Cold Pressing and Hot Curing Process for Assembly of Hexagonal Pre-shaped Bamboo Culm Sections

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Bamboo is widely used in the construction industry due to its excellent mechanical properties, short production cycle, and environmental concerns. Reconstructing and processing bamboo into biomass-based composite materials that can replace wood alleviates the imbalance between wood supply and demand. This article uses cold press setting and hot press curing molding processes to prepare small samples of Hexagonal Recombinant Bamboo Material (glued HexBam). Through orthogonal analysis, the preparation process parameters, adhesive types, adhesive application amounts, and the relationship between the temperature and time of hot pressing solidification molding and the mechanical properties of glued HexBam were determined. A phenolic adhesive (PF) was used with a dosage of 200 g/m^2, a heat setting and molding temperature of 130 °C, and a heat setting molding time of 10 minutes. Under these process conditions, the prepared glued HexBam had a longitudinal compressive strength of 73.8 MPa and a specific strength of 0.0535 N•m/kg, which is superior to ordinary steel.

DOI: 10.15376/biores.18.4.7963-7980

Keywords: Bamboo raw material; Multi-party reconstituted material; Cold pressing; Hot setting molding; Longitudinal compressive strength; Orthogonal design

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INTRODUCTION

With the growing understanding and development of bamboo resources, as well as the updating and innovation of bamboo processing technology, the bamboo processing industry is experiencing new economic growth in many developing countries. Bamboo has excellent physical and mechanical properties. Reconstructing bamboo into biomass-based composite materials that replace wood has the potential to alleviate the imbalance between wood supply and demand (Krzysik and Youngquist 1991; Nugroho and Ando 2001). In recent years, the bamboo processing industry in China has flourished, and improving the utilization rate of bamboo and reducing industrial energy consumption have become the focus of upgrading the bamboo processing industry (Fu and Zhou 2010; Zhao et al. 2014).

While the use of recombinant bamboo in structural materials has been proposed, the density of the existing recombinant bamboo is high, such that the products tend to be heavy (Sanadi *et al.* 1994; Saeed *et al.* 2007; Correal and Ramirez 2010). Fu and Zhou (2010) analyzed the stress of the original multi-party recombination material of bamboo, and pointed out that the stress of honeycomb bamboo is different in different directions. The shear strength and shear modulus of elasticity of edges and corners are higher than those of edges, and honeycomb bamboo has high rigidity and strength. These attributes make it suitable for use as a strength component and in interior building materials. Fan (2012) designed and manufactured a hexagonal forming equipment and auxiliary feeding system for bamboo raw state multi-party recombination materials, enabling the multi-party recombination unit to mill culms into hexagonal form in one go. The equipment runs smoothly and has an annual production capacity of 1500 m^3/a. The hexagonal shape of the processed recombination unit is regular, such that it can meet the production requirements of multi-party recombination materials in the original state of bamboo manufacturing. However, its surface smoothness is poor, its surface roughness is high, and the proportion of materials with a positive variation greater than 60% is relatively small. Liu (2013) designed and manufactured a bamboo original multi-party recombination material finger joint equipment, and they used this equipment to study the finger joint performance of the basic unit of bamboo original multi-party recombination material. The end pressure was 10 MPa, the finger length was 15 mm, and the adhesive amount was 250 g/m^2. After 2 h of cold pressing at room temperature, the finger joint performance was found to be excellent, such that it met the production requirements for finger joint strength. However, this composite finger joint material did not reflect the unique physiological structure and physical characteristics of bamboo itself, and the internal force performance per unit mass was not high, which could not meet the requirements of long-distance and large-span composite. Meanwhile, it cannot be used for structural materials with mechanical strength or high span requirements.

At the same time, bamboo, as an anisotropic material, has significant differences in its models and research methods. The model and research methods still need further improvement. The current research on multiple reconstitutions of bamboo raw materials is based on cold pressing and room temperature curing processes, with a long production cycle. The cold pressing method has the phenomenon of tearing and local compression of the adhesive layer, as well as the problem of excessive bending strain. Curing at room temperature takes about 7 days, and there was no hot pressing or thermosetting molding process applied (Tong and Arnell 1998; Wang and Li 2011; Fu and Zhao 2014).

In view of the performance and production process issues of bamboo composite reconstituted materials mentioned above, this article proposes a preparation method for hexagonal reconstituted bamboo materials (glued HexBam), in which the individual hexabonal bamboo units are assembled and glued together to form hexagonal composite materials similar to honeycomb (Figs. 1 and 2). This structure has a central symmetric and axial symmetric structure, which can greatly improve the mechanical properties and stability of the material. At the same time, it proposes a process method for preparing this material by cold pressing and hot pressing solidification. A small sample of glued HexBam was prepared using cold pressing and hot pressing solidification molding processes. Through orthogonal analysis, the preparation process parameters, adhesive type, adhesive application amount, and the relationship between the temperature and time of hot press curing and the mechanical properties of the glued HexBam (Hernández *et al.* 2008), providing a design basis for the preparation process and related equipment research and development of bamboo original multi-party reconstituted materials for industrial production.


Fig. 1. HexBam structural diagram


Fig. 2. Honeycomb structure diagram

EXPERIMENTAL

Materials

The HexBam was prepared from 4- to 6-year-old *Phyllostachys pubescens* with a diameter of 90 to 115 mm, length of 500 ± 5 mm, and taper ≤ 1/50. The urea formaldehyde adhesive (UF) was a milky white liquid with the following properties: solid content 52.62%, viscosity 62CPS, pH 8.8, and density 1.212 g/cm³ (Beijing Taier Chemical Co., Ltd.). The phenolic aldehyde adhesive (PF) was a red liquid with the following properties: solids content 43.58%, viscosity 72 CPS, pH 13.0, and density 1.205 g/cm ³ (Beijing Taier Chemical Co., Ltd.). The two component water-based isocyanate adhesive (API), main agent, with a curing agent=100:15, was purchased from Beijing Saint Noah Technology Development Co., Ltd.

Equipment

The equipment used included the following: horizontal forming fixture equipment (Fig. