The Preparation of Laminated Timber Based on the Characteristics of Moso Bamboo

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Abstract:
China ranks first worldwide in rich in bamboo forestry and bamboo production whereby various bamboo composite boards have been developed so far. Meanwhile, it still faces many challenges associated with low lateral strength, poor dimensional stability, and large variability in different parts of bamboo. In this study, special attention was paid to the influence of bonding interface and bamboo pitch properties on the bonding performance of bamboo strips. The effects of 'micro-hole treatment' technology, bamboo pitch, hot pressing conditions and assembly method on the performance of bamboo laminated wood were investigated as well. The response surface analysis method was used to optimize the production of bamboo laminated timber via high temperature heat treatment of 5-year-old bamboo strips at a height of 3 meters from the ground. The results showed that the bonding interface forms (QQ, QH, and HH) exerted no significant impact on the shear strength, bending strength and elastic modulus of glued bamboo strips. Moreover, independently of whether bamboo strips had bamboo nodes or not, they imposed no significant effect on compressive strength and shear strength, but strongly influenced flexural strength, flexural modulus of elasticity and tensile strength of the timber. Besides that, the mechanical properties of non-jointed bamboo strips were superior to those of jointed bamboo strips, and the dislocation distance between adjacent bamboo strips in the range of 3-10 cm was beneficial for the improvement of the mechanical parameters of glued bamboo strips. The preparation process of laminated timber was optimized, which promoted the efficient utilization of bamboo and laid a foundation for the green processing and industrialization development of laminated timber.

Keywords: moso bamboo, bamboo characteristics, laminated timber, gluing form, bamboo node.

INTRODUCTION

In recent years, with the increasing concern for environmental protection, bamboo-based wood-based panels have aroused great interest as a potential green material in the domestic and international markets. The extensive development and utilization of bamboo-based man-made panels in China began in the 1970s, whereby seven major types of bamboo-based products including bamboo plywood, bamboo laminated timber, bamboo integrated timber, bamboo composite board, bamboo scrap board, bamboo flooring and reconstituted bamboo have been discovered [1]. For instance, the largest output in the bamboo-based panel industry localized in Fujian Province accounts for recombinant bamboo, bamboo laminated timber, and bamboo plywood. However, the fabrication technology of bamboo laminated timber products is not yet mature enough, being mainly employed for the production of small daily necessities or crafts, such as vegetable plates, tea plates, lamps and boxes [2]. Therefore, forestry authorities and related enterprises in Fujian Province look to upgrade bamboo laminated timber products so as to seize market opportunities. For this reason, a thorough study is required to establish the optimal preparation parameters of advanced bamboo laminated timber.

Currently, bamboo laminated timber in the market is presented by bamboo gabion laminated timber and bamboo bundle laminated timber. The research on bamboo laminates mainly includes preparation process, performance optimization, and quality influencing factors. Laminated bamboo gabion is produced from bamboo strips, which are horizontally or vertically placed and glued together into panels or beams under hot pressing [3]. Guan et al. [4] prepared double-layered bamboo laminates from charred moso bamboo by applying hot pressing at the temperature of 140℃ and the pressure of 1.2 MPa for 15 min. The glue amount of 140 g/m2 was used, and the gluing shear strength of the final product reached 12.6 MPa. Sumardi et al. [5] and De Lima et al. [6] found that the interface bonding form of bamboo lamination and the presence or absence of bamboo joints had a great influence on the bonding shear strength of the products. Bamboo-bundle laminated veneer lumber (BLVL) is a kind of bamboo laminated lumber made from traditional reconstituted bamboo, which is made of fibrous bamboo-bundle veneer after whole sheet treatment, dipping, drying, forming along the grain, intermittent hot pressing and other processes. This material has high mechanical strength and dimensional stability, and has high utilization rate of bamboo [7]. Brito et al [8] explored the bonding properties of laminated timber at different temperatures by resorcinol-formaldehyde (RF), urea-formaldehyde (UF), and crosslinked polyvinyl acetate (PVAc), and concluded that the structural stability of laminated timber heat-treated at 160 °C is the best. Li et al. [9] found that the position and bending direction of the internal nodes of bamboo laminated timber had a significant effect on its mechanical properties, especially the position of the internal link point had a greater influence on the tangential bending. Some scholars have also studied the prediction of the characteristics of bamboo-wood composite materials. For example, Niederwestberg [10] used the finite element method to predict the mechanical properties of bamboo-wood composite materials with high precision. Wu et al. [11] constructed the theoretical elastic model constants of the whole material by using the surface and core material properties of bamboo-wood composite materials. Bamboo glulam is also a research hotspot of bamboo-based wood-based panels, and its research contents and methods can also provide reference for the development of this paper. The study found that the mechanical properties of bamboo glulam with different assembly methods are very different. The mechanical properties of flat-pressed and flat-side-pressed bamboo glulam are relatively poor, which is suitable for non-heavy-duty weighing plate structure, while the mechanical properties of side-pressed bamboo glulam are excellent, which is suitable for various stress structures [12]. In the manufacturing process of bamboo glulam, Nguyen et al. [13] used phenolic resin as adhesive and discussed its high frequency hot pressing bonding technology. Sharma et al. [14] and Huang et al. [15] found that the vascular bundle density of bamboo from bamboo green to bamboo yellow had a gradient change, forming a gradient tissue structure, and this porous multi-level tissue structure gave bamboo unique flexibility. However, for bamboo laminated timber, the orientation and flexibility of bamboo make it face two major problems. One is that the mechanical properties of the vertical and horizontal directions are quite different, and the other is that it is prone to warping deformation [16]. Therefore, the current bamboo laminated products on the market are mainly used for small handicrafts, tea trays, etc., which cannot meet the needs of large structural panel materials such as furniture and bamboo buildings.

In view of the above, the present study aims to analyze the effect of bamboo nodes on the mechanical properties of laminated bamboo timber made from moso bamboo. Special attention is paid to the possibility to increase the interfacial gluing properties through low-carbon and environmental friendly physical methods, as well as to find the techniques improving the lateral mechanical characteristics of bamboo. The optimization of the hot pressing and forming process of bamboo laminated timber are also within the scope of this work. The final step of the research is dedicated to establishing the response relationship between the characteristics of bamboo and laminated timber.

MATERIALS AND METHODS

Moso bamboo (Phyllostachys edulis) (Figure 1) with the initial moisture content of 10-30%, produced in Xiaotao Town (Sanming, Fujian Province), was used in the experiment after heat treatment at 160°C for 5 h. The specific parameters of the material are shown in Table 1.

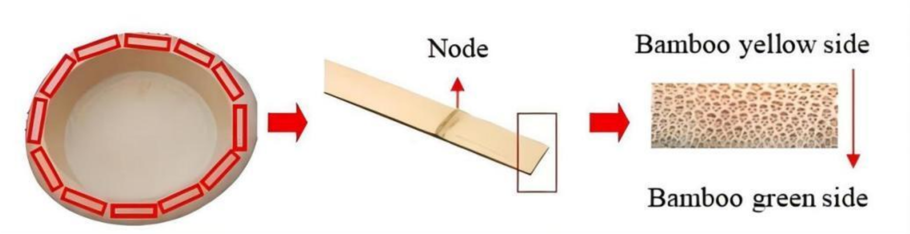


Figure 1. Tangential bamboo slabs

Table 1. Detailed parameters of moso bamboo

Takenaka	Bamboo age/a	Fetching height/m	Average diameter at breast/cm
Moso bamboo	5	3-4	10

The specific parameters of phenolic resin adhesives are shown in Table 2.

Table 2. Detailed parameters of phenolic resin adhesive

Adhesives	Solid content %	Curing time	Curing temperature	PH value
Phenolic resin adhesives	50.20	6′ 05″	130-150°C	9.59

The testing equipment included the universal mechanical testing machine (CMT5504), hot press (KS100H), constant temperature and humidity chamber (HWS-150Y), drying oven (DHG-9246A), biological digital microscope (Leica), constant temperature water bath, Petri dish, glass beaker, measuring cylinder, slide, coverslip, filter paper, tweezers, glue-tip dropper, Vernier caliper, band saw machine, home-made board X-ray section analyzer (IMAL), etc.

Study of factors affecting material properties

STUDY ON THE INFLUENCING FACTORS OF MATERIAL PROPERTIES

Study of Gluing Properties

Analysis of the influence of gluing interface on the gluing performance of bamboo strips

Straight defect-free chordwise bamboo slices with dimensions of 600 mm×20 mm×5 mm (length× width× thickness) were selected for three gluing experiments at a glue application rate of 130g/m2, via bonding two yellow sides (HH), two green sides (QQ), and the green and yellow sides (QH) (Figure 2). The specimens were hot-pressed at 1.2 MPa and 130°C for 15 min and then cooled for 48 h. After being processed with a band saw and numbered, the samples were stored under the conditions of 20℃ and 65% relative humidity until their mass was constant. The specimens were tested for gluing shear strength, flexural strength and flexural modulus of elasticity according to ASTM D906-20 [17] and ISO 22157-1:2004(E) [18] Standards ("Veneer laminated timber" and "Test method for physical and mechanical properties of bamboo timber", respectively), and the corresponding dimensions and test methods are depicted in Figure 3.

