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ORIGINAL ARTICLE

Influence of characteristic inhomogeneity of bamboo culm on mechanical properties of bamboo plywood: effect of culm height

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Abstract The aim of this study was to evaluate the influence of *Neosinocalamus affinis* bamboo culm height on selected properties of original bamboo and the mechanical properties of bamboo plywood (BP). The results indicated that vascular bundle density, fiber proportion, specific gravity and compression strength parallel to grain (CSPG) increased from culm bottom to top. Bamboo culm height could significantly affect the mechanical properties of the BP. The shear strength (SS) of the BP decreased with increasing culm height, while the compressive strength (CS) increased. The maximum modulus of rupture (MOR) and tensile strength (TS) was observed at middle portion of culm. Significant correlation was found between vascular bundle density, specific gravity, culm wall thickness of original bamboo and the CS, SS of the BP.

Keywords Bamboo plywood · Culm height · Bamboo characteristics · Bechanical properties · Relationship

Introduction

Neosinocalamus affinis bamboo could be found in enormous quantities in southwest of China, and its craftworks had been widely used in daily life since ancient times to modern day. The bamboo, such as moso bamboo which has large diameter culm and thicker culm wall, has been used as a prominent non-wood resource in such applications as flooring, furniture manufacturing, and construction materials because of its culms' high growth rate, abundantly available, renewable nature, and short maturity cycle (4–5 years). However, the application of *Neosinocalamus affinis* bamboo in the manufacturing of construction materials attracted less attention because of its thin culm wall thickness, which results in a lower production yield.

Large diameter bamboo had been largely used in the bamboo-based panel, bamboo glue-laminated timer, and bamboo flooring industries as sustainable raw materials of wood [1]. Even so, the efficient use of bamboo in manufacturing these bamboo-based composites was particularly low, about 30–50 %, due to the limited processing technologies. Recently, a novel process to improve yield of bamboo-based composites has been extensively promoted in China, with which the bamboo composite panel yield was over 90 % and small diameter bamboo with thin culm wall thickness was also suitable to the process [2]. Meanwhile, the fabricated composites via the novel process showed excellent mechanical performance and has been proposed in the manufacturing of blades of wind turbine.

For structural design purpose using bio-based composites as main materials, the uniformity of the raw materials' properties was required. Though the new type of bamboo-based composites exhibited high mechanical properties, drawbacks such as uneven stress distribution severely limit its application as a commonly used structural material [3]. While the previous studies had focused the research on the fabrication or quality evaluation of these new composites, the investigation on the impact factors on uniformity of mechanical properties has been ignored. Bamboo properties were reported to be significantly different within bamboo culm heights [4–6]. Meanwhile, differences in

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bamboo properties with species, ages, locations, and portions could also significantly affect its processing procedures and the performance of end products [7].

Thus, to estimate the influence of bamboo culm height on the mechanical properties of the new type composite, bamboo fiber mat was prepared from *Neosinocalamus affinis* bamboo via a promoted mechanical treatment process. The objective of this study was to provide primarily understanding of the effect of bamboo culm characteristics on the variation in mechanical properties distribution in bamboo plywood.

Materials and methods

Materials

Neosinocalamus affinis bamboo (4-year old) was obtained from Sichuan province, China. Fifty culms were cut at about 10 mm above the ground. These culms were removed of branches and the top parts, 10-m-long logs were left, followed by subdividing them into ten parts with length of 1 m for each height portion. A commercial phenol formaldehyde (PF) resin obtained from the Taier Corporation (Beijing, China) was used as matrix material for the composite fabrication. The parameters of the PF resin were as following: 44.6 % of solid content, 41 CP·s of viscosity, 11.2 pH, and ability of dissolve in water is 7−8 times.

