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Temperature Influence on the Bending Performance of Laminated Bamboo Lumber

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Abstract: In order to study the effect of temperatures on the bending performance of laminated bamboo lumber (LBL), 11 temperature conditions were set to test the bending performance in radial and tangential directions ranging from -60℃ to 200℃, and 132 specimens were tested in total. Three typical failure modes were proposed. The bending strength and bending elastic modulus for all specimens were obtained from the test, and the effects of temperatures and loading direction on them were compared. Then the mass loss rate of the specimens was calculated, and the variation law of the load-displacement curve was analyzed. Finally, the reduction (increase) factors of bending strength and bending elastic modulus varying with temperature were calculated, and the empirical formula for reference was proposed. It was found that the temperatures had a significant influence on the bending performance of LBL, and the loading direction had little effect on it.

Keywords: temperature influencing; laminated bamboo lumber; mass loss rate; bending performance; reduction (increase) factor

Introduction

Bamboo, as a fast-growing plant with short growth cycle, is a widely distributed and ecofriendly biomaterial (Li et al., 2016; Chen et al., 2020; Liu et al. 2022). With the increasing shortage of forest resources, the realization of “substituting bamboo for wood” can effectively alleviate the situation of excessive deforestation (Wei et al.,2020; Sharma et al., 2020; Dauletbek et al. 2021). However, the inherent performance defects of original bamboo (Hong et al., 2019), such as uneven structure and anisotropy, make it unable to fully meet the requirements of modern construction (Takeuchi et al., 2015; Felice et al. 2021). In order to broaden application prospect, the engineered bamboo (Yu et al., 2017; Sun et al., 2020; Su et al. 2021), represented by laminated bamboo lumber (LBL), has been produced. Numerous scholars have carried out lots of researches on the mechanical properties of LBL (Jiang et al., 2005; Zhang et al., 2007; Mahdavi et al., 2011; Correal et al., 2014; Sharma et al., 2015; Li et al., 2018), and find that it has excellent properties of high strength, good stiffness, and low shrinkage.

Since both bamboo and timber are combustible, they will be carbonized under high temperatures (Konig et al., 2006), and then thermally decompose to produce combustible gases, accompanied by a loss of mass (Kubojima et al., 2000). Many researchers have studied the effect of temperature on the mechanical properties of engineered timber (Sinha et al. 2011a; Sinha et al. 2011b; Zhou et al. 2012; Zhong et al. 2015) and engineered bamboo (Yang et al. 2016; Zhong et al. 2016; Xu et al. 2017), and concluded that the increase of temperature would result in a decrease in the strength, and an increase in mass loss. Gonzalez et al. (2020) evaluated the changes of mechanical properties of bamboo at high temperatures, showing that the compressive strength and tensile strength of bamboo at 200°C were only 20% and 42% of those at ambient temperature, respectively. Xu et al. (2019) presented the effect of temperature on the compressive and tensile properties of LBL, then established the mathematical model of the elastic modulus and strength reduction factors changing with temperature. The formula had a similar change tendency with those of the timber addressed in BS EN 1995-1-2 (2004), providing a meaningful reference for studying the mechanical properties of engineering bamboo under fire conditions.

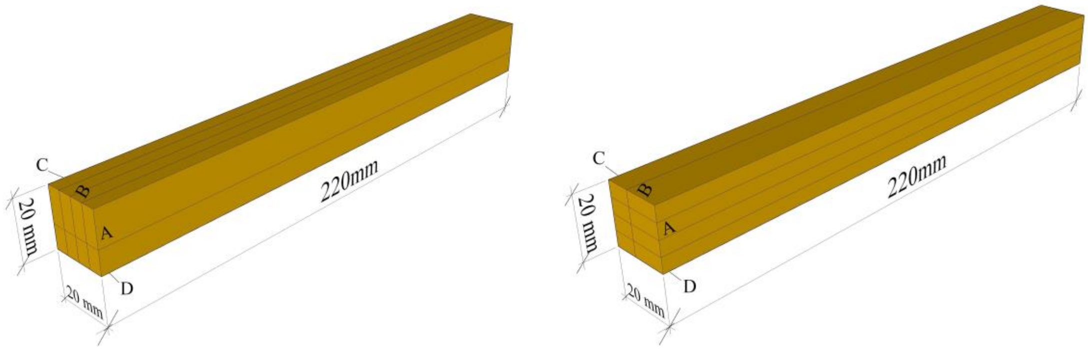
Studies have showed that the main chemical components of bamboo are cellulose, hemicellulose and lignin, which play different roles in the cell wall (Bao 2009; Chen et al. 2022). Moreover, the content of these three celluloses will directly affect the mechanical properties of bamboo, so it is necessary to clarify their content changes with temperature. Bao (2009) calculated that compared with the untreated bamboo, the cellulose content of bamboo decreased by 15.02%, the holocellulose (general term of cellulose and hemicellulose) content decreased by 29.08%, and the lignin content increased by 24.26% when the heat treatment temperature was from 20℃ to 210℃. Zhang et al. (2013a) studied the steam heating on the chemical properties of *Neosinocalamus Affinis* Bamboo, results showed that the contents of holocellulose and α-cellulose decreased after steam treatment, with a decrease of 19.33% and 11.84% respectively.

As mentioned above, the current research on the effect of temperature on the mechanical properties of bamboo has not been fully investigated. The research was mainly focused on compressive and tensile properties, less on bending properties, even less was concerned with negative temperatures. Therefore, this paper studied the temperatures influencing on the bending performance of LBL, and compared the bending performance of different loading directions. On this basis, the temperature reduction (increase) factor of bending strength and elastic modulus was determined, and the corresponding empirical formula was proposed.

Materials and methods

Fabrication of specimens

In this study, all specimens that were made from bamboo as raw material produced by Guizhou Xinjin Bamboo and Wood Products Co., Ltd. The factory selected the original bamboo with good quality and processed it into a bamboo chip unit with a cross-sectional size of 5 mm × 12.5 mm according to a certain technological process. Subsequently, it was placed under the condition of 0.35 MPa for carbonization for 1 hour, in which the first half hour was heated and boosted, and the last half hour was placed for maintenance. Finally, the carbonized bamboo was hot-pressed at 80℃ with pressure steam of 8~10 MPa for about 8 minutes to make usable LBL.



(a) Radial direction (b) Tangential direction

Fig. 1. Size and shape of the test specimens

All bending specimens were made with reference to the national standard "Test Method for Physical and Mechanical Properties of Bamboo for Construction JG/T 199–2007". Fig.1 showed the size of bending specimens with a length of 220 mm and a width of 20 mm and a thickness of 20 mm.

Nomenclature of specimens

All tests were completed in Nanjing Forestry University, using a SANS-5t universal mechanical testing machine with temperature control box. The temperature of the test machine can be adjusted in the range of -70℃ to 350℃. The effects of 11 temperature levels, including -60℃, -40℃, -20℃, 0℃, 20℃, 60℃, 100℃, 130℃, 175℃, 185℃ and 200℃, on the bending performance both radial and tangential direction were investigated. 132 specimens were tested in total, including twelve at each temperature level: six specimens were tested for bending strength in radial direction, and the other six were tested in the tangential direction.

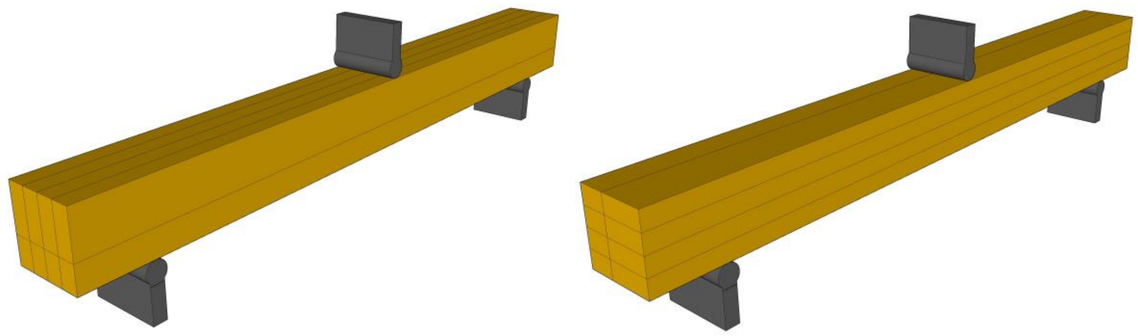
Table 1. Nomenclature of specimens at different temperatures

Temperature (℃)	Loading direction			
	Radial direction	Number	Tangential direction	Number
-60	BLV-60	6	BLH-60	6
-40	BLV-40	6	BLH-40	6
20	BLV-20	6	BLH-20	6
0	BLV0	6	BLH0	6
20	BLV20	6	BLH20	6
60	BLV60	6	BLH60	6
100	BLV100	6	BLH100	6
130	BLV130	6	BLH130	6
175	BLV175	6	BLH175	6
185	BLV185	6	BLH185	6
200	BLV200	6	BLH200	6
Total		66		66

The nomenclature of specimens was in accordance with the order of "bending test + fiber direction + temperature + serial number". For example, at the temperature of -60℃，the first radial bending specimen was "BLV-60-1", and the first tangential bending specimen was "BLH-60-1". Meanwhile, in order to record and distinguish the test phenomena, the radial specimens were recorded with the wide face of the bamboo unit as face A and the tangential specimens with the narrow face of the bamboo unit as face A, and then they were recorded as faces B, C and D respectively in the counterclockwise direction. The nomenclature of all specimens was shown in Table 1.

Test methods

Fig. 2 showed a schematic of the test loading system. Before the test, the specimen was put into the temperature control box, in which the temperature was raised to the test value with a rate of 5°C/min, and kept for 30 minutes to ensure the specimen was heated evenly. In this process, it should be guaranteed that the load of the testing machine and the humidity of the temperature control box were zero. Meanwhile, the temperature should remain stationary at the test value during the loading process.



(a) Radial loading (b) Tangential loading

Fig. 2. Bending test loading system

Three-point bending loading was used in the test, with the spacing of supports was 180 mm, and each end of the specimen extending outwards by 20 mm. The loading method was a combination of force and displacement control. When the temperature was lower than or equal to 60°C, the specimen was first loaded at 10 N/s to 70% of the ultimate load, and then loaded at 1 mm/min until the specimen was damaged; when the temperature was higher than 60°C, the load was first loaded at 5 N/s to 70% of the ultimate load, then at 0.5 mm/min until the specimen was damaged.