Figure 2. Three gluing methods

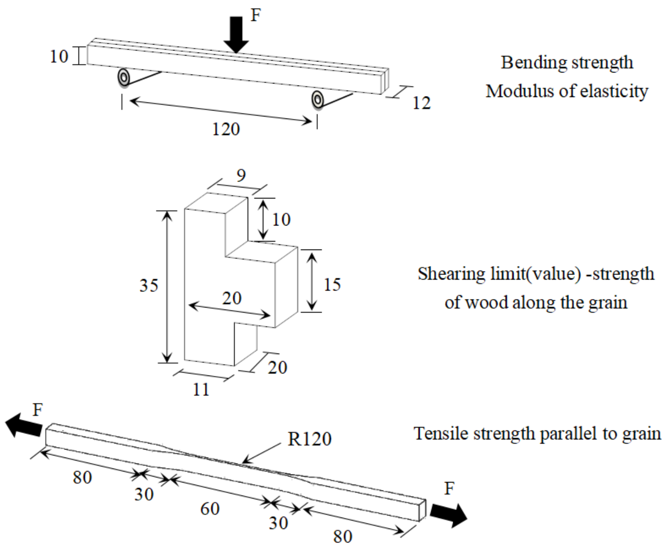


Figure 3. Sample size and test methods in mechanical strength testing

Study on the effect of pitch on the gluing performance of bamboo strips

Based on the glued surface optimization results, glued bamboo strips were further prepared with a bamboo joint spacing of 0 cm, 3 cm, 6 cm, and 10 cm (Figure 4). In turn, glued bamboo strips without bamboo joints were used as the reference to analyze the effects of bamboo joint spacing on the smooth compressive strength, flexural strength, flexural modulus, smooth shear strength, and smooth tensile strength. Considering the size of the specimens, only the flexural strength, flexural modulus of elasticity and smooth grain tensile strength were measured for the specimens with 3 cm, 6 cm and 10 cm pitches. The tests were repeated 20 times to record the damage profile and the moisture content, and the data were then analyzed after removing the error values.

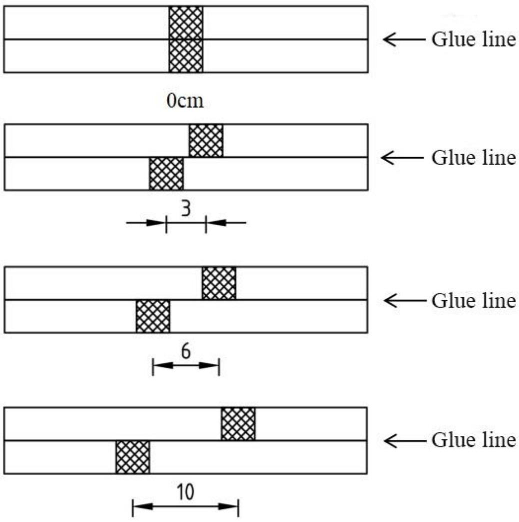


Figure 4. The design and gluing modes of bamboo node spacing

Influence of Processing Process on Material Properties

Microporous pretreatment process research

The bamboo slices with dimensions of 600 mm×20 mm×6 mm (length× width× thickness) were selected from defectless straight chordwise bamboo slices. After high-temperature heat treatment, micro-perforation was performed in the thickness direction conforming to CNC punching technique along the lengthwise direction, with the parameters of micro-perforation spacing, micro-perforation diameter and micro-perforation depth, as shown in Table 3. The specimens were then exposed to 48 h of aging, numbered and stored at 20°C and 65% relative humidity until their quality was constant. After that, the flexural strength and flexural moduli of samples were measured in transverse (vertical) and longitudinal (horizontal) directions, respectively, as shown in Figure 5. The test specimens without microporous pretreatment were used for the reference, and the measurements were repeated 16 times for each group of parameters.

Table 3. Single factor experimental design

Group number	Hole spacing/mm	Hole diameter/mm	Hole depth/mm
1	10	1.5	2
2	20	1.5	2
3	30	1.5	2
4	40	1.5	2
5	50	1.5	2
6	30	0.5	2
7	30	1.0	2
8	30	1.5	2
9	30	2.0	2
10	30	2.5	2
11	30	1.5	1
12	30	1.5	2
13	30	1.5	3

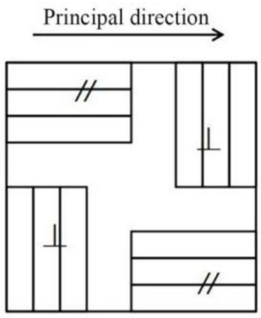


Figure 5. Sampling processing layout

Hot pressing

The straight and defect-free chordwise bamboo slices with dimensions of 600 mm×20 mm×6 mm (length× width× thickness) were selected for hot pressing procedure. After high-temperature heat treatment, In the thickness direction, the laser drilling technology is used to pretreat the micropores along the length direction. The pretreatment process is based on the analysis and optimization parameters. The micro-hole pretreated bamboo slabs were hot-pressed into 12 mm thick bamboo laminates, with the diameter surface between the same layers and the chord surface staggered between adjacent layers. Given that the main pressure used in the hot pressing (4 MPa) could not be adjusted, the hot press side pressure, hot press temperature and hot press time were selected as the influencing factors in response surface testing according to Table 4. The test specimens were numbered and stored at 20°C and 65% relative humidity until their mass was constant. Their flexural strength and flexural moduli of elasticity were then measured in the transverse (vertical) and longitudinal (horizontal) direction, respectively; the test specimen dimensions were 290 mm×50 mm×12 mm.

Table 4. Experimental Design

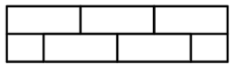
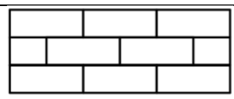
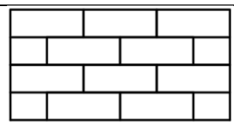
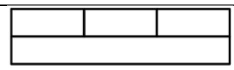
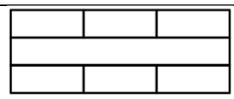
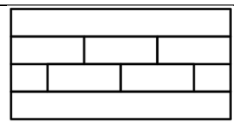
Group number	Hot pressing time/min	Hot pressing temperature/°C	Hot press side pressure/MPa
1	8	155	2
2	8	135	3
3	8	145	4
4	12	135	4
5	14	145	4
6	12	135	2
7	10	145	1
8	14	135	1
9	10	145	2
10	10	155	4
11	8	135	1
12	12	145	2
13	12	145	2
14	12	145	3
15	10	155	4
16	8	155	2
17	12	145	3
18	14	155	1
19	10	145	1
20	14	155	3

Study on the influence of assembly method

The straight and defect-free chordwise bamboo slices with dimensions of 600 mm × 20 mm × 6 mm (length × width × thickness) were selected. After high-temperature heat treatment, In the thickness direction, the laser drilling technology is used to pretreat the micropores along the length direction, and the pretreatment process is analyzed and optimized according to the parameters.

After the micro-hole pretreatment, the bamboo slabs were hot-pressed into 12 mm thick bamboo laminates (600×600×12 mm) in six ways conforming to the parameters shown in Table 5. The test specimens were numbered and stored at 20°C and 65% relative humidity until their mass was constant. Their flexural strength and flexural moduli were then measured in the transverse (vertical direction) and longitudinal (parallel direction) directions, respectively. The samples were afterward exposed to X-ray sectional density (DPX) experiments. The trials were repeated 18 times for each group of parameters.

Table 5. Assembling patterns

	Number of layers	Single layer thickness/mm	Direction	Figure explanation
Isotropic assembly	2	6	‖→‖	
	3	4	‖→‖→‖	
	4	3	‖→‖→‖→‖	
	2	6	‖→⊥	
Interlaced assembly	3	4	‖→⊥→‖	
	4	3	‖→⊥→⊥→‖	

Validation tests

According to the optimized production process, the bamboo laminated products with dimensions of 1800 mm×2100 mm were prepared for subsequent testing of their static flexural strength (MOR) and flexural modulus of elasticity (MOE). To assess the impregnation and peeling properties, specimens were boiled in boiling water for 4 h, dried in a drying oven at 63℃ for 20 h, then boiled again for 4 h and dried for 3 h. Consider the production reality and set up a comparison scheme.

RESULTS AND DISCUSSION

The Gluing Properties

The influence of the gluing interface on the gluing performance

The results on flexural strength, flexural modulus of elasticity and gluing shear strength, obtained via different gluing modes, are shown in Figures (6 to 8) and Table 6. According to the data, the P-values were less than 0.05, which indicated that the effect of gluing surface on the mechanical strength was negligible. Therefore, there was no need to consider the selection of gluing surface when forming blanks.