Preparation of bamboo fiber mat (BFM)

Bamboo logs with length of 1000 mm were first split longitudinally into two semicircular bamboo tubes. After bamboo inner nodes were removed, the semicircular bamboo tubes were pushed into a fluffer. With brooming and rolling, the bamboo tubes were processed into a loosely laminated reticulate sheet. The laminated sheet was cross-linked in the width direction with a series of dotted and/or linear shaped cracks along the longitudinal/fiber direction. The netlike bamboo sheet with uniform thickness and maintaining the original bamboo fiber arrangement was finally cut into pieces with length of 500 mm using an electrical saw. Consequently, the bamboo fiber mat (BFM) was formed. The BFMs were dried to moisture content of 10 %.

Preparation of bamboo plywood (BP)

The PF resin was diluted with water to a solid content of 15 %. The BFMs were immersed into the PF resin for 3 min and placed for 5 min to avoid PF resin flowing out; the amount of the glue was controlled to about 12 % of the oven dry weight of the BFM, and then air-dried to a moisture content of 9 %. The BFMs were weighted out according to the desired density (otherwise stated, the density was 1.1 g/cm^3 in this present study) and were assembled in a designed mold. A hot press was used to press the BP at a platen temperature of 150 °C. The pressure was kept 2.5 MPa for a holding time of 1.5 min/mm. The dimension of the BP was 450 mm (length) × 160 mm (width) × 15 mm (thickness).

Determination of original bamboo properties

The anatomical characteristics of original bamboo, such as vascular bundle density, proportions of cell types were measured according to the methods presented in the past research papers [8–10]. Anatomical samples from the middle portion of internodes were sliced into cross-sections of 10 × 10 mm × culms wall thickness × 30 μm (thickness of parallel to grain). Followed by, the cross-sections of bamboo culms were projected under a digital camera microscope (OLYMPUS DP20). The vascular bundle density was determined by counting the vascular bundle numbers on the cross-section images per mm^2. The proportions of cell types were calculated in a line, which was crossed from inner side to the epidermis, i.e. by counting the numbers of grids covering the fiber, parenchyma and vessel cells on the coordinate paper in the line. Six replicates were carried out for each portion samples.

The dimension of the specific gravity for each location was impossible to standardize due to the changing dimension of culm. Based on the paper reported by Ahmad [8], a 2.5-cm section was used for specific gravity test, which was obtained from the middle portion of each internode at different culm heights. A total of 120 samples were prepared for specific gravity test. Volumetric shrinkage was estimated on green and oven dry volume dimensions. All of 120 samples for volumetric shrinkage studies were oven dried at 105 ± 2 °C until constant weight was obtained. The green volume of samples was determined using the water displacement method.

Mechanical properties of original bamboo, including compression strength parallel to grain (CSPG) and shear strength parallel to grain (SSPG), were determined using a universal testing machine (Reger, RGM-4100, China). A size of 20 × 20 mm × culm wall thickness for CSPG test was organized with two steel plants of testing machine, one attaching upper surface and the other supporting lowwhiler surface of test pieces. Only the maximum load was recorded from the obtained data. The results were calculated using formula (1). A total of 300 samples were prepared for CSPG test. SSPG test was measured by loading the specimen at a constant rate of 0.5 mm/min until the maximum load was reached or when failure occurred.

SSPG was calculated using Eq. (2). Thirty replicates of SSPG test were carried out for each portion samples.

$$\text{CSPG (MPa)} = \frac{p_{\max}}{ab} \quad (1)$$

$$\text{SSPG (MPa)} = \frac{P_{\max}}{Lb} \quad (2)$$

where $P_{\max}$ is maximum load at which the sample fails (*N*), *L* represents length of shear surface, *a* represents the width (mm), *b* represents the depth (culms wall thickness, mm).