Test results and analysis

Specimen color changes

Since the whole process of heating, maintaining and loading of the specimens took place in the temperature control box, it was not possible to observe the specimens from the start of loading to fail, only the color and shape of the specimens after damage.

Fig. 3. Color change of the specimen with temperature

As shown in Fig. 3, the surface color of the specimens continued to deepen with the increase of temperature. At temperatures ranging from -60℃ to 20℃, the surface of the specimens was relatively bright, and the change was slight. This was because the main changes at this stage were due to the loss of water and volatile organic compounds, resulting in physical changes. Then the color of the specimens between 60℃ and 100℃ was slightly darker than before, but the original color of the LBL was still retained on the whole. When the temperature reached 130℃, the color of the specimens began to gradually deepen, and the surface of the specimens had all shown brown at 200℃. This was because the carbohydrates, cellulose components and phenolic resin in bamboo gradually decompose, and they were transferred from the inside to the outside of the specimens with the evaporation of water, finally deposited on the surface of the specimens.

Specimen failure modes

After comparing the failure modes of 132 specimens, they could be divided into the following three failure modes.

The failure mode I： as shown in Fig. 4 (a), no obvious bending deformation of the specimens occurred. Cracks appeared on the face D of the tensile zone perpendicular to the fiber direction, and evolved into full-length cracks, while cracks along the fiber direction extended from the middle to both ends. Cracks appeared on both faces A and C, with cracks perpendicular to the fiber direction extended from bottom to top, and cracks along the fiber direction extended from the middle to both sides. Comparing the specimens in the two directions, it could be found that the crack distribution area of the tangential specimens was larger. No obvious test phenomenon was observed on the face B of the specimen, and no yield occurred.

The failure mode II: as shown in Fig. 4 (b), the specimens showed apparent bending deformation and buckling. Cracks appeared on the face D perpendicular to the fiber direction and eventually extended into full-length cracks, but did not extend further along the fiber direction. Cracks also appeared on faces A and C, among which cracks perpendicular to the fiber direction appeared on the surface of radial specimens, extending from bottom upwards to about 1/3 of the height of the specimens; while cracks extending not only perpendicular to the fiber direction but also along the fiber direction appeared on the surface of the tangential specimens, and extended from the middle of the specimens to both sides. The bamboo fibers on the face B appeared to be wrinkled and yield.

The failure mode III: as shown in Fig. 4 (c), the specimens underwent bending deformation. There was no obvious crack in the tensile zone on face D. Faces A and C cracked along the splicing layer of the bamboo unit and extended to the middle of the specimens along the fiber direction, The damage was concentrated on one side of the specimens, with no obvious phenomenon on the other side. The indentation on the face B yielded under compression. The adhesive layer failure occurred in the tangential specimens at 185℃, while it occurred in the radial specimens only when the temperature reached 200℃. And the adhesive layer cracking position of radial specimens was located in the middle part, while it was distributed in the middle and lower parts of the tangential specimens.

(a) Failure mode I (b) Failure mode II

(c) Failure mode III

Fig. 4. Failure modes of bending specimens

Subsequently, the number of specimens with the above three failure modes in the bending test was counted, as shown in Table 2. It could be found that the failure mode I was mostly the failure mode shown by the specimens under low temperatures (-60℃~-20℃), which was because the specimens would be hardened to a certain extent. When the specimens were failed, the face B did not yield, and the cracks on the faces A, C and D extended more along bamboo fibers. Between 0℃ and 185℃, the vast majority of specimens occurred in the failure mode II. With the gradual increase of temperature, both the bamboo fibers and the adhesive showed softening, so that when the specimens were failed, yielding occurs on the face B and cracks on the faces A, C and D did not extend very long. Failure mode III occurred only under the high temperatures of 185℃ and 200℃, which was due to the instability of phenolic resin adhesive and the sharp decrease of bonding performance when the temperature exceeded 180℃. As the test continued, the adhesive layer failed when the bamboo fiber was not significantly damaged, and finally the specimens underwent adhesive layer damage. In conclusion, failure mode II was the most common failure mode in this test.

Table 2. Summary of observed failure modes in specimens

Group	Failure mode I	Failure mode II	Failure mode III	Total
BLV	15	42	9	66
BLH	16	38	12	66
Total	31	80	21	132

By comparing the effects of test temperature and loading direction on the failure mode of specimens, it could be found that both factors would affect the failure modes of specimens. Among them, the temperature would directly affect whether the compressed surface of the specimen yielded and whether the adhesive layer failure occurred, which in turn determined the failure modes of the specimens. The loading direction would affect the extension direction, extension length and cracking location of the crack on the surface of specimens.

Calculation results

The bending strength of the specimen was calculated by the Eq. (1):

$$f = \frac{3P_{max} l}{2Ah} \tag{1}$$

Where, f was bending strength, P_{max} was ultimate load, l was the span of specimen, $l = 180$ mm, A was the section area of specimen, h was the section height of specimen.

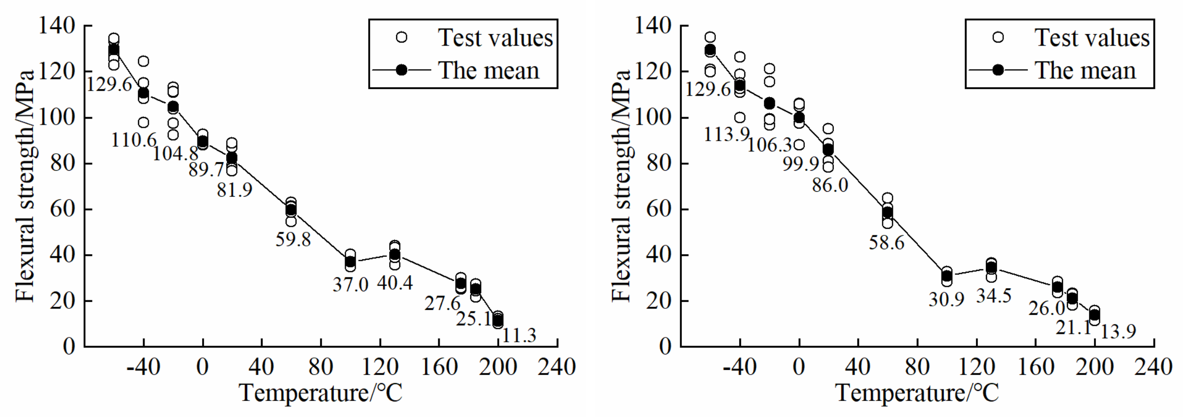
The bending elastic modulus of the specimen was calculated by the Eq. (2):

$$E = \frac{P_e l^3}{48 w_e I} \tag{2}$$

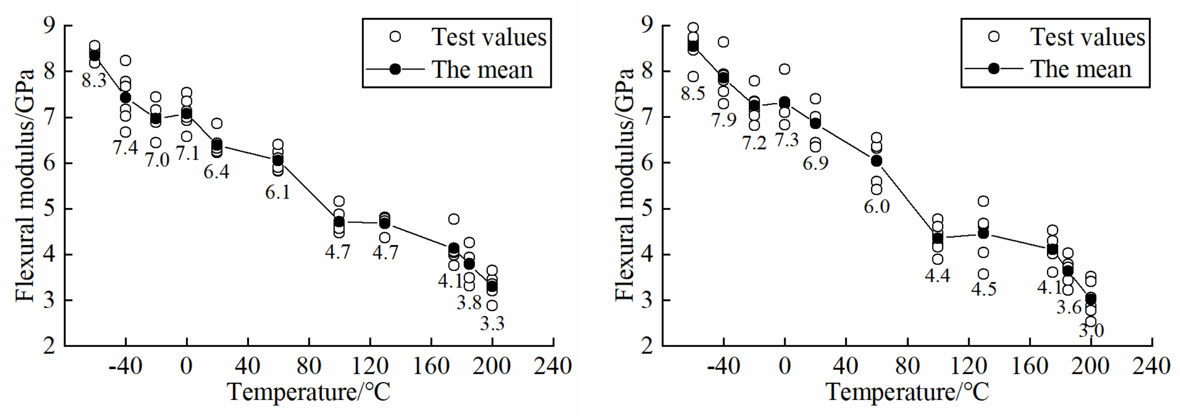
Where, E was bending elastic modulus, P_e, w_e were the load in the elastic phase and the corresponding displacements respectively, l was the span of specimen, $l = 180$ mm, I was the cross-section moment of inertia.

Bending strength

The curves of bending strength with temperature for the radial and tangential specimens were given in Fig. 5 (a) and (b), which showed the bending strength of specimens decreased continuously with the increase of temperature. The factors affecting the bending strength of bamboo at different temperatures were complex, including the test temperature, moisture content of the specimens, the softening effect of bamboo adhesive and the coupling effect of temperature and moisture content.



(a) Bending strength of BLV (b) Bending strength of BLH



(c) Bending elastic modulus of BLV (d) Bending elastic modulus of BLH

Fig. 5. Comparison of test results The bending strength of the specimens under low temperature conditions (-60°C to 0°C) was significantly greater than that at normal temperature and high temperature. This was because the moisture content of the specimens was higher at low temperature, while the moisture content of the specimens and its distribution changed as the temperature increased, resulting in a gradual decrease in the strength of the bamboo material. Between 20°C and 100°C, the distribution of free water inside the specimen changed under the action of temperature. At the same time, the molecular motion of the cell wall material intensified, and the internal friction decreased, resulting in a decrease in the strength of bamboo. The radial bending strength decreasing from 81.94 MPa to 37.00 MPa and the tangential bending strength decreasing from 86.03 MPa to 30.91 MPa. Between 100°C and 130°C, due to the evaporation of water inside the bamboo, a crystalline protective film was formed on the surface of the specimen, which enhanced the bending strength of the specimen. Therefore, the bending strength at this stage did not decrease with the increase of temperature, but increased. Then the temperature further increased, the protective effect disappeared, and the bending strength continued to decrease with the increase of temperature. Moreover, the bamboo and the adhesive between bamboo units softened due to heat in the range of 130°C to 185°C, which

also led to a continuous decrease in bending strength from 40.37 MPa to 25.05 MPa in the radial direction and from 34.53 MPa to 21.11 MPa in the tangential direction. And when the temperature reached 200°C, the adhesive quitted working, the specimen cracked along the adhesive layer, and the rate of decrease in bending strength increased.

