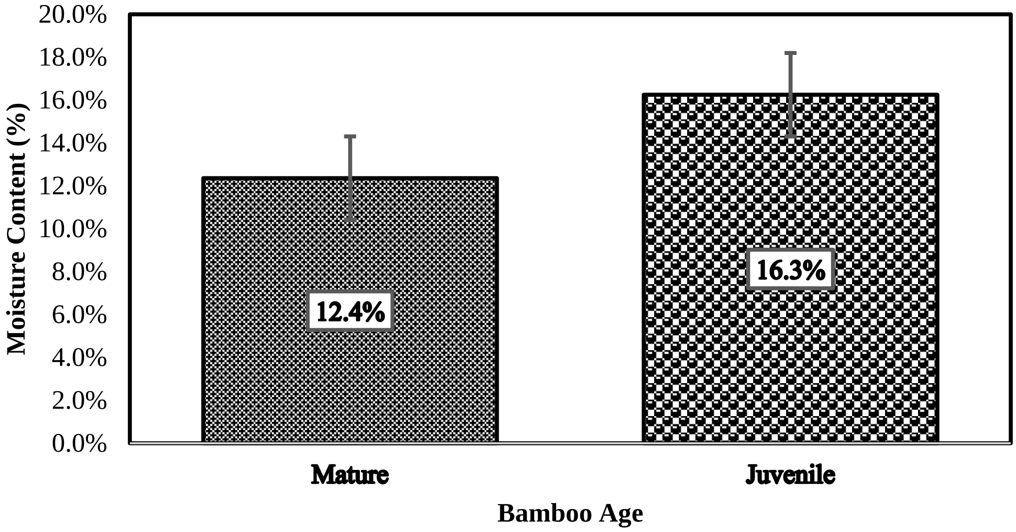


Fig. 2 Moisture content of glue-laminated bamboo; N=10

The results show that the age difference contributed to the variations in MC. Razak et al. [29] indicated that bamboo age has an influence on its moisture content. Results of this study also show that the MC decreases as the bamboo matures as indicated in **Fig. 2** The difference in MC could be as a result of the high presence of parenchyma cells found in *Bambusa vulgaris* [30]. A study by Awotwe-Mensah [31] revealed that juvenile bamboo contained higher parenchyma cells than the matured bamboo. The high amount of parenchyma cells tends to influence the MC since it serves as water storage for the bamboo plant and therefore, the higher the parenchyma cells the more water it contains.

The lower MC of the matured glue-laminated bamboo could enhance its mechanical properties. Xu et al. [32] reported that compressive strength decreased with increasing moisture content in the bamboo. The lower moisture content of the matured glue-laminated bamboo could also improve its dimensional stability and therefore enhance its selection for structural applications, especially in building and furniture construction [33]. The ANOVA in **Table 1** shows that at 5% level of significance, the bamboo age has a significant effect on the moisture content of the glue-laminated bamboo.

Table 1. ANOVA for physical properties of *Bambusa vulgaris* glue-laminated bamboo

Physical Properties	df	F-value	Sig.
Basic Density	1	121.636	0.001**
Moisture Content	1	14.029	0.001**

Note: ** = Significant at p<0.01; * = Significant at p<0.05; ns = Not significant

3.1.2 Basic Density

Fig. 3 presents the density of the specimens. The basic density of the matured glue-laminated bamboo was 827.93 kg/m ^{3} whilst that of the juvenile glue-laminated bamboo was 705.87 kg/m ^{3}. The findings of this study are comparable to that of [19] and [34]. Sharma et al. [19] reported that the density of glue-laminated bamboo was 686 kg/m^3 and Rusch et al. [34] reported the density of glue-laminated bamboo to be 770 kg/m^3. The higher density in the matured glue-laminated bamboo could be due to the increased volume of fibre fractions. Awotwe-Mensah [31] reported that matured bamboo contained a higher proportion of fibres than that of the juvenile bamboo and this could account for density variation.

Density is a variable known to influence the strength properties of bamboo [34]. Therefore, the higher basic density for matured glue-laminated bamboo could enhance its strength properties and increase its acceptability for structural applications as constructional material [33-34]. Both the matured and juvenile glue-laminated bamboo could be used for structural applications like roof trusses, ceiling joists, ceiling panels, door and window frames, flooring panels, furniture products like bookshelves, carcass construction, etc. [16, 33, 35].