Mechanical properties of BP

A total of 120 samples with equal dimension for modulus of rupture (MOR) measurement were taken from BP (300 × 20 × 15 mm) with free span of 240 mm. The MOR was measured by the formula (3). Figure 1 illustrates the tensile strength (TS) test specimen (370 × 15 × 15 mm). The middle section of the specimens was necked down to 4 mm to resemble a dog-bone shape. A total of 120 samples were used for TS tests, and TS was calculated using Eq. (4). Sample size for compressive strength (CS) was 15 mm (width) × 15 mm (thickness) × 80 mm (length). A total of 120 samples were prepared for CS test, and the results were calculated by formula (5). Horizontal shear strength (SS) test (90 × 40 × 15 mm) was calculated using Eq. (6), and a total of 120 samples were used in this test. All the mechanical properties of BP were conditioned at 20 °C and 65 % relative humidity for at least 4 weeks prior to testing.

$$\text{MOR (MPa)} = \frac{3}{2} \times \frac{p_{\max} \times l}{ef^2} \quad (3)$$

$$\text{TS (MPa)} = \frac{p_{\max}}{gh} \quad (4)$$

$$\text{CS (MPa)} = \frac{p_{\max}}{ij} \quad (5)$$

$$\text{SS (MPa)} = \frac{3p_{\max}}{4mn} \quad (6)$$

where $P_{\max}$ is maximum load at which the sample fails (*N*), *e* represents the width (mm), *f* represents the thickness (mm), *l* is the free span (mm), *g* is width of the effective fracture section (mm) and *h* is the thickness of the effective fracture section (mm) of TS sample, *i* represents the width and *j* is the thickness of CS sample, *m* represents the width and *f* represents the thickness of SS sample (mm).

Statistical analysis

Statistical analysis was carried out using SAS (version 9.1, SAS Institute, Cary, NC). Analysis of variance (ANOVA) and regression analysis were performed to determine significant differences ($\alpha = 0.05$) among different culm height portions and the relationship between original properties and mechanical properties of bamboo plywood.

Results and discussions

Effect of culm height on original bamboo properties

Variations in bamboo characteristics/properties including culm wall thickness, cell type proportions, vascular bundle distribution, specific gravity, volumetric shrinkage, compression strength parallel to grain and shear strength parallel to grain of *Neosinocalamus affinis* bamboo along culm height were first investigated to provide basic information for the evaluation of mechanical properties of bamboo plywood (BP).

As shown in Table 1, the culm wall thickness showed a decreasing trend as the culm height increased from 1 to 10 m. Accordingly, the bamboo culm wall tissues consist of fiber, parenchyma, and vessel cells [11]. To further evaluate the culm wall structural variations within bamboo culm, the cell proportions were measured. The fiber proportion consisting of fibers with dimensions of 2.61 mm (length), 14.54 μm (width), 9.85 μm (cell wall thickness), and 4.71 μm (lumen diameter) and which was reported to be corresponding to the bamboo density and mechanical properties [12], increased slightly with the culms heights. According to the variance analysis results, the difference in fiber proportion among different heights was significant ($p < 0.05$). The variation in vessel proportion along the culm height showed a similar trend to that of fiber proportion. The parenchyma proportion showed a decreasing trend as increasing culm height, which was converse to that of fiber and vessel proportions. Good regression correlation was found between cell proportion and culm height with R^2 values of 0.88, 0.95, and 0.95 for fiber, parenchyma, and vessel proportion, respectively. The fitting equations were determined as follows:

Fiber proportion via culm height: $Y = 0.0004X^2 - 0.0015X + 0.4148$, $R^2 = 0.88$

Parenchyma proportion via culm height: $Y = -0.0003X^2 - 0.0036X + 0.5110$, $R^2 = 0.95$

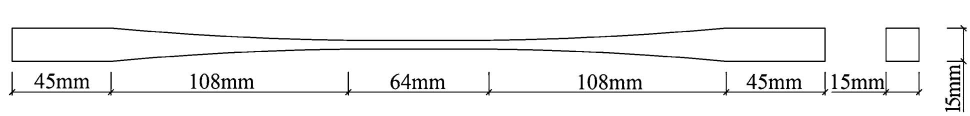

Fig. 1 Tensile strength test specimen

Table 1 Effect of culm height on selected properties of *Neosinocalamus affinis* bamboo