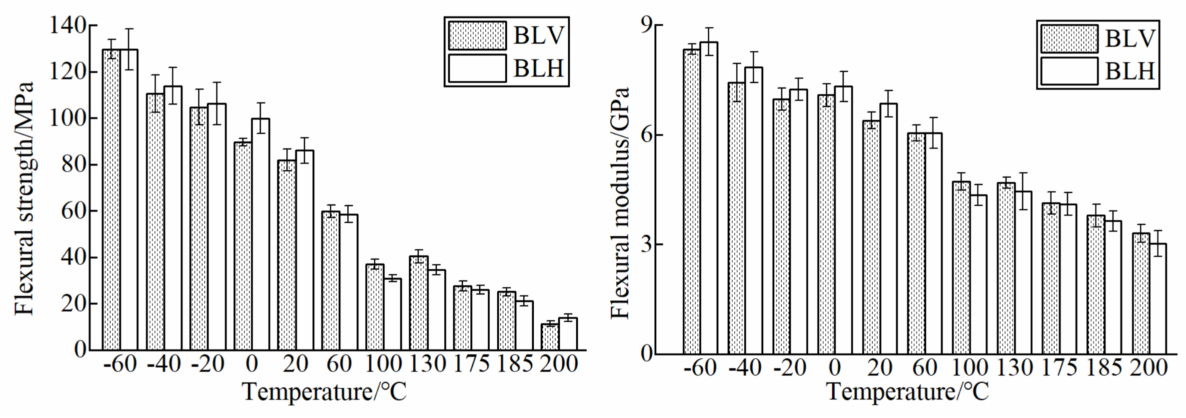
Bending elastic modulus

The curves of bending elastic modulus with temperature for the radial and tangential specimens were shown in Fig. 5 (c) and (d), the bending elastic modulus of specimens decreased continuously with the increase of temperature.

Under negative temperature conditions (-60°C to -20°C), a certain hardening of the bamboo fibers occurred, which made the bending elastic modulus of the specimens significantly higher than that at normal temperature and high temperature. In the temperature interval from -20°C to 0°C, a slight increase in bending elastic modulus occurred in both directions, which could be interpreted as a change in the free water content and distribution within the specimen when the temperature changed from negative to positive. As the positive temperature gradually increased, the water content within the bamboo gradually decreased, while the bamboo fibers would also soften, resulting in a continuous decrease in bending elastic modulus. From 0°C to 100°C, the radial bending elastic modulus decreased from 7.08 GPa to 4.72 GPa, and the tangential bending elastic modulus decreased from 7.32 GPa to 4.35 GPa. Between 100°C and 130°C, the bending elastic modulus of the specimens changed less due to the enhancement of the protective film formed by the evaporation of water. And then the temperature further increased, the bamboo fibers underwent pyrolysis reaction, resulting in bamboo strength loss increased, bending elastic modulus decreased rate also increased.

Loading direction comparison

Fig. 6 (a) and (b) respectively compared the bending strength and bending elastic modulus of radial and tangential bending specimens at 11 temperatures. It can be found from the histogram that there was not much difference between the bending strength and bending elastic modulus in both directions at all test temperatures, which indicated that the radial and tangential bending properties of LBL are similar.



(a) Comparison of bending strength (b) Comparison of bending elastic modulus

Fig. 6. Comparison of test results in different loading directions

The maximum value of bending strength in both directions was obtained at low temperature (-60°C) and the minimum value was obtained at high temperature (200°C). The maximum radial bending strength was 129.60 MPa and the minimum was 11.30 MPa; the maximum tangential bending strength was 129.58 MPa and the minimum was 13.90 MPa. From -60°C to 200°C, the radial bending strength decreased by 91.28%, and the tangential bending strength decreased by 89.27%. At -60°C, the radial and tangential bending strength was almost equal. Between -40°C and 20°C, the tangential bending strength was always greater than the radial; when the temperature rose to 60°C, the radial bending strength began to be greater than the tangential; until 200°C, the tangential bending strength was greater than the radial again.

However, in general, the difference of bending strength in both directions at 11 temperatures was not large.

The bending elastic modulus in both directions also reached maximum at low temperature (-60℃) and minimum at high temperature (200℃). The maximum radial bending elastic modulus was 8.34 GPa and the minimum was 3.30 GPa, the maximum tangential bending elastic modulus was 8.54 GPa and the minimum was 3.02 GPa. From -60℃ to 200℃, the radial bending elastic modulus decreased by 60.43%, and the tangential bending elastic modulus decreased by 64.64%. In the range of -60℃ to 20℃, the tangential bending elastic modulus was always greater than the radial bending elastic modulus; when the temperature rose to 60°C, the bending elastic modulus of the two directions was nearly equal; subsequently, the temperature further increased, and the decrease of the tangential bending elastic modulus increased, and the radial bending elastic modulus was greater than the tangential bending elastic modulus.

It could be found that the loading direction had no significant effect on the bending strength and bending elastic modulus of the specimens, and the bending properties of the radial and tangential bending specimens were relatively close at various temperatures. The test results showed that the bending performance of the tangential specimens was slightly better than that of the radial specimens below 60℃; above 60℃, the bending performance of the radial specimens was better.