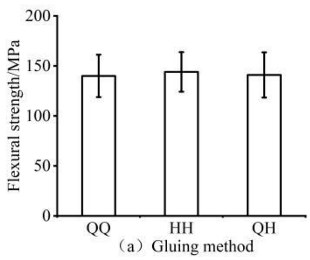


Figure 6. MOR for different bonding surfaces

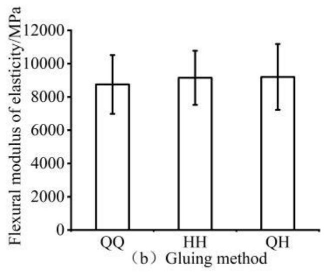


Figure 7. MOE for different bonding surfaces

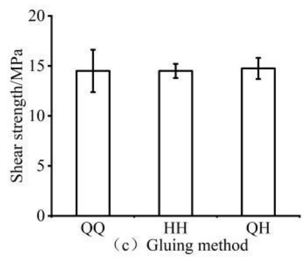


Figure 8. shear strength for different bonding surfaces

Table 6. Variance analysis data

Mechanic property	P-value	Statistical significance
MOR	0.64889	Not significant
MOE	0.33946	Not significant
Shear strength	0.34596	Not significant

The effect of bamboo pitch on gluing performance

Compressive strength along the grain

The mean compressive strength of glued bamboo strips without bamboo nodes was 51.9 MPa with a coefficient of variation of 5.76. In turn, the mean compressive strength of strips with zero node spacing was 50.4 MPa with a coefficient of variation of 6.72 (Figure 9). Thus, the effect of bamboo nodes on the compressive strength was not significant (Table 7). The main cells in bamboo contain the basic tissue and the vascular system, in which the basic tissue is predominately composed by axial thin-walled tissue cells and the vascular system is made by thick-walled vascular bundles [19]. When the vascular bundle content is at a moderate level, there is the interaction between vascular bundles and basic tissues, causing the emergence of extrusion damage, as shown in Figure 10(a). If the vascular bundles are not uniformly distributed, damage will occur first at their sparse sites. Under the prolonged effect of pressure, the splitting will arise upon continuous tearing along the fiber direction, as shown in Figure 10(b).

Table 7. Variance analysis data

Source of difference	SS	df	MS	F	P-value	Statistical significance
Intergroup	31.87562	1	31.87562	0.815967	0.357491	Not significant
Within the group	1601.109	40	40.03649			
Total	1633.095	41				

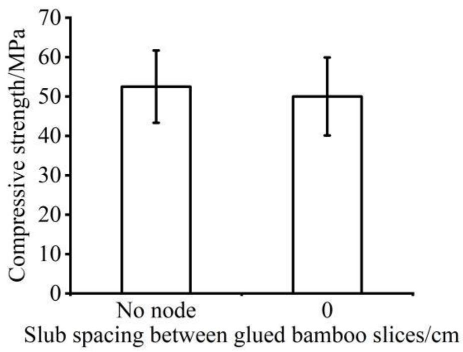


Figure 9. Compressive strength without and with nodes

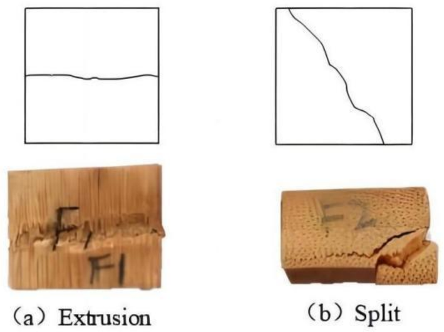


Figure 10. Failure patterns

Flexural strength and flexural modulus of elasticity

The mean flexural strength of glued bamboo strips without bamboo nodes was 141.7 MPa with a coefficient of variation of 15.39, whereas that of strips containing bamboo nodes with zero spacing between them was 92.4 MPa with a coefficient of variation of 13.28. The corresponding values for glued bamboo strips with bamboo nodes spaced 3 cm, 6 cm and 10 cm apart were 108.7 MPa, 110.9 MPa and 110.7 MPa at the coefficients of variation of 17.79, 13.98 and 14.96 respectively. The mean flexural strength of the 6-cm glued bamboo strips with bamboo nodes was 110.9 MPa with a coefficient of variation of 13.98, and the relevant value for the 10-cm glued bamboo strips with bamboo nodes was 110.7 MPa with a coefficient of variation of 14.96 (Figure 11(a)). The highest values of flexural strength were obtained for the bamboo strips without bamboo nodes, and the increase in node spacing from 0 cm to 3 cm led to the increase in flexural strength of the bamboo material by 17.04%. However, once the spacing increased from 3 cm to 10 cm, the flexural strength increased by 2.20% and then decreased by 0.54%. Combined with the variance analysis data (Table 8), the change of bamboo node spacing exerted no noticeable effect on the flexural strength when the bamboo node spacing was greater than 3 cm.

The mean flexural modulus of elasticity of glued bamboo strips without bamboo nodes was 9135 MPa with a coefficient of variation of 1212.19. The relevant value for bamboo strips with bamboo nodes was 9089 MPa with a coefficient of variation of 1156.12, and that of strips with bamboo nodes spaced 10 cm apart was 8789 MPa with a coefficient of variation of 1276.87 (Figure 11(b)). Thus, the greatest flexural modulus of elasticity was achieved in glued bamboo strips without bamboo nodes, and this parameter increased by 13.08% with the increase in node spacing from 0 cm to 6 cm. However, the modulus of flexural elasticity decreased by 3.27% with a further increase in pitch from 6 cm to 10 cm. Taking the ANOVA results into account (Table 8), it was found that the variation of bamboo node spacing did not have a significant effect on the flexural modulus of elasticity when the node spacing was greater than 6 cm.

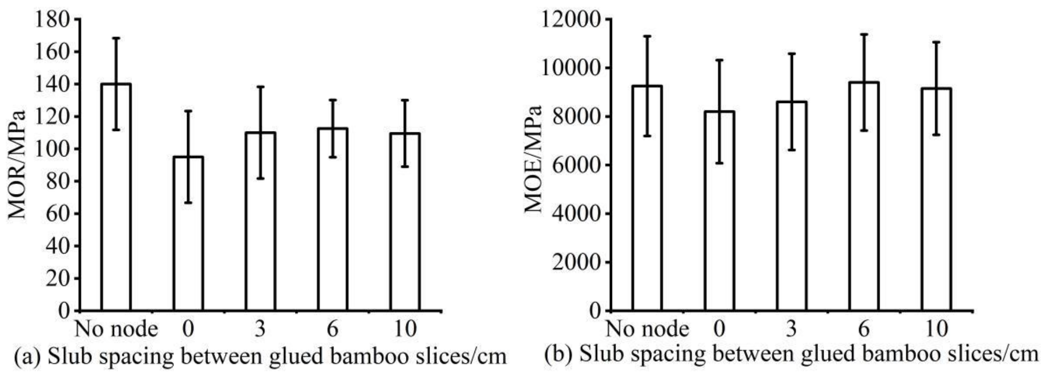


Figure 11. Effects of node spacing on strength: (a)MOR; (b)MOE

Table 8. Variance analysis data on MOR and MOE with different node spacing

	Bamboo pitch/cm	P-value	Statistical significance
MOR	0, 3, 6, 10	0.001040	Significant
	3, 6, 10	0.856025	Not significant
MOE	0, 3, 6, 10	0.054368	Not significant
	0, 3, 6	0.024936	Significant
	3, 6, 10	0.342381	Not significant

The bending damage specimens with 0 cm, 3 cm, 6 cm and 10 cm pitches of glued bamboo strips were further divided into tensile and crushing types conforming to their damage patterns. The tensile damage occurred mainly on the tensile side of the specimen, and the shear damage caused the bamboo fibers to slide. In turn, crushing arose on the tensile or compressive side of the specimen due to the relatively low density of vascular bundles and the damage of thin-walled axial tissues under pressure (Figure 12).

Glued bamboo strips with zero pitch could have undergone damage at the nodes for two reasons. First, the vascular fibers at the nodes had a curved form, reducing their strength and modulus of elasticity. Second, the cellular tissues composing culm sheath rings and septa intersperses in the longitudinal fibers shortened the vascular bundles and caused a decrease in their strength. There are different forms of damage occurring at bamboo nodes: pulling, interlaminar pulling, splitting, and crushing. Among them, crushing takes its place when the axial thin-walled tissue in the node section exceeds the vascular bundle content. Splitting is observed when the axial thin-walled tissue in the node section is lower than the vascular bundle content and the bundles are evenly distributed. At last, pulling and interlaminar pulling occur when the vascular bundles are not evenly distributed. The damage types observed in glued bamboo strips with 3 cm pitches were: interlaminar pulling at the bamboo nodes, splitting pulling and crushing at the middle of the two bamboo nodes. Since the axial thin-walled tissue in the nodes was lower than the vascular bundle content and the bundles were unevenly distributed, the fiber structure underwent interlaminar breakage. In the absence of nodes, the kind of damage depended on the amount of vascular bundles: the high vascular bundle content led to splitting and pulling, while the low vascular bundle content was conducive to crushing. The types of damage in glued bamboo strips with 6 cm pitches were pulling, interlaminar pulling, splitting pulling and crushing, all proceeding at the middle of two bamboo nodes. The kind of damage was determined by the content and distribution uniformity of vascular bundles: in the case of abundant and unevenly distributed vascular bundles, pulling and interlaminar pulling were the predominant damage mechanisms. In turn, the multiple and uniformly distributed vascular bundles were beneficial for splitting and pulling, whereas scarce vascular bundles promoted crushing. The damage types of glued bamboo strips with 10 cm pitches were pulling, interlaminar pulling, splitting pulling and crushing, all occurring in the middle of two bamboo nodes (±2 cm). The damage type was dependent on the level of vascular bundle content and the uniformity of vascular bundle distribution: at the high amount of vascular bundles and their uneven distribution, pulling off and interlaminar pulling off were observed. On the contrary, high content of vascular bundle and their uniform distribution were conducive to splitting and pulling off. Finally, crushing took its place at the low vascular bundle content.

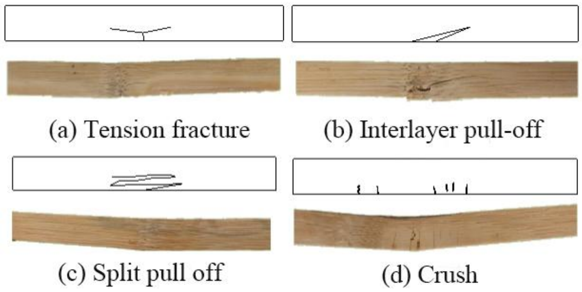


Figure 12. Failure patterns

Shear strength

The mean shear strength of glued bamboo strips without bamboo nodes was found to be 10.0 MPa with a coefficient of variation of 2.51, and the relevant value for strips with zero node spacing was 10.7 MPa with a coefficient of variation of 3.16 (Figure 13). Thus, the effect of bamboo nodes on the compressive strength of strips was negligible (Table 9).

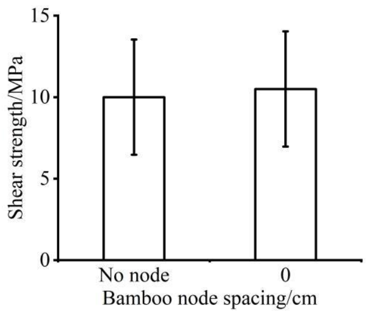


Figure 13. Shear strength

Table 9. Variance analysis data

Source of difference	SS	df	MS	F	P-value	Statistical significance
Intergroup	5.918967	1	5.918967	0.718982	0.401393	No Significance
Within the group	311.4758	38	8.184501			
Total	317.4430	39				

Tensile strength

The mean tensile strength of bamboo strips without bamboo nodes was 168.7 MPa with a coefficient of variation of 19.85, whereas that of strips with zero distance between bamboo nodes enriched 100.9 MPa at a coefficient of variation of 13.74. The mean tensile strength of bamboo strips with bamboo nodes spaced 3 cm, 6 cm and 10 cm apart was 114.9 MPa, 121.7 MPa and 148.5 MPa with the coefficients of variation of 15.63, 16.87 and 21.62, respectively. In turn, the mean tensile strength of the 6-cm and 10-cm glued bamboo strips with bamboo nodes was 121.7 MPa and 148.5 MPa at the coefficients of variation of 16.87 and 21.62, respectively (Figure 14). Therefore, the highest values of tensile strength were found for glued bamboo strips without bamboo nodes. At the same time, the increase in node spacing from 0 to 10 cm led to the increase in tensile strength of bamboo strips by 47.49%. Therefore, bamboo nodes exerted a strong impact on the tensile strength of strips (Table 10).

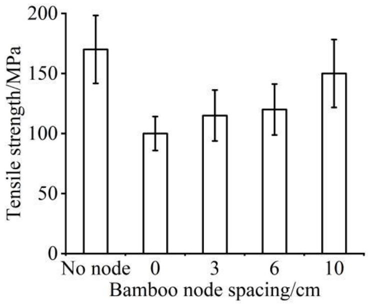


Figure 14. Tensile strength

Table 10. Variance analysis data

Bamboo pitch/cm	P-value	Statistical significance
3, 6, 10	2.78E-07	Significant

In the tensile strength tests, the main forms of damage split along the bamboo nodes were manifested by tensile shear damage, brittle tensile or shear damage. Conforming to other mechanical tests, these kinds of damage were inseparable from the content and dense distribution of vascular bundles at the bamboo nodes and the culm sheath ring structure, which also confirmed that bamboo nodes had a large influence on the tensile strength of the specimens (Figure 15).

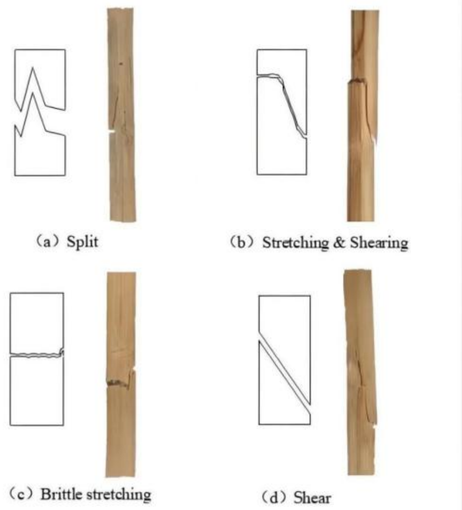


Figure 15. Failure patterns

Study on Microporous Pretreatment Process of Chordwise Bamboo Strip

Microporous spacing

The spacing between micropores has a significant effect on MOR and MOE (Table 11): independently of whether being parallel or perpendicular to the main direction of strips, the MOR and MOE parameters show first the upward and then downward trend at the spacing greater than 30 mm. A comparative analysis of data before and after microporous pretreatment revealed the increase in the MOE perpendicular to the main direction in the treated specimens, and the relevant values at the spacing of 30 mm and 50 mm were close to each other. In turn, the MOE parallel to the main direction, MOR parallel to the main direction and MOR perpendicular to the main direction were either higher or lower than those before treatment, reaching their maxima at 30 mm after treatment. The MOE and MOR, both perpendicular to the main direction, increased by about 50% and 20%, respectively, whereas the increase in MOR and MOE parallel to the main direction was relatively small (approximately 10%).

In summary, the microporous spacing ensuring the most optimal mechanical characteristics of bamboo strips was 30 mm (Figures 16 to 19).

Table 11. Variance analysis data

	Source of difference	SS	df	MS	F	P-value	Statistical significance
MOE∥	Intergroup	3.1E+07	5	6375643	6.84699	2.2E-05	Significant
	Within the group	7.6E+07	84	926398			
	Total	1.2E+08	89				
MOE⊥	Intergroup	1877632	5	378215	6.04531	7.5E-05	Significant
	Within the group	5501254	88	62663.8			
	Total	7384965	93				
MOR∥	Intergroup	9089.2	5	1818.39	9.32895	4.3E-07	Significant
	Within the group	16251.6	83	194.63			
	Total	25365.7	88				
MOR⊥	Intergroup	162.265	5	32.1854	4.9568	0.00048	Significant
	Within the group	573.166	88	6.51457			
	Total	733.209	93				