Culm height (m)	Culm wall thickness (cm)	Parenchyma proportion (%)	Fiber proportion (%)	Vessel proportion (%)	Vascular bundle density (bundle/mm^2)	Specific gravity (g/cm^3)	Volumetric shrinkage (%)	Compression strength parallel to grain (MPa)	Shear strength parallel to grain (MPa)
1	4.48 ± 0.23	50.94 ± 1.38	41.06 ± 1.78	8.00 ± 0.88	4.11 ± 0.63	0.65 ± 0.09	14.81 ± 0.94	63.81 ± 2.96	13.69 ± 0.81
2	4.40 ± 0.35	50.16 ± 1.22	41.44 ± 1.72	8.40 ± 0.64	4.28 ± 0.71	0.70 ± 0.02	13.90 ± 0.68	64.01 ± 2.73	13.99 ± 0.33
3	3.69 ± 0.20	49.98 ± 0.90	41.38 ± 0.97	8.64 ± 0.93	4.31 ± 0.54	0.70 ± 0.07	12.91 ± 0.53	64.41 ± 2.27	14.14 ± 0.61
4	3.62 ± 0.31	48.41 ± 1.12	42.34 ± 1.35	9.25 ± 0.76	4.37 ± 0.80	0.71 ± 0.06	12.38 ± 0.57	64.87 ± 3.24	14.19 ± 0.89
5	3.40 ± 0.25	48.00 ± 1.08	41.75 ± 1.22	10.25 ± 0.70	4.40 ± 0.56	0.72 ± 0.07	11.97 ± 0.97	68.11 ± 1.13	15.47 ± 1.02
6	3.38 ± 0.39	47.94 ± 1.08	41.77 ± 1.43	10.29 ± 0.46	4.44 ± 0.83	0.73 ± 0.03	11.92 ± 0.36	73.75 ± 4.01	15.57 ± 0.98
7	3.24 ± 0.27	47.82 ± 0.81	41.86 ± 1.12	10.32 ± 0.27	4.54 ± 1.01	0.73 ± 0.03	11.57 ± 0.82	75.97 ± 4.30	14.79 ± 0.39
8	2.88 ± 0.23	46.52 ± 1.01	42.93 ± 1.54	10.55 ± 0.89	5.04 ± 0.83	0.75 ± 0.05	11.35 ± 0.67	76.74 ± 3.64	14.65 ± 0.87
9	2.79 ± 0.19	44.43 ± 1.09	43.72 ± 0.94	11.85 ± 0.73	5.32 ± 1.02	0.76 ± 0.02	11.12 ± 0.85	78.95 ± 3.59	14.17 ± 0.76
10	2.58 ± 0.14	44.23 ± 0.36	44.25 ± 0.81	11.52 ± 0.35	5.79 ± 1.03	0.81 ± 0.10	10.67 ± 0.56	79.95 ± 3.31	12.22 ± 0.42

Vessel proportion via culm height: $Y = 0.4159X + 7.6193$, $R^2 = 0.95$

The lower value of positive slope (<1) in the linear equation of vessel proportion revealed a slight improvement on vessel proportion with increasing culm height. Moreover, from the determining value of R^2, a higher value for parenchyma proportion was observed compared to the fiber proportion, which indicated that the stability of curvilinear correlation between parenchyma proportion and culm height was much more significant than that for fiber proportion.