Comprehensive analysis

Mass loss rate

The Eq. (3) gave the calculation method of mass loss rate of specimens， which was calculated from the difference of specimen quality before and after the test.

$$w = \frac{|M_1 - M_2|}{M_1} \tag{3}$$

Where, w was the mass loss rate, M_1 was the mass of the specimen before the test, and M_2 was the mass of the specimen after the test.

It was found that the mass of the specimen was almost unchanged before and after the test at low and normal temperature. Only at high temperature, with the increase of temperature, the mass of the specimen decreased gradually. Therefore, the curves of mass loss rate in the range from 20℃ to 200℃ were plotted in Fig. 7.

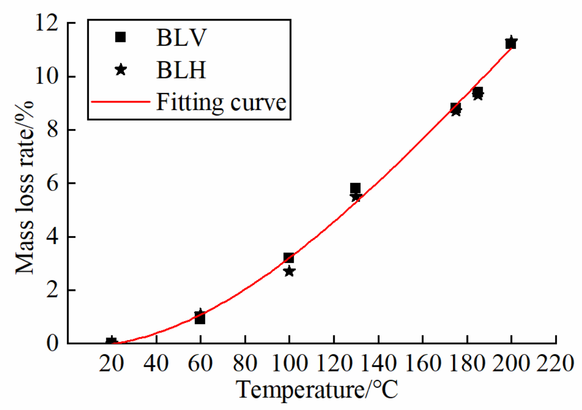


Fig.7. Curve of mass loss rate with temperature

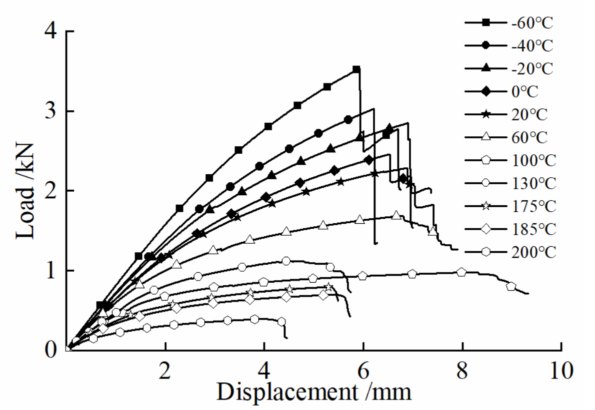
The results showed that the mass loss rate of the specimen was very small and the growth was very slow, only about 1% between 20℃ and 60℃; when the temperature increased to 100℃, the evaporation of water inside the specimen gradually increased, resulting in the speed of specimen mass loss began to accelerate, and the mass loss rate reached about 3%. Subsequently, the temperature further increased, the moisture content of the specimen continued to decrease, and the hemicellulose and cellulose in the bamboo began to decompose, resulting in the increase of mass loss rate. When the temperature reached 200℃, the lignin inside the bamboo also began to decompose, and the cell wall of bamboo fiber was further decomposed, and the mass loss rate was significantly increased to more than 10%. Zhang et al. (2013b) Hakkou et al. (2005) and Zhong et al. (2016) found similar trends in their research on the influence of high temperature on bamboo, hard wood species and bamboo scrimber.

Through the analysis of test results, the difference in mass loss rate of two directions was small, which could be neglected, so both can be expressed according to Eq. (4):

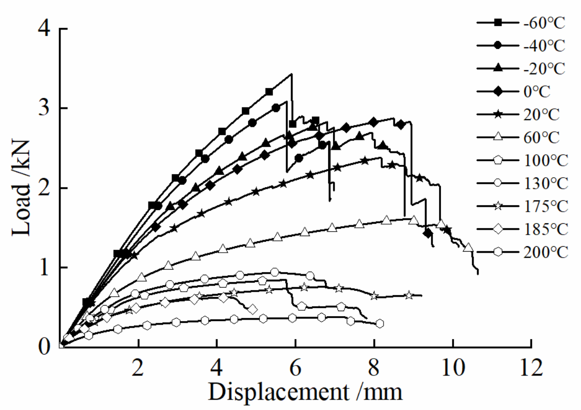
$$w = -7.59\times10^{-9}T^3 + 4.55\times10^{-6}T^2 - 4.88\times10^{-5}T - 0.001 \qquad (20°C \le T \le 200°C) \tag{4}$$

Load-displacement relationship

Fig. 8 (a) and (b) showed the load-displacement curves of the radial and tangential specimens, respectively. Comparing the two figures, it could be found that the curve shapes and change trends in both directions were similar, and they all went through the elastic stage, elastic-plastic stage and damage stage.