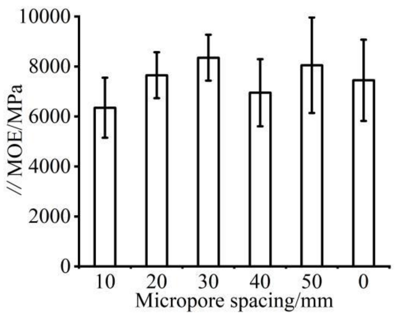


Figure 16. ∥MOE at different microporous spacing

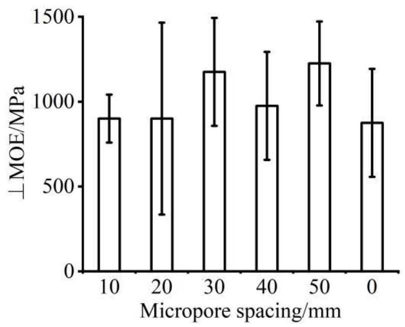


Figure 17. ⊥MOE at different microporous spacing

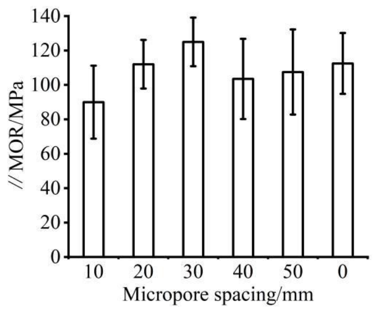


Figure 18. ∥MOR at different microporous spacing

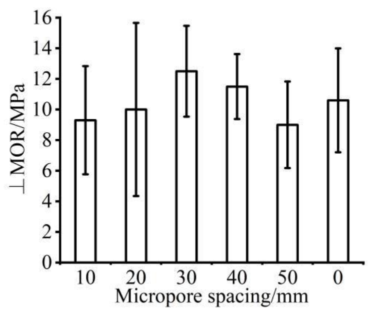


Figure 19. ⊥MOR at different microporous spacing

Micropore diameter

The micropore diameter exerts a noticeable impact on the MOR and MOE, except for the MOE parallel to the main direction (Table 12). The comparison of data before and after microporous pretreatment showed that both the MOR and MOE perpendicular to the main direction increased after pretreatment, and the greatest increase in strength (by about 20% and 36%, respectively) was recorded at the micropore diameter of 1 mm. For the MOR and MOE parallel to the main direction, the maximum values were reached at a micropore diameter of 1.5 mm, with an increase of 3.5% and 0.7%, respectively. In contrast, the strength at 1 mm was less than that before pretreatment, decreasing by about 8% and 7%, respectively. Given that the purpose of microporous pretreatment was to increase the strength perpendicular to the main direction, the most optimal results were achieved at the micropore diameter of 1 mm (Figures 20 to 23).

Table 12. Variance analysis data

	Source of difference	SS	df	MS	F	P-value	Statistical significance
MOE‖	Intergroup	6231457	5	1245936	1.21497	0.3085	Not significant
	Within the group	9.1E+07	89	1025412			
	Total	9.7E+07	94				
MOE⊥	Intergroup	993198	5	198587	10.0991	1.2E-07	Significant
	Within the group	1711308	87	19670.7			
	Total	2704503	92				
MOR‖	Intergroup	3458.19	5	691.389	4.35309	0.00138	Significant
	Within the group	13819.4	87	158.871			
	Total	17305.6	92				
MOR⊥	Intergroup	40.981	5	8.1949	2.94687	0.01659	Significant
	Within the group	241.89	87	2.78098			
	Total	282.919	92				

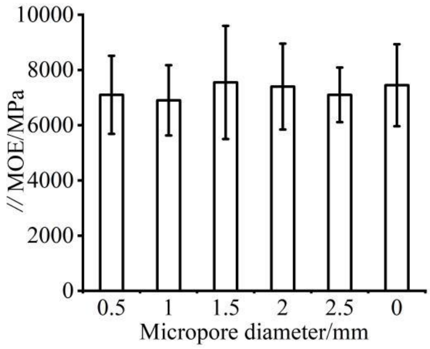


Figure 20. ‖MOEs at different microporous diameters

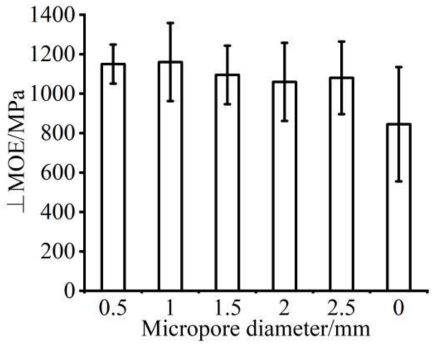


Figure 21. ⊥MOEs at different microporous diameters

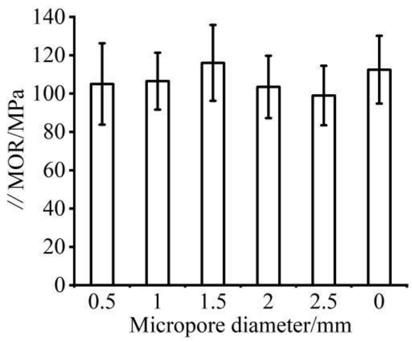


Figure 22. ‖MORs at different microporous diameters

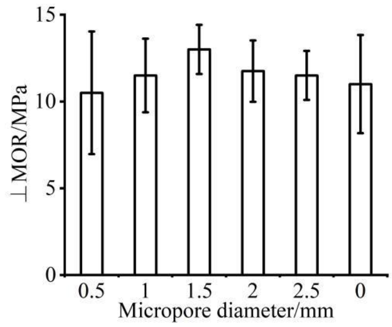


Figure 23. ⊥MORs at different microporous diameters

Microporous depth

It is known that the microporous depth only has a significant effect on the MOE perpendicular to the principal direction (Table 13), According to the ANOVA significance analysis data in this study, the highest strength increase of about 40% was achieved at the microporous depth of 1 mm. Moreover, the MOR perpendicular to the main direction was maximum at the microporous depth of 1 mm. In view of the above, the most optimal microporous depth was 1 mm (Figures 24 to 27).

Table 13. Variance analysis data

	Source of difference	SS	df	MS	F	P-value	Statistical significance
MOE‖	Intergroup	5097981	3	1698946	1.75899	0.16449	Not significant
	Within the group	5.8E+07	60	965587			
	Total	6.3E+07	63				
MOE⊥	Intergroup	1377694	3	459198	8.37194	0.0001	Significant
	Within the group	3236276	59	54849.2			
	Total	4614097	62				
MOR‖	Intergroup	955.859	3	318.619	1.7387	0.168	Not significant
	Within the group	10619.5	58	183.187			
	Total	11579.3	61				
MOR⊥	Intergroup	30.4587	3	10.1486	2.32269	0.08426	Not significant
	Within the group	253.45	58	4.37009			
	Total	283.92	61				

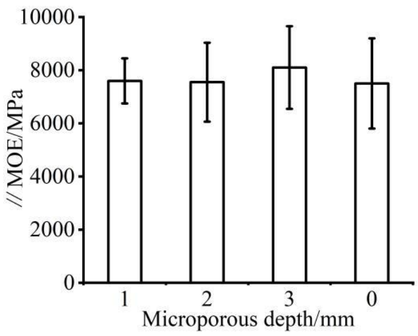


Figure 24. ‖MOEs at different microporous depths

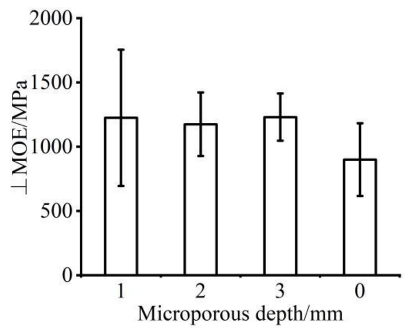


Figure 25. ⊥MOEs at different microporous depths

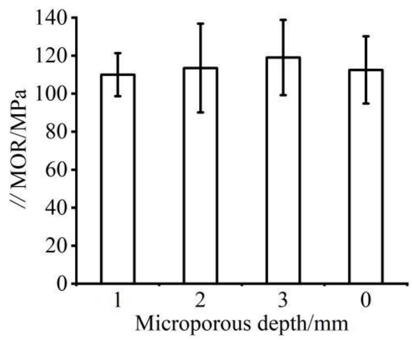


Figure 26. ‖MORs at different microporous depths

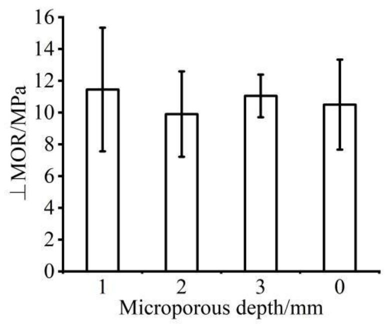


Figure 27. ⊥MORs at different microporous depths

Bamboo Laminated Timber after Hot Pressing

The response surface models were of great significance for the described objects, whereas the misfit errors had a very low impact on the data obtained. In particular, the effects of hot pressing time and hot pressing temperature were significant for both the MOR and MOE values parallel and perpendicular to the principal direction, but those of side pressure and interaction were negligible (Tables 14 to 17). The combined response surface analysis (Figures 28 and 29) revealed that the most optimal hot-pressing temperature, hot-pressing time and hot-pressing side pressure were 145°C, 11 min/12 mm, and 2 MPa, respectively.

Table 14. ANOVA for Response Surface Model of // MOR

Source of variation	SS	df	MS	F	P-value
Model	2173.39	9	241.38	22.00	<0.0001
A-press time	107.87	1	107.87	9.83	0.0105
B-press temperature	54.65	1	54.65	4.97	0.0496
C-hot pressing side pressure	30.57	1	30.57	2.78	0.1260
AB	2.20	1	2.20	0.20	0.6635
AC	7.944E-003	1	7.944E-003	7.247E-004	0.9789
BC	6.31	1	6.31	0.57	0.4654
A^2	318.66	1	318.66	29.02	0.0003
B^2	615.18	1	615.18	56.04	<0.0001
C^2	99.17	1	99.17	9.03	0.0131
Residual	109.75	10	10.97		
Lack of Fit	86.14	5	17.22	3.64	0.0908
Pure Error	23.59	5	4.71		
Cor Total	2282.16	19			

Table 15. ANOVA for Response Surface Model of // MOE

Source of variation	SS	df	MS	F	P-value
Model	3.145E+006	9	3.496E+005	9.51	0.0008
A-press time	2.877E+005	1	2.877E+005	7.83	0.0188
B-press temperature	5.079E+005	1	5.079E+005	13.82	0.0040
C-hot pressing side pressure	44526.68	1	44526.68	1.21	0.2968
AB	44019.42	1	44019.42	1.20	0.2994
AC	29797.85	1	29797.85	0.81	0.3891
BC	31712.62	1	31712.62	0.86	0.3748
A^2	6.319E+005	1	3.319E+005	17.19	0.0020
B^2	4.889E+005	1	4.889E+005	13.30	0.0044
C^2	34984.49	1	34984.49	0.95	0.3522
Residual	3.676E+005	10	36768.28		
Lack of Fit	2.872E+005	5	57462.51	3.57	0.0941
Pure Error	80374.31	5	16074.05		
Cor Total	3.513E+006	19			

Table 16. ANOVA for Response Surface Model of ⊥ MOR

Source of variation	SS	df	MS	F	P-value
Model	173.25	9	19.35	16.89	<0.0001
A-press time	9.32	1	9.32	8.13	0.0171
B-press temperature	6.80	1	6.80	5.93	0.0350
C-hot pressing side pressure	0.054	1	0.054	0.048	0.8286
AB	0.016	1	0.016	0.015	0.9050
AC	0.38	1	0.38	0.33	0.5710
BC	2.85	1	2.85	2.50	0.1451
A^2	47.06	1	47.06	41.09	<0.0001
B^2	18.36	1	18.36	16.03	0.0025
C^2	10.25	1	10.25	8.95	0.0135
Residual	11.44	10	1.14		
Lack of Fit	9.08	5	1.81	3.84	0.0826
Pure Error	2.35	5	0.46		

Cor Total	185.69	19			

Table 17. ANOVA for Response Surface Model of ⊥ MOE

Source of variation	SS	df	MS	F	P-value
Model	6.428E+005	9	71435.70	10.87	0.0004
A-press time	67549.50	1	67549.50	10.28	0.0093
B-press temperature	34711.87	1	34711.87	5.28	0.0442
C-hot pressing side pressure	2226.65	1	2226.65	0.33	0.5731
AB	0.48	1	0.48	7.515E-005	0.9932
AC	10486.98	1	10486.98	1.60	0.2348
BC	4.25	1	4.25	6.493E-004	0.9801
A^2	90479.28	1	90479.28	13.78	0.0040
B^2	1.105E+005	1	1.105E+005	16.84	0.0021
C^2	76558.07	1	76558.07	11.65	0.0065
Residual	65641.07	10	6562.18		
Lack of Fit	51969.36	5	10392.25	3.80	0.0844
Pure Error	13669.68	5	2733.13		
Cor Total	7.085E+005	19			

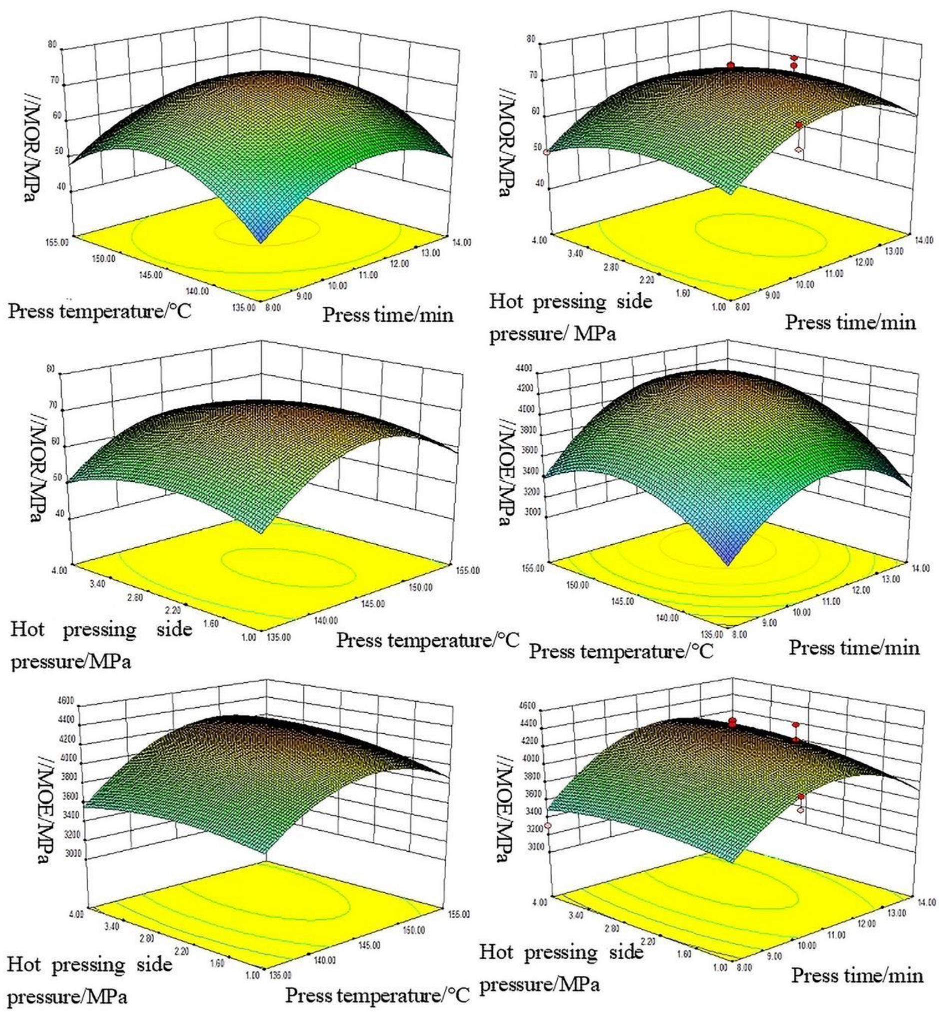


Figure 28. Response surfaces for // MOR and // MOE

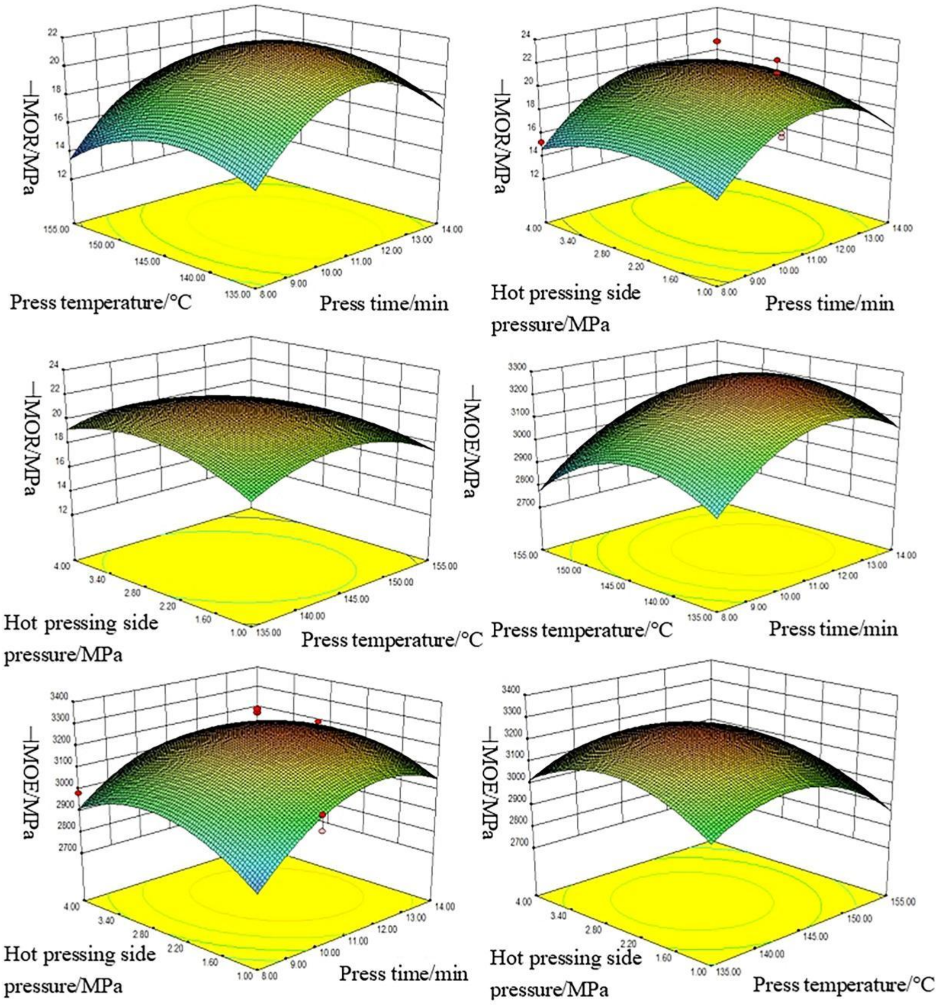


Figure 29. Response surface for ⊥MOR and ⊥MOE

Grouping Process of Bamboo Laminated Timber

Formation process and DPX analysis

For an isotropic assembly bamboo laminated timber, the MOR and MOE values perpendicular to the principal direction remained almost unchanged as the number of layers increased, while those parallel to the principal direction decreased with the increase in the amount of layers. For staggered bamboo laminates, the MOR and MOE perpendicular and parallel to the principal direction, respectively, varied to a large extent for odd-layered bamboo laminates and were closer to each other for even-layered bamboo laminates (Figures 30 (a) and (b)). For example, the strength of 4-layered staggered laminates was better than that of 2-layered (Figures 31 to 33) ones. According to the cross-sectional density analysis, it was evident that the greatest glued surface density was in the range of 1.0-1.2 g/cm3, followed by the surface layer density. For the 2-layer and 3-layer isotropic configurations, the chordwise bamboo strips basically maintained their original thickness and density. However, for the 4-layer isotropic structure (Figures 34 to 36), the density was asymmetrically distributed, and the density of the third section tended to increase significantly, which might be due to the microstructure collapse of the bamboo material. For the bamboo laminated timber with staggered grouping, the density showed a regular distribution and the densities of the gluing surfaces were relatively close to each other at the uniformly distributed force. On the whole, the most satisfactory mechanical properties of the bamboo laminated timber were achieved in 4-layer staggered blanks.

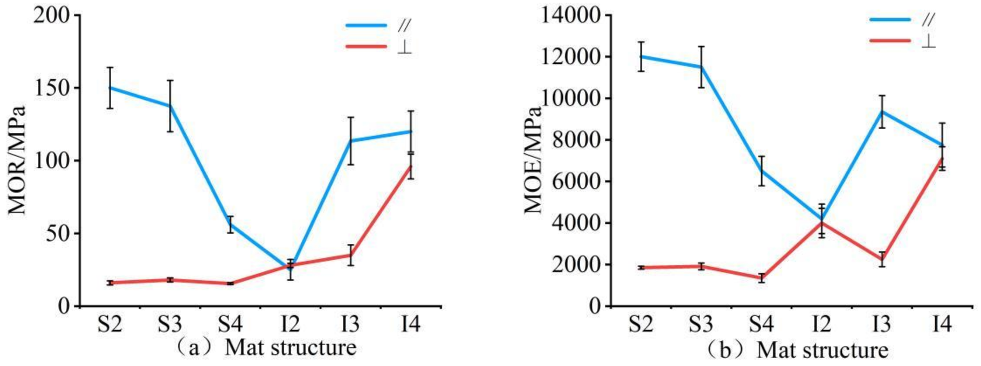


Figure 30. MOR and MOE values of bamboo laminated timber with different assembling patterns