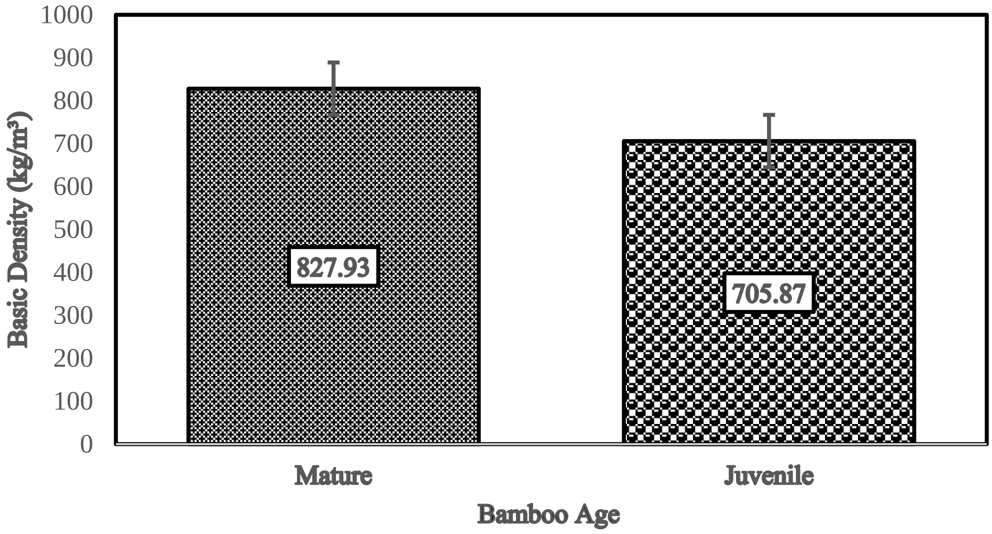


Fig. 3 Basic density of glue-laminated bamboo; N=10

The ANOVA (**Table 1**) indicates that at 5% level of significance, bamboo age had a significant effect on the basic density of glue-laminated bamboo. This implies that the variation in basic density among matured and juvenile bamboo species could be explained by the age difference.

3.1.3 Shrinkage

Fig. 4 shows the radial, tangential and longitudinal shrinkage for both matured and juvenile glue-laminated bamboo. The shrinkage of the matured glue-laminated bamboo was 2.47% for radial, 2.8% for tangential and 0.13% for longitudinal whilst the shrinkage of the juvenile glue-laminated bamboo was 6.32% for radial, 6.51% for tangential and 0.22% for longitudinal.

The results show that the matured glue-laminated bamboo had lower shrinkage properties than the juvenile glue-laminated bamboo. The values obtained for the juvenile glue-laminated bamboo were more than twice that of matured glue-laminated bamboo. This implies that the matured glue-laminated bamboo has better dimensional stability than that of the juvenile glue-laminated bamboo and this could enhance its selection for utilization as a constructional material for structural and non-structural applications [33, 36].

The tangential shrinkage for both juvenile and matured glue-laminated bamboo was higher than their corresponding values for radial and longitudinal shrinkage. For the radial shrinkage studied, the matured glue-laminated bamboo was 3.85% lower than that of the juvenile glue-laminated bamboo. A similar trend of results was recorded for tangential and longitudinal shrinkage respectively.

The differences in the values between matured and juvenile glue-laminated bamboo could be attributed to the variations in MC. Razak et al. [29] reported that age influences MC in *Bambusa vulgaris*. This study has also shown that the MC decreases as bamboo matures, as indicated in **Fig. 2** This could explain the variability of the shrinkage in the glue-laminated bamboo. Additionally, the shrinkage variation could be traced to anatomical properties since they influenced MC [29, 37] as Liese [37] and Razak et al. [29] indicated that differences in MC of bamboo could be due to differences in anatomical structure between the culms age. Vetter et al. [30] also reported that a higher content of parenchyma cells in bamboo increases its water holding capacity due to its storage of water and minerals in the bamboo culm. There is a higher parenchyma cell proportion in juvenile bamboo compared to that of the matured bamboo [31] and this might have contributed to the moisture levels and thereby accounted for higher shrinkage values in the juvenile glue-laminated bamboo.