(a) BLV



(b) BLH

Fig. 8. Load-displacement curve

In the initial stage of loading, the relationship between axial displacement and load increased linearly. As the test continued, when the load increased to 60%~70% of the ultimate load, the deformation of the specimen entered the elastic-plastic stage and the slope of the curve decreased, Therefore, it could be inferred that the compression area of the specimen began to yield and the tensile area began to crack at this stage. When the load increased to near the ultimate load, the tearing sound of the bamboo could be heard. After reaching the ultimate load, the bamboo pieces in the tensile area at the bottom of the specimen fractured and the load decreased. It was noteworthy that between -60℃ and 20℃, the falling section of the load-displacement curve of the specimen after reaching the ultimate load presented a ladder shape, that is, the load first decreased and then increased, but did not exceed the ultimate load of the specimens. The reason for the ladder shape of the falling section of the load-displacement curve may be due to the fact that compared with the high temperature, the moisture content of the specimens was higher between -60℃ and 20℃, and the specimen was “harder”, resulting in that the cracks in the tensile zone did not penetrate the whole section in the first time, and the specimen could still withstand part of the load, thus causing multiple fractures. At the same time, the LBL was a layered structure, so even if the external bamboo pieces were stretched and broken, the internal bamboo pieces could still bear some loads. Between 60℃ and 200℃, as the temperature continued to rise, the chemical composition of bamboo began to soften, the moisture content decreased, and the specimen became “softer”. Therefore, the ladder shape of the load-displacement curve disappeared, showing an oblique linear decline, but the decline rate was different. The curve fell more gently between 60℃~130℃, and the rate of load drop increased between 175℃~200℃.

Analysis of reduction (increase) factor

In order to describe the bending strength and bending elastic modulus of the specimen at different temperatures conveniently, taking the normal temperature (20℃) as the reference temperature, the bending strength and bending elastic modulus at other temperatures were compared with the bending strength and bending elastic modulus at the 20℃, and the reduction (increase) factor of bending strength and bending elastic modulus were calculated respectively. Those greater than 1 were called the increase factor, and those less than 1 were called the reduction factor.

Reduction (increase) factor

Table 3 listed the temperature reduction (increase) factors of bending strength and bending elastic modulus of LBL at 11 temperatures.

Table 3. Bending strength and bending elastic modulus reduction (increase) factors

Factor	-60℃	-40℃	-20℃	0℃	20℃	60℃	100℃	130℃	175℃	185℃	200℃
$f_{T,BLV}$ / $f_{20,BLV}$	1.58	1.35	1.28	1.09	1.00	0.73	0.45	0.49	0.34	0.31	0.14
$f_{T,BLH}$ / $f_{20,BLH}$	1.51	1.32	1.24	1.16	1.00	0.68	0.36	0.40	0.30	0.25	0.16
$E_{T,BLV}$ / $E_{20,BLV}$	1.31	1.16	1.09	1.11	1.00	0.95	0.74	0.73	0.65	0.59	0.52
$E_{T,BLH}$ / $E_{20,BLH}$	1.25	1.15	1.06	1.07	1.00	0.88	0.64	0.65	0.60	0.53	0.44

Notes: $f_{T,BLV}$ was the bending strength of the radial specimens at different temperatures; $f_{T,BLH}$ was the bending strength of the tangential specimens at different temperatures; $f_{20,BLV}$ and $f_{20,BLH}$ were the bending strength of radial and tangential specimens at 20°C, respectively. $E_{T,BLV}$ was the bending elastic modulus of the radial specimens at different temperatures; $E_{T,BLH}$ was the bending elastic modulus of the tangential specimens at different temperatures; $E_{20,BLV}$ and $E_{20,BLH}$ were the bending elastic modulus of radial and tangential specimens at 20°C, respectively.

Under normal temperature (20℃), the radial bending strength was 81.94 MPa, and the tangential was 86.03 MPa. Compared with normal temperature, the radial bending strength at low temperature (-60℃) increased by 58.16%, the tangential increased by 50.62%; and the radial bending strength at high temperature (200℃) decreased by 86.21%, the tangential decreased by 83.84%.

Under normal temperature (20℃), the radial bending elastic modulus was 6.39 GPa, and the tangential was 6.84 GPa. Compared with normal temperature, the radial bending elastic modulus at low temperature (-60℃) increased by 30.52%, the tangential increased by 24.85%;

and the radial bending elastic modulus at high temperature (200°C) decreased by 48.36%, the tangential decreased by 55.85%.

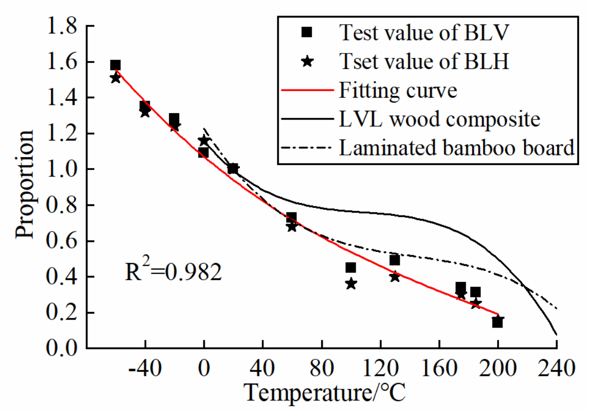
Empirical formula for the reduction (increase) factor

Fig. 9 (a) was the curve of bending strength reduction (increase) factor with temperature for LBL in radial and tangential directions, which showed a non-linear downward trend with increasing temperature. Eq. (5) was fitted according to the curve to express the temperature reduction (increase) factors of the bending strength in radial and tangential directions.