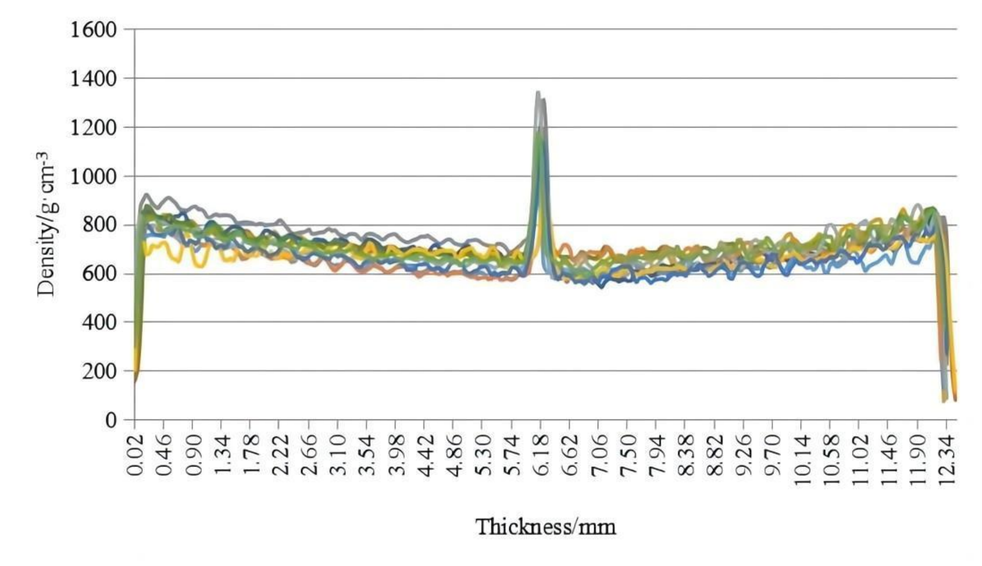


Figure 31. The density profiles of two cross bamboo laminated timber

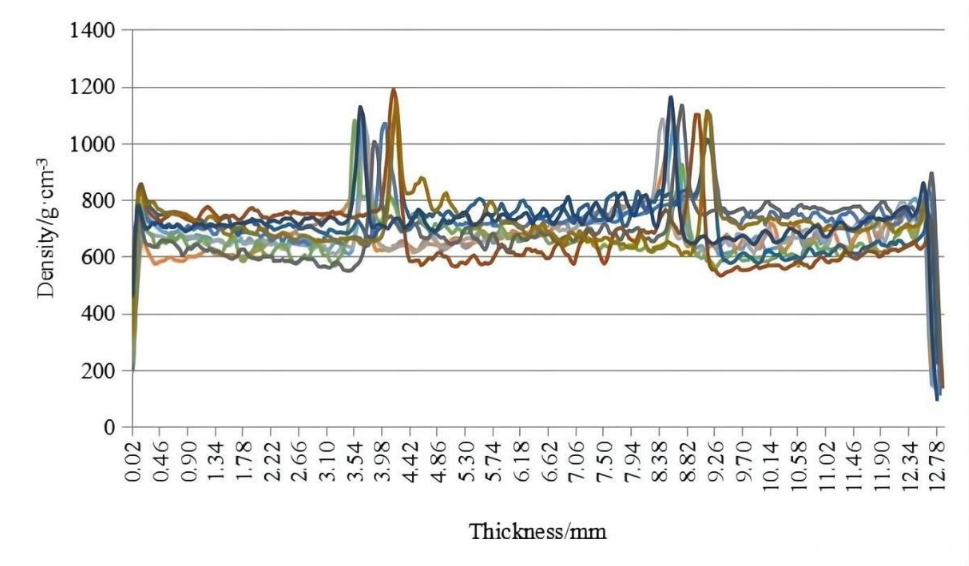


Figure 32. The density profiles of three cross bamboo laminated timber

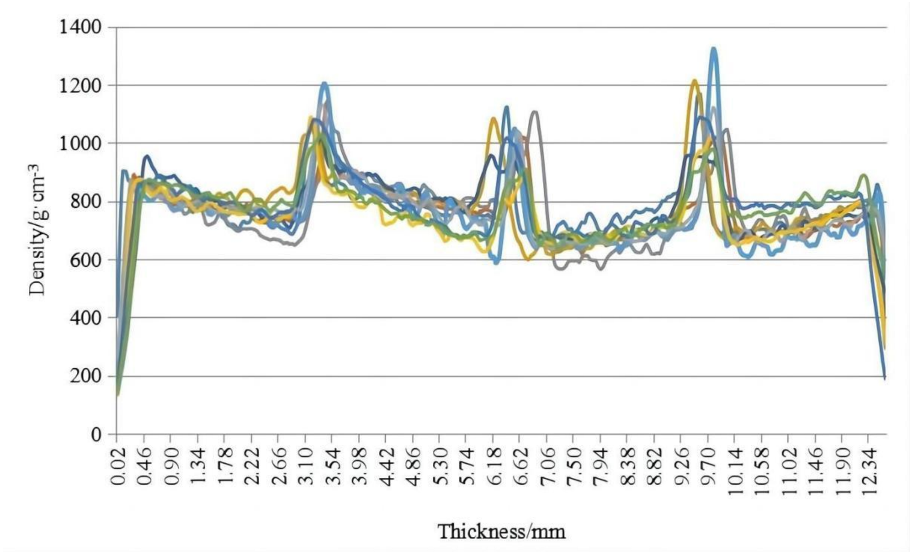


Figure 33. The density profiles of four cross bamboo laminated timber

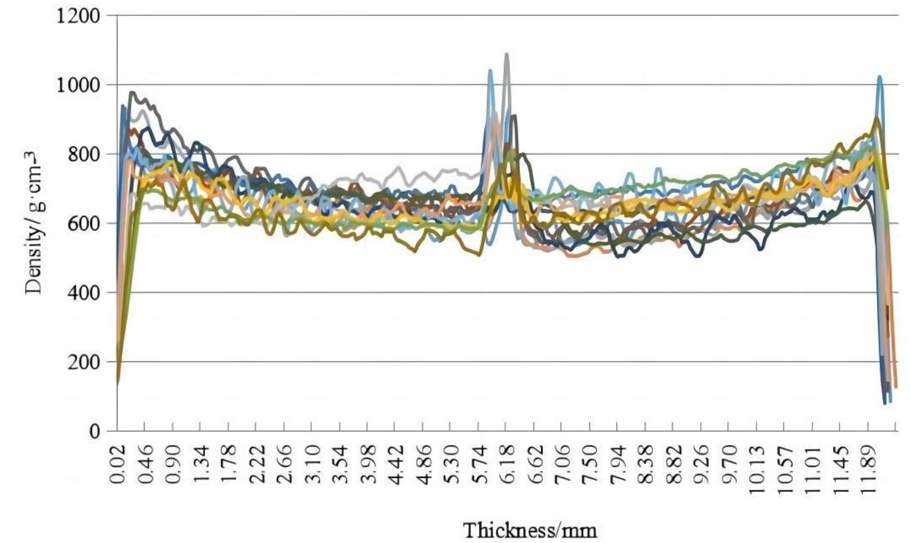


Figure 34. The DPX of two bamboo laminated timber of the same direction

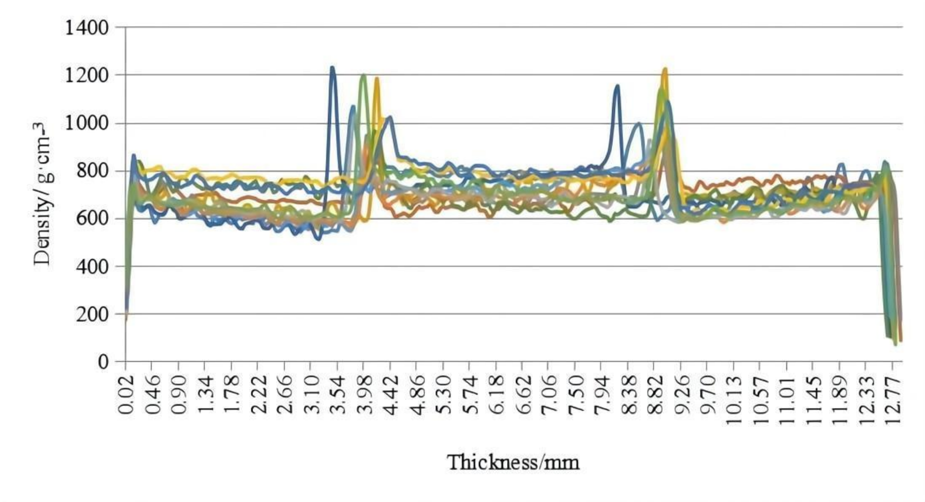


Figure 35. The DPX of three bamboo laminated timber of the same direction

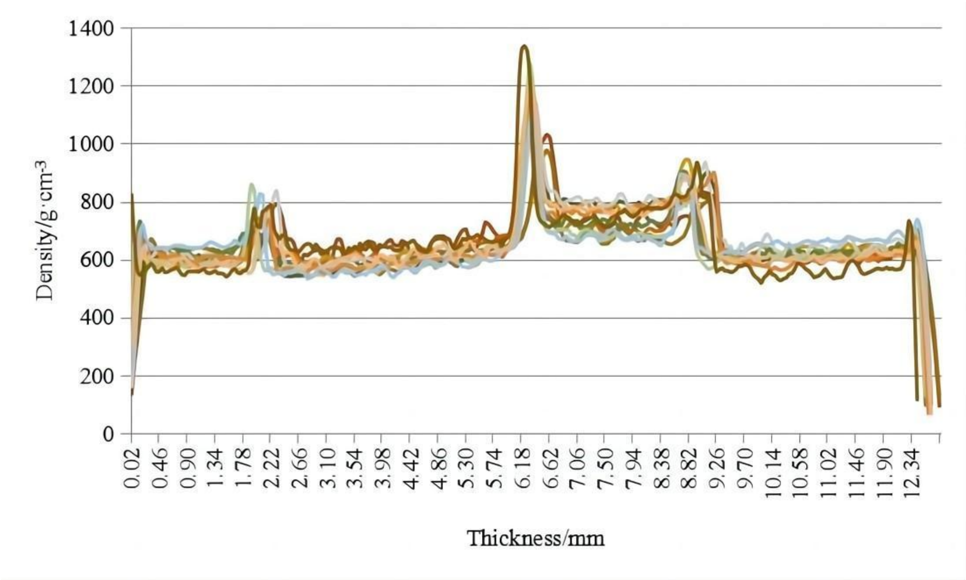


Figure 36. The density profiles of four bamboo laminated timber of the same direction

Validation test

The pilot production workshop of bamboo laminated timber was commissioned by Yong 'an Youzhu Industry Co., Ltd. of Fujian Province to manufacture the product and verify its performance. The specific product types and conditions are shown in Table 18 below.

Table 18. Test conditions for performance verification of laminated bamboo

Programs	Group	Features
A	Optimization Process Group	3-5 years old middle moso bamboo exposed to heating and microporous treatment, optimized grouping and hot pressing
B	Semi-optimized process group	3-5 years old moso bamboo with random height subjected to heat treatment, microporous treatment, optimized grouping and hot pressing

Each type of bamboo laminates was pressed into one board with the dimensions of 1800 mm×2100 mm, and the test samples were then randomly taken from the board and prepared according to ISO 13608:2014 Standard [20] (the methods for testing the physical and chemical properties of wood-based panels and surface decorated wood-based panels). In particular, the transverse and longitudinal MOR and MOE values as well as the impregnation peeling properties were evaluated at the Quality Inspection Department of Fujian He Qichang Bamboo Industry Co., Ltd, 20 times for each index, and the results are summarized in Table 19.

Table 19. Test results on performance verification of bamboo laminated timber

Number	Density g/cm^3	Water content %	MOR/MPa		MOE/MPa		Impregnation Stripping Performance
			‖(≥90)	⊥ (≥30)	‖(≥8000)	⊥	
A	0.74	8.06	121.35±6.75	88.23±9.31	8130.66±123.14	7510.78±222.56	Neither Stripping
B	0.76	8.17	113.18±6.77	85.77±12.57	8006.38±117.66	7428.42±314.35	Neither Stripping

According to the findings, the density of bamboo laminate was reduced compared with those of bamboo gabions, bamboo bundle laminates and bamboo integrated laminates. Meanwhile, the bamboo laminates prepared in this study met the mechanical requirements for "Type A" bamboo plywood conforming to ISO 13609:2021 Standard [21] ("Bamboo Gabion Plywood for Underbody of Automobile"). Compared with the test group A, the mechanical properties of the bamboo laminated timber from the test group B dramatically decreased, but still fell within the range defined by the above standard. Therefore, in the actual production, the height of the selected material can be disregarded in order to save costs.

CONCLUSIONS

In order to prepare bamboo laminates with advanced mechanical properties, the 5-year-old moso bamboo strips collected at a 3-m height from the ground and exposed to high-temperature pretreatment were used to explore the optimization scheme of manufacturing process and the bonding strength mechanism of relevant products. It was found that, independently of the gluing type (QQ, QH or HH), the interface had no significant effect on the shear strength, bending strength, compressive strength and elastic modulus of glued bamboo strips under consideration (with or without bamboo joints). However, the glued interface type exerted a noticeable impact on the flexural strength, flexural elastic modulus, and tensile strength of glued strips. Moreover, the mechanical properties of strips without nodes exceeded those of strips with nodes. At the same time, the dislocation of adjacent bamboo nodes by 3-10 mm caused the increase in mechanical characteristics of the bamboo strips. In addition, the lateral and longitudinal strength of bamboo laminated timber could be improved through the side microporous treatment process. The optimum mechanical properties were achieved at the following parameters: the hole spacing of 30 mm, the hole diameter of 1 mm, and the depth of 1 mm. In turn, hot-pressing time, hot-pressing temperature and assembly method strongly influenced the mechanical properties and cross-sectional density (DPX) distribution of bamboo laminated timber, while the effects of lateral pressure and interaction were negligible. According to the result, the optimum hot pressing process was realized conforming to four-layer cross-grouping method under the following conditions: the hot pressing temperature of 145 °C, the hot pressing time of 11 min/12 mm, the hot pressing side pressure of 2 MPa. This allowed one to prepare laminated timbers with different directions and insufficient layers with evenly distributed DPX and relatively stable MOR and MOE values parallel and perpendicular to the principal direction of strips. The third-party testing revealed that the product with the MOR of 88.22 MPa (121.36 MPa) and MOE of 7510.77 MPa (8130.65 MPa) in the parallel (perpendicular) direction with respect to the principal axis of strips accomplished the requirements imposed by LYT1575-2000 Standard on the mechanical properties of floor bamboo plywood for bus flooring, as well as met the Chinese industry standards.

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