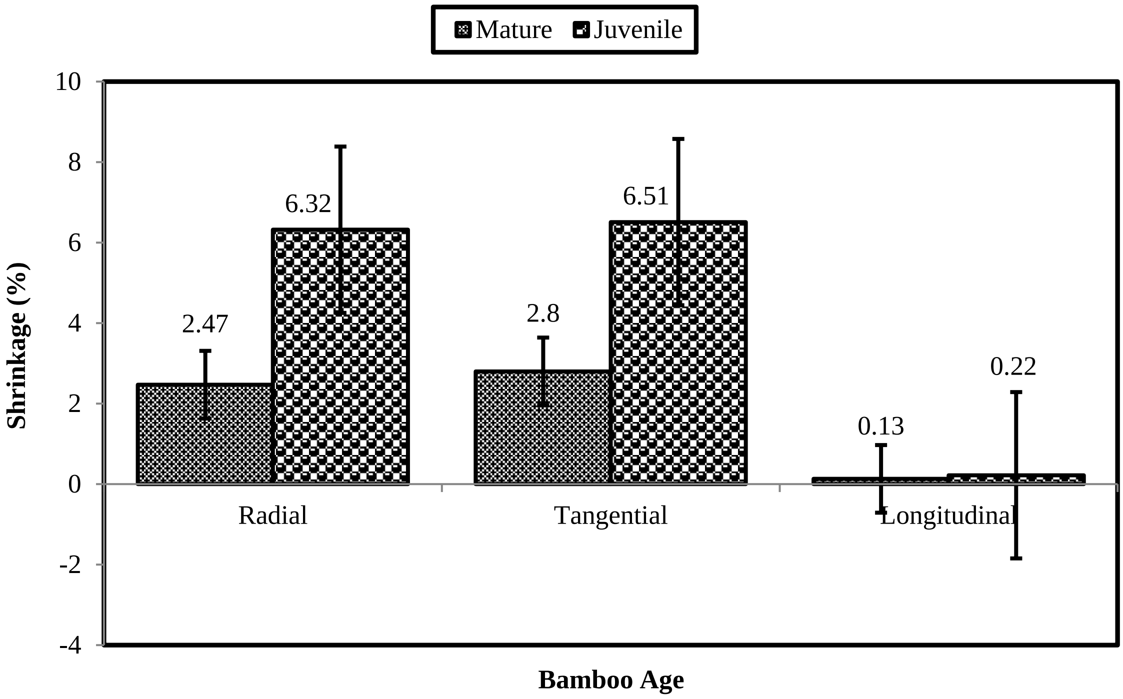


Fig. 4. Shrinkage of glue-laminated bamboo; N=10

The result of this study is similar to the findings reported by Ogunsanwo et al. [38]. For conventional wood, the tangential direction has been accepted as where the greatest dimensional shrinkage occurs whilst the longitudinal shrinkage has been largely reported as the least ranging from 0.1 - 0.3% [28, 39]. Comparatively, the result of this study shows that longitudinal shrinkage is lower than the trend of tangential and radial shrinkage values. This means that shrinkage in glue-laminated bamboo along the three directional planes could be different at all times from each other.