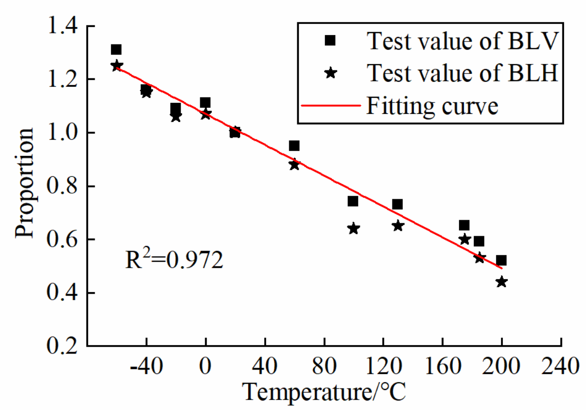
$$f_T / f_{20} = -3.07\times10^{-8}T^3 + 1.86\times10^{-5}T^2 - 6.88\times10^{-3}T + 1.07 \quad (-60°\text{C} \le T \le 200°\text{C}) \quad (5)$$

Where, f_T was the bending strength of specimens at different temperatures, f_{20} was the bending strength at 20°C.

The fitted correlation coefficient R^2 was 0.982, indicating a high degree of agreement between the fitted and measured values.



(a) Bending strength



(b) Bending elastic modulus

Fig. 9. Reduction (increase) factor curve

Fig. 9 (b) was the curve of bending elastic modulus reduction (increase) factor with temperature for LBL in radial and tangential directions, which showed a downward trend as a whole and was approximately linear. Moreover, the factors and variation trends of radial and tangential directions were close, so they could be expressed as Eq. (6):

$$E_T / E_{20} = -2.89 \times 10^{-3} T + 1.07 \qquad (-60°C \le T \le 200°C) \tag{6}$$

Where, E_T was the bending elastic modulus of specimens at different temperatures, E_{20} was the bending elastic modulus at 20℃.

The fitted correlation coefficient R^2 was 0.972, indicating a high degree of agreement between the fitted and measured values.

Comparison of current research formulas

Zhong et al. (2014a; 2014b) studied the bending performance of laminated bamboo board and LVL wood composite at high temperatures, and proposed the relationship model between bending strength and temperature, as shown in Eq. (7) and Eq. (8) respectively:

$$f_t = -5.360 \times 10^{-5} t^3 + 2.260 \times 10^{-2} t^2 - 3.465t + 324.770 \quad (20°C \le t \le 225°C) \tag{7}$$

$$f_t = -2.638 \times 10^{-5} t^3 + 8.607 \times 10^{-3} t^2 - 9.495 \times 10^{-1} t + 100.611 \quad (20°C \le t \le 225°C) \tag{8}$$

Fig. 9 (a) also showed the variation of the bending strength reduction factors of laminated bamboo board and LVL wood composite at high temperatures. It was found that the factors showed a nonlinear decreasing trend with the increase of temperature, but showed different characteristics. It could be seen that the bending strength reduction factors of LVL wood composite was distributed over the factors of the other two. The bending strength reduction factors of laminated bamboo board at high temperature was closer to that of LBL, but there was still a certain gap. This indicated that neither of the two models was suitable for predicting the variation law of the bending strength reduction factor of LBL.

There was no empirical formula for the reduction factors of wood bending strength at high temperature in BS EN 1995-1-2 (2004), and the formula proposed in the existing research was not accurate for the prediction of LBL. Therefore, it is necessary and essential to formulate specific standard applicable to bamboo.

Conclusion

The following conclusions can be drawn from the test results on the bending performance of LBL exposed to different temperatures.

（1）The specimens showed different failure modes in different temperature ranges, which could be summarized into three failure modes: the specimens in Mode I was not bent, cracks appeared on the faces A, C and D, and the face B did not yield; in mode II, the specimens was obvious bending, cracks appeared on faces A, C and D, and yield on face B; in mode III, the specimens were bent, and adhesive layer failure occurred. At the same time, the radial and tangential specimens also had certain differences under the corresponding failure modes, which were manifested in the crack direction, extension length and crack location.

（2）Under low and normal temperature conditions, the mass loss rate of bending specimens before and after test was almost 0. However, as the temperature increased, the moisture inside the bamboo began to evaporate and the mass loss of the specimens began to increase. After further increase of temperature, the fibers inside the bamboo decomposed and the mass loss rate kept increasing.

（3）Under normal temperature (20°C), the bending strength in the radial and tangential directions was 81.94 MPa and 86.03 MPa, the bending elastic modulus was 6.39 GPa and 6.84 GPa. Compared with normal temperature, the bending strength in the radial and tangential directions at low temperature (-60°C) increased by 58.16% and 50.62%, respectively; and the bending elastic modulus increased by 30.52% and 24.85%. At high temperature (200°C), the bending strength of radial and tangential direction decreased by 86.21% and 83.84% respectively, and the bending elastic modulus decreased by 48.36% and 55.85%.

（4）With the increase of temperature, the bending strength and bending elastic modulus of radial and tangential bamboo integrates showed an overall decreasing trend. However, a rising section appeared between 100℃ and 130℃, which was inferred to be the evaporation of water inside the bamboo material and the formation of a shell-like protective film, improving the bending performance of the specimens. Subsequently, the temperature continued to rise, the bamboo fiber composition further decomposed, and the bending strength and bending elastic modulus continued to decrease.

（5）Compared with the existing research on bending performance of bamboo and wood based on temperature effect, the bending strength reduction factors of LBL at high temperature also showed a downward trend. But the reduction factors in laminated bamboo board and LVL wood composite are not fully applicable for LBL. Therefore, the empirical equations with higher accuracy of bending strength and bending elastic modulus reduction (increase) factors of LBL with temperature change was proposed.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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