In addition, the culm wall was also characterized by vascular bundle embedded in parenchyma cells. As presented in Table 1, the vascular bundle density, which was usually considered to be closely associated with the mechanical properties of bamboo, increased with increasing culm height, i.e., from 4.11 to 5.79 bundle/mm^2. The specific gravity of *Neosinocalamus affinis* bamboo varied vertically from bottom to top portions of culms, varying between 0.65 and 0.81 g/cm^3. This may mainly depend on the variation in vascular bundle density among the height portions of bamboo, since both vascular bundle density and specific gravity showed an increasing trend from bottom to top. An interesting finding was that there was a positive correlation between vascular bundle density and specific gravity ($R = 0.93$, $p < 0.05$). As shown in Table 1, bottom portion showed maximum proportion of volumetric shrinkage (14.81 %) while the top portion, the lowest (10.67 %). A decrease in volumetric shrinkage was observed from bottom toward top, which is consistent with the finding of Kamruzzaman et al. [13]. With the increase of specific gravity and supported by the higher proportion of vascular bundles per square unit, the volumetric shrinkage decreases (Killmann 1983) [14]. According to correlation analysis, a positive correlation was found between specific gravity and culm height ($R = 0.94$, $p < 0.05$), whereas a negative correlation was observed between volumetric shrinkage and culm height ($R = 0.95$, $p < 0.05$). Great linear regression correlation was found between specific gravity, volumetric shrinkage and culm height with R^2 values of 0.89 and 0.91, respectively. The fitting equations were determined as follows:

Specific gravity via culm height: $Y = 0.0132X + 0.6533$, $R^2 = 0.89$

Volumetric shrinkage via culm height: $Y = -0.4061X + 14.493$, $R^2 = 0.91$

In terms of CSPG and SSPG, there was a significant difference ($p < 0.05$) along the culm height. The CSPG generally increased from base to top, ranging from 63.81 to 79.95 MPa, whereas SSPG increased from bottom to middle and then decreased at the top, ranging from 12.22 to 15.57 MPa; the highest SSPG value exists in the sixth meter (Table 1). A positive correlation was observed between CSPG and culm height ($R = 0.97$, $p < 0.05$), while there was no correlation between SSPG and culm height in this present study. Great linear regression correlation was found between CSPG and culm height with R^2 value of 0.97. The fitting equation was determined as follows:

CSPG via culm height: $Y = 2.1238X + 59.3760$, $R^2 = 0.93$

Effect of culm height on mechanical properties of BP

The mechanical properties of BP varying along the culm height are presented in Fig. 2. As shown in Fig. 2a, the CS of the BP varied between 119 and 128 MPa. As the culm height increased, the CS increasing linearly, and reached maximum at the top of the culm ($R^2 = 0.85$). In terms of the original bamboo, the CS was reported to be correlated with the strengths of fiber cells [15]. Since the BFMs obtained in this study maintained its original fiber arrangement, it could be concluded that the CS of the BP was also corresponding to the strengths of original bamboo fibers. Thus, the higher CS of the BP manufactured from the higher portion culms mainly contributed to the higher proportions of fiber bundles it contains (see Table 1). To further clarify the relationship between fiber proportion and the CS of the BP, regression analysis was conducted, and significant positive linear relationship was observed with R^2 of 0.87, (i.e., $Y = 0.77X + 120.58$). Meanwhile, significant positive correlation was also observed between CS and vascular bundle, specific gravity, and their relationships are shown in Fig. 2. The CS of the BP increased with increasing vascular bundle and specific gravity of the original bamboo. Fitting equations for the relationship between CS and vascular bundle density, and specific gravity were: $Y = -1.13 \times \exp(-X/0.133) - 52.012 \times \exp(-X/2.332) + 132.76$, $R^2 = 0.88$ and $Y = 56.50X + 83.78$, $R^2 = 0.91$, respectively.

Converse to the variation of the CS with respect to culm height, the shear strength (SS) decreased linearly ($R^2 = 0.97$), varying between 14.2 and 24.5 MPa. The significant difference in SS of BP between the higher and lower culm height may be associated with the density of original bamboo and the untwining process. In the fluffer process, it was found that the BFMs manufactured from the bottom culm were much loose and possessed much more linear shaped cracks than those from the top culm due to the fact that the top portion bamboo was much denser. And that resulted in a much more uniform distribution of PF resin in the BFMs from bottom culm, which created a better bonding quality in the BP made from bottom portion bamboo compared to that from the top. It was worthy to note that significant negative correlation was observed between the SS of the BP and vascular bundle density and specific gravity. The SS decreased with the increasing in vascular bundle density and specific gravity. Linear and exponential functions were found between the SS and vascular bundle density and specific gravity, respectively (Fig. 3).

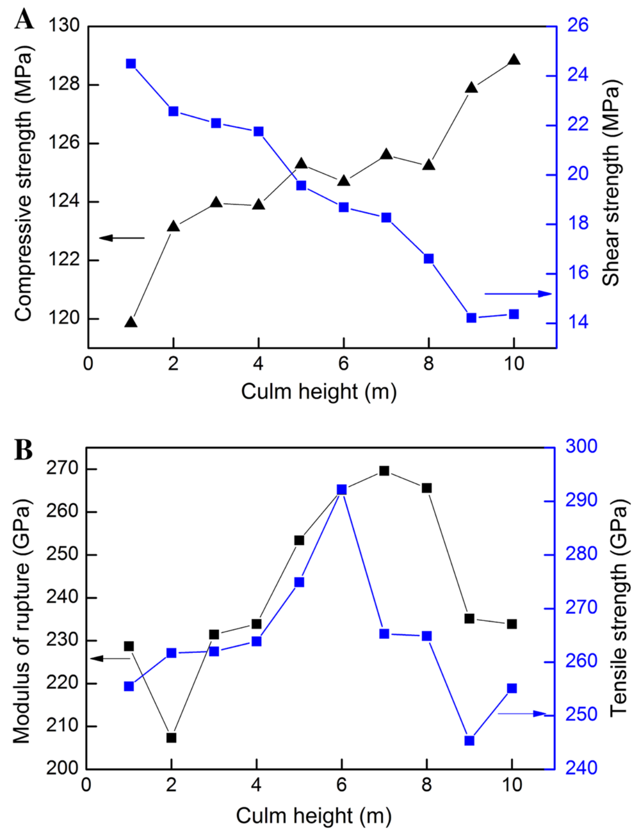

Fig. 2 Effect of culm height on mechanical properties of bamboo plywood

From bottom to top, the tensile strength (TS) first increased, and the maximum value was found at 6 m portion, followed by decreasing dramatically, see Fig. 2b. The minimum of the TS was observed at 9 m portion. Similar to the variation of the TS, the modulus of rupture (MOR) also exhibited a first increasing and then decreasing variation along the culm height. The variance analysis results revealed that the differences in mechanical properties of BP were significant. No significant correlation between original bamboo properties and the MOR and TS of the BP was found in this study.

Bamboo culm wall thickness is an easy evaluation index in the practical production; thus, the relationship between the mechanical properties was also investigated. The results revealed that only the CS and SS had significantly correlations with culm wall thickness. As shown in Fig. 3a, significant linear correlation was observed between the CS, SS and culm wall thickness; however, the difference was that the CS decreased significantly, and the SS increased with increasing culm wall thickness.

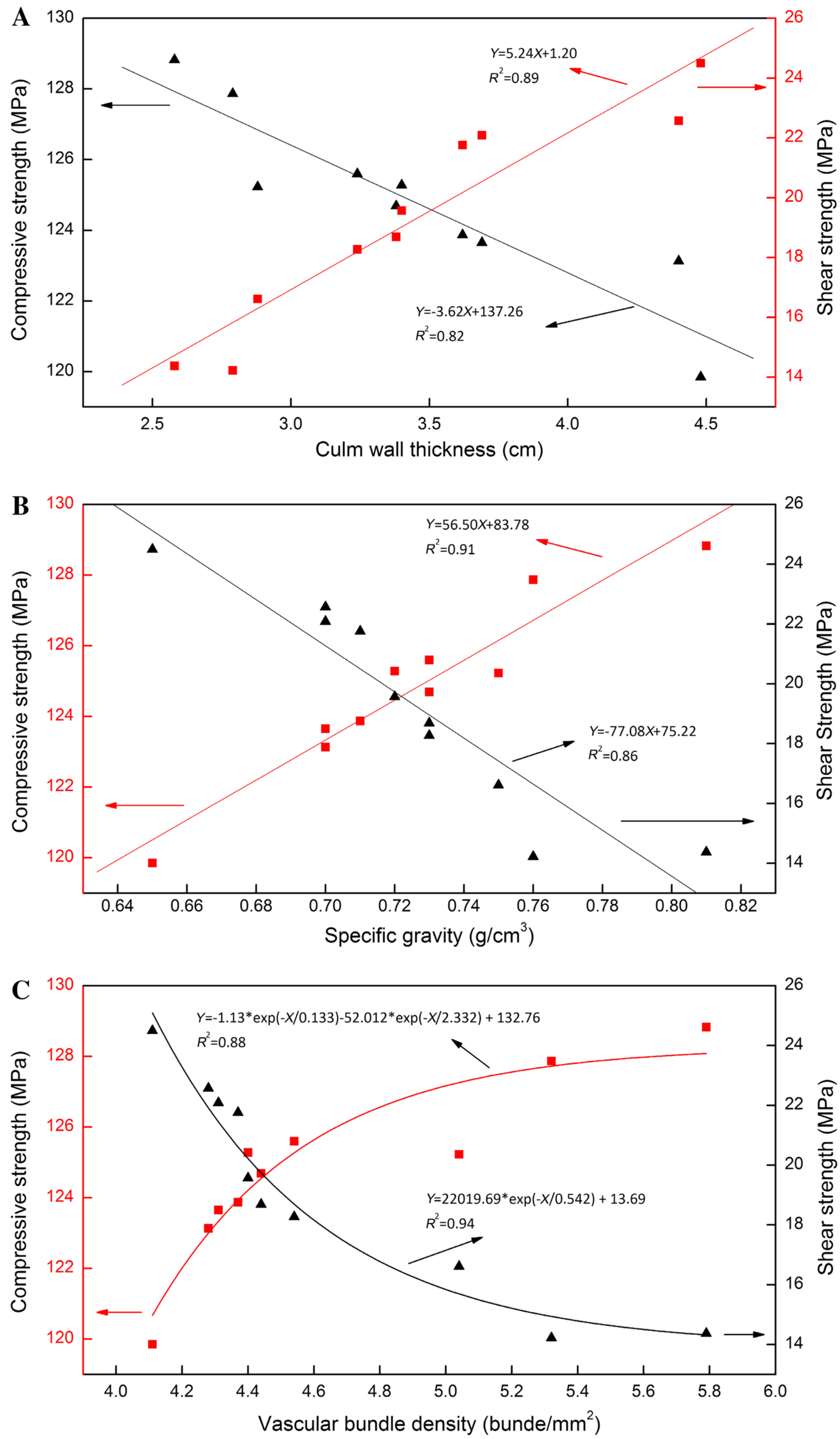

Fig. 3 Relationship between selected properties of original bamboo and the compressive strength, shear strength of bamboo plywood

Conclusion

Significant differences in culm wall thickness, vascular bundle density, cell proportions, specific gravity, compression strength parallel to grain (GCPG), and shear strength parallel to grain (SSPG) among different *Neosinocalamus affinis* culms heights were found. The compressive strength (CS), shear strength (SS), modulus of rupture

(MOR), and tensile strength (TS) of the bamboo fiber-based composites (BP) showed different variation patterns along culm height. The mechanical properties of the BP had somewhat associations with the properties of the original bamboo according to statistical analysis. The CS of the BP increased with increasing vascular bundle and specific gravity of the original bamboo; while the SS decreased with the increasing in vascular bundle density and specific gravity. Significant linear correlations were found between culm wall thickness of original bamboo and the CS and SS of the BP. No significant correlation between original bamboo properties and the MOR and TS of the BP was found in this study.

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