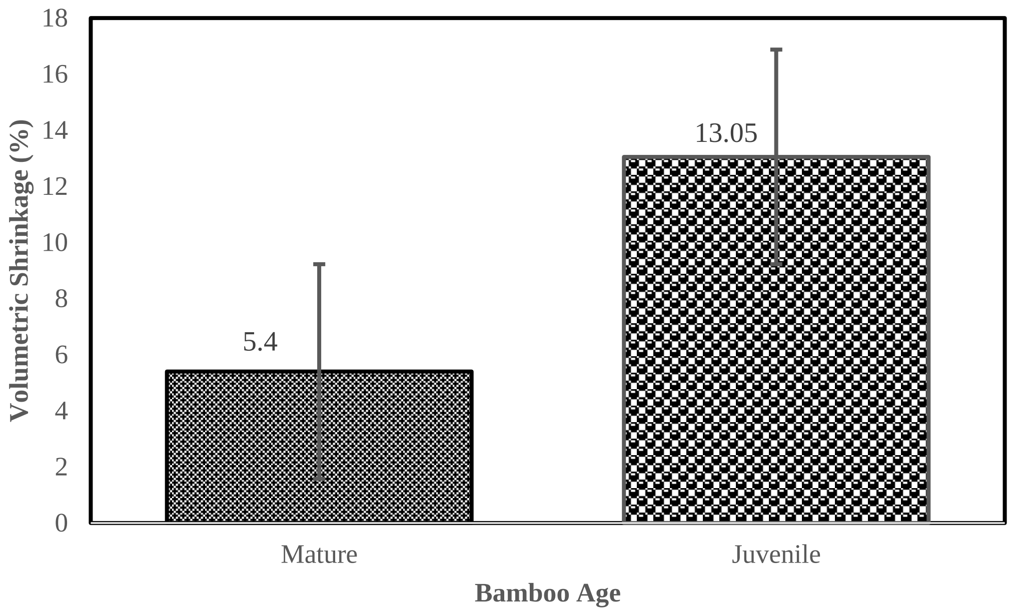


Fig. 5 Volumetric shrinkage of glue-laminated bamboo; N=10

The shrinkage values of the matured glue-laminated bamboo could provide greater assurance for the use of glue-laminated bamboo for structural purposes due to its dimensional stability compared to the shrinkage values of the juvenile glue-laminated bamboo as presented in **Fig. 4.** Additionally, good dimensional stability of a material such as glue-laminated bamboo could produce better mechanical properties (**Fig. 3, 4 & 5**) and thereby promote its utilization potential for structural applications in the construction industry since high moisture levels always tend to influence the mechanical properties [33, 36, 40]. The ANOVA in **Table 2** shows that at a 5% level of significance, bamboo age has a significant effect on the radial, tangential and longitudinal shrinkage of glue-laminated bamboo.

Fig. 5 presents the volumetric shrinkage for the matured and juvenile glue-laminated bamboo. The volumetric shrinkage of the juvenile glue-laminated bamboo was 13.05% whilst that of the matured glue-laminated bamboo was 5.4%. The observed difference in volumetric shrinkage is a result of shrinkage that is unequal along the three-dimensional planes and that could be largely influenced by the rate of radial and tangential shrinkages respectively.

The juvenile glue-laminated bamboo volumetric shrinkage value of 13.05% was more than twice that of the matured glue-laminated bamboo. This means that the dimensional stability of matured glue-laminated bamboo was better than that of juvenile glue-laminated bamboo. This supports the selection of matured glue-laminated bamboo over juvenile glue-laminated bamboo for use in structural purposes in the furniture and construction industries [33]. The ANOVA in **Table 2** shows that at a 5% level of significance, bamboo age has a significant effect on the volumetric shrinkage of glue-laminated bamboo.

Table 2. ANOVA of shrinkage for *Bambusa vulgaris* glue-laminated bamboo

Physical Properties	df	F-value	Sig.
Radial Shrinkage	1	40.832	0.001**
Tangential Shrinkage	1	38.436	0.001**
Longitudinal Shrinkage	1	11.915	0.003**
Volumetric Shrinkage	1	40.029	0.001**

Note: ** = Significant at p<0.01; * = Significant at p<0.05; ns = Not significant

3.2 Mechanical Properties of Glue-Laminated Bamboo Composites

3.2.1 Modulus of Elasticity

Modulus of Elasticity (MOE) is an important property of glue-laminated bamboo that measures its stiffness or resistance to bending when subjected to stress. The MOE of the matured glue-laminated bamboo was 13379 MPa whiles that of the juvenile glue-laminated bamboo was 5876 MPa (**Fig. 6**). This higher variation in MOE could be attributed to the age difference. Age plays a critical role in determining the mechanical properties of bamboo. The culm matures as the bamboo ages and this tends to improve the fibre quality and thereby display more resilience in load bearing capacity resulting in enhancement of the material strength properties as shown in **Fig. 6, 7& 8**. Additionally, age influences anatomical properties such as fibre proportion which tends to affect the MOE of the bamboo culm. The fibre proportion occupied by vascular bundles determines the physical and mechanical properties of a bamboo species [46-47]. This implies that the distribution, shape and size of the bundles change continuously from the periphery towards the middle of the culm. The change in fibre bundle concentration also affects the MOE positively along the periphery towards the middle and negatively towards the inner portion due to higher fibre proportions at the periphery than that of the middle and inner portions of the culm.

The result is comparable to that of glue-laminated bamboo [15, 17, 41]. Huang et al. [41] found that the mean MOE of glue-laminated bamboo ranged from 7000 - 14000 MPa. Appiah-Kubi et al. [15] also reported that the mean MOE of *Bambusa vulgaris* glue-laminated bamboo made with three different formaldehyde adhesives ranged from 9794 - 9923 MPa and lastly, Sharma et al. [17] reported that the MOE of glue-laminated bamboo ranged from 1000 - 12000 MPa. This implies that the MOE of *Bambusa vulgaris* species especially the matured (4-year) could be able to bear stress levels within approximately 13000 MPa without failure. This could further suggest that higher MOE is an assurance in terms of material utilization potential, especially for structural and non-structural applications in both the furniture and building construction industries.

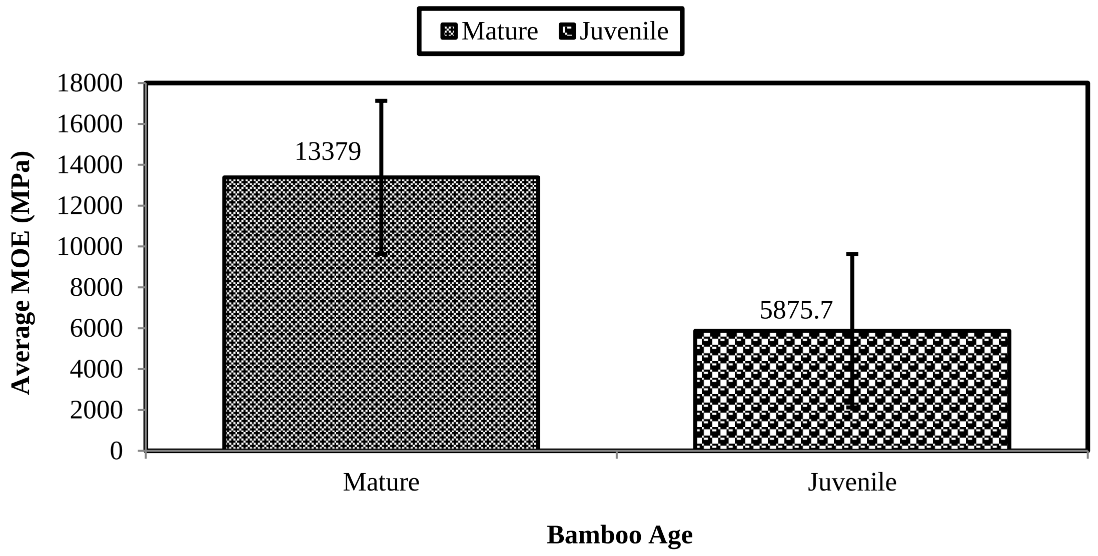


Fig. 6 Average MOE of glue-laminated bamboo; N=10

In addition, matured glue-laminated bamboo compares favourably with some of the tropical hardwood species like *Khaya ivorensis* with an MOE of 9113 MPa [42-43], *Sterculia rhinopetala* with an MOE of 13382 MPa [44], *Combretodendron africanum* with an MOE of 9739 MPa [45]. The matured glue-laminated bamboo with MOE of 13379 MPa could be used for similar construction works in Ghana since the MOE compares favourably with the above wood species.

The high MOE of matured glue-laminated bamboo makes it a preferable material for structural applications like roofing truss, ceiling joists, ceiling panels, door and window frames, flooring panels, furniture products like bookshelves, carcass construction, bedside cabinet [16, 35] compared to the juvenile glue-laminated bamboo. The ANOVA in **Table 3** shows that at 5% level of significance, bamboo age has a significant effect on the MOE of glue-laminated bamboo. This implies that the difference in MOE could be explained by the bamboo age.

Table 3. ANOVA for mechanical properties of glue-laminated bamboo

Mechanical Properties		df	F-value	Sig.
Modulus of Rupture (MOR)	Between Groups	1	368.116	0.001**
Modulus of Elasticity (MOE)	Between Groups	1	641.003	0.001**
Compressive Strength (CS)	Between Groups	1	238.440	0.001**

Note: ** = Significant at p<0.01; * = Significant at p<0.05, ns = Not significant

3.2.2 Modulus of Rupture

Fig. 7 shows the modulus of rupture (MOR) of matured and juvenile glue-laminated bamboo. The MOR of the matured glue-laminated bamboo was 82.48 MPa whilst that of the juvenile glue-laminated bamboo was 43.42 MPa. The difference in the MOR between the matured and juvenile glue-laminated bamboo could be attributed to the age variation which tends to affect the fibre proportions of the bamboo culm. The fibre proportion occupied by vascular bundles determines the physico-mechanical properties of bamboo [46-47]. Specimens with higher proportions of fibre as reported by Tomalang et al. [48] have better mechanical properties. Furthermore, the proportion of vascular bundle and fibre properties of the matured bamboo was higher than the juvenile bamboo as reported by Awotwe-Mensah [30], hence resulting in the matured glue-laminated bamboo having better MOR than the juvenile glue-laminated bamboo.

Additionally, Rusch et al. [34] reported that density is a variable that influences mechanical properties. Other studies have shown that higher densities result in better mechanical properties [37, 49] and this study confirmed the assertion that the density of the glue-laminated bamboo (**Fig. 3**) has an influence on the MOR results (**Fig. 7**). The MOR results of matured glue-laminated bamboo could have contributed to its general acceptability for wider applications [16, 33, 35].

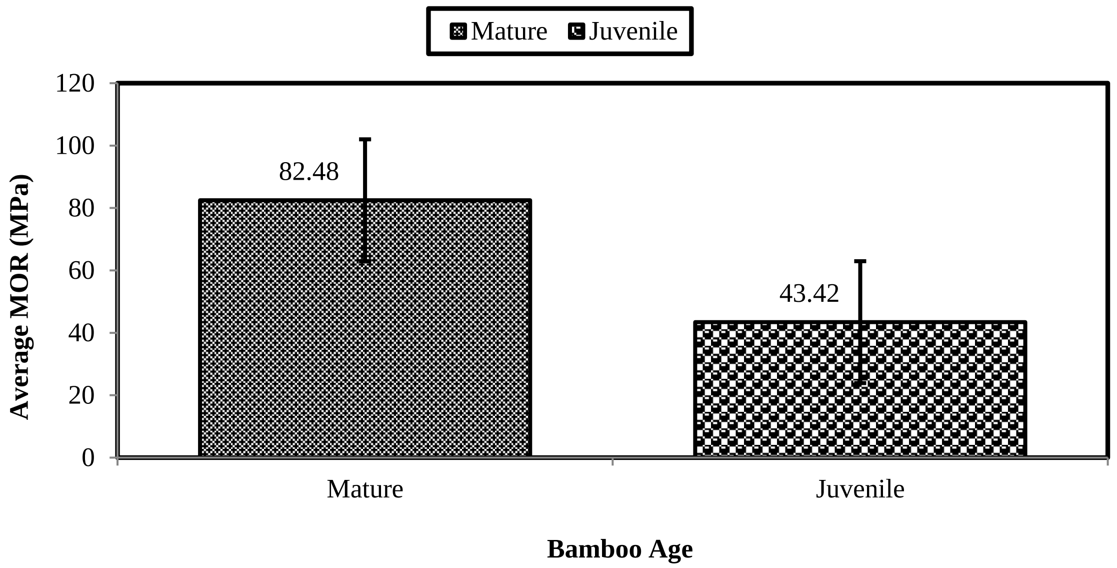


Fig. 7 MOR of bamboo glue-laminated bamboo; N=10

The result is comparable to similar glue-laminated bamboo study findings reported Huang et al. [41] found that the mean MOR results of glue-laminated bamboo ranged from 39 - 145 MPa. Appiah-Kubi et al. [15] indicated that the mean MOR results of *Bambusa vulgaris* glue-laminated bamboo made with three different formaldehyde adhesives ranged from 62.58 - 94.3 MPa. Sharma et al. [17] also reported that the mean MOR results of glue-laminated bamboo ranged from 78 - 88 MPa. This implies that the MOR of *Bambusa vulgaris* species especially the matured (4-year) could be deformed with stress levels of approximately 83 MPa. This could further suggest that a higher MOR value has an influence on material utilization potential, especially for structural and non-structural applications in both the furniture and building construction industries.

Additionally, matured glue-laminated bamboo could also compare favourably with some of the tropical hardwood species like *Khaya ivorensis* with an MOR of 73.9 MPa [43], *Sterculia rhinopetala* with an MOR of 81.7 MPa [44], *Combretodendron africanum* with an MOR of 103.7 MPa [45]. Comparatively, the matured glue-laminated bamboo with an MOR of 82.48 MPa could be used for similar construction works in Ghana since the MOR compares favourably with the above wood species. The ANOVA (**Table 3**) shows that at 5% level of significance, bamboo age has a significant effect on the MOR of glue-laminated bamboo. This implies that the difference in MOR could be explained by the bamboo age.

3.2.3 Compressive Strength Parallel to Grain

Fig. 8 presents the results of compressive strengths of both the matured and juvenile glue-laminated bamboo. The compressive strength of the matured glue-laminated bamboo was 62.78 MPa whilst that of the juvenile glue-laminated bamboo was 37.58 MPa. This result shows that the matured glue-laminated bamboo could withstand more applied compressive loads than the juvenile glue-laminated bamboo. This could be attributed to the fibre proportion of bamboo culms. The higher proportion of fibre constitutes 40 - 50% of the culm tissue as reported by Tomalang et al. [48]. Furthermore, the proportion of vascular bundle and fibre properties of the matured bamboo was higher than the juvenile bamboo as reported by Awotwe-Mensah [31].

The vascular bundle could also influence the compressive strength of the matured glue-laminated bamboo due to their denser nature at the outer portions of the culms. The smaller vascular bundles are denser in distribution than the larger ones, and the outer portions had higher density and strength properties than the inner portions [37, 49]. Additionally, the wide variation in the compressive strength could be attributed to moisture content levels. According to Xu et al. [32], compressive strength decreased with increasing moisture content in the bamboo. This suggests that the lower compressive strength value recorded for juvenile glue-laminated bamboo was affected by the high moisture content as presented in **Fig. 2**. Furthermore, the lower Moisture Content enhances the mechanical properties as it improves the compressive strength of the matured glue-laminated bamboo as presented in **Fig. 8**. The higher compressive strength of the matured glue-laminated bamboo could also contribute to its general acceptability as it enhances its selection for structural applications, especially in building and furniture construction [33].

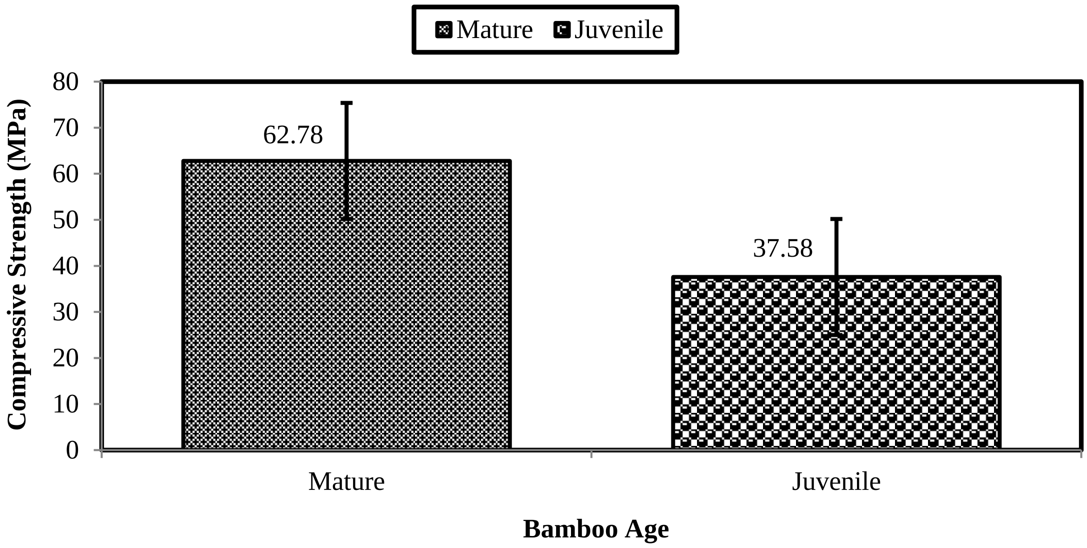
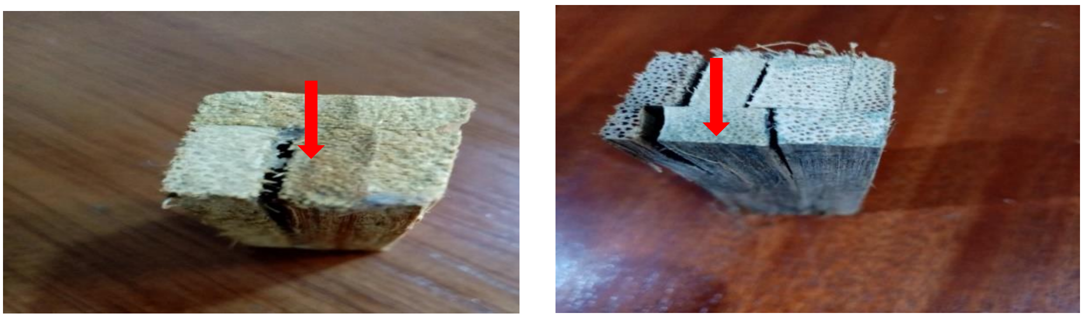


Fig. 8 Compressive strength of glue-laminated bamboo; N=10

Additionally, the compressive strength of *Bambusa vulgaris* glue-laminated bamboo could be influenced by the adhesive used for manufacturing. The performance in service of any adhesives is greatly influenced by their composition [50]. The quality of bonding always influences the extent to which the laminated material could withstand the maximum load applied to it as shown in **Fig. 9**. The analysis of the compressive strength test (**Fig. 9**) of this study revealed that the failure of the test largely occurred through the glue line as indicated with the red arrow. This implies that the bonding quality contributed greatly to the failure of the compressive strength for the glue-laminated bamboo composite. Comparatively, the failure along the glue lines of the juvenile specimen indicated weaker bonding as compared to matured glue-laminated bamboo as presented in **Fig. 9**. This suggests that age plays a critical role in determining the mechanical properties of glue-laminated bamboo as it tends to influence moisture content variation and thereby affecting the mechanical properties.



(a)Matured specimen (b) Juvenile specimen

Fig. 9 Glue-laminated bamboo sample after compressive test with red arrow indicates glue line

The result of this study is comparable to similar findings reported by [15, 17, 19]. Sharma et al. [19] reported that the mean compressive strength parallel to the grain of glue-laminated bamboo was 77 MPa. Appiah-Kubi et al. [15] reported a mean compressive strength for *Bambusa vulgaris* glue-laminated bamboo, ranging from 47.71-52.41 MPa. This implies that the compressive strength of *Bambusa vulgaris* especially the matured (4-year) could be able to bear load within approximately 60 MPa without failure. This could further suggest that higher compressive strength is an assurance in terms of the utilization potential of glue-laminated bamboo, especially for structural and non-structural applications in both the furniture and building construction industry. The ANOVA (**Table 3**) shows that at a 5% level of significance, bamboo age has a significant effect on the compressive strength of the glue-laminated bamboo. This suggests that the difference in compressive strength could be explained by the bamboo age.

Table 4 presents a summary of the mean values of the results obtained with standard deviations (indicated as ±) as well as the coefficient of variations (COV).

Table 4. Summary of mean results of properties obtained for juvenile and matured glue-laminated bamboo

Bamboo Age	Basic Density (kg/m^3)	Moisture Content (%)	MOE (MPa)	MOR (MPa)	Compressive strength (MPa)
Juvenile (2 years)	705.87 ± 17.86 COV (2.5%)	16.3 ± 1.42 COV (6.4%)	5875.7 ± 210.54 COV (3.6%)	43.42 ± 2.62 COV (6.0%)	37.58 ± 2.39 COV (6.4%)
Matured (4 years)	827.93 ± 28.42 COV (3.4%)	12.4 ± 0.58 COV (4.7%)	13379 ± 350.91 COV (2.6%)	82.48 ± 3.43 COV (4.2%)	62.78 ± 3.27 COV (5.2%)

4 Conclusions

The study assessed the physical and mechanical properties of *Bambusa vulgaris* glue-laminated bamboo using both juvenile and matured culms. The juvenile glue-laminated bamboo had higher moisture content which tends to affect its mechanical properties, especially with the compressive strength. It could be further concluded that the lower moisture content of the matured glue-laminated bamboo will have an improved dimensional stability. The basic density of the matured glue-laminated bamboo was higher than that of the juvenile glue-laminated bamboo. The differences in basic density were significant. It could be further concluded that the radial, tangential and longitudinal shrinkage values for juvenile glue-laminated bamboo were more than twice the values for matured glue-laminated bamboo.

Glue-laminated bamboo shrinks higher along the tangential direction than in the radial and longitudinal directions. Additionally, higher basic density resulted in higher strength properties. The matured glue-laminated bamboo had better mechanical properties than juvenile glue-laminated bamboo. The matured glue-laminated bamboo of *Bambusa vulgaris* possesses overall better physical and mechanical properties than that of the juvenile glue-laminated bamboo and their differences were significant. Therefore, matured glue-laminated bamboo composite was found to be useful for structural and non-structural applications in the furniture and building industry.

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CRediT authorship contribution statement

Appiah-Kubi: Conceptualization, Supervision, Formal analysis, Writing - review & editing. **Awotwe-Mensah**: Conceptualization, Formal analysis, Investigation, Writing - original draft. **Mitchual**: Supervision, Writing - review & editing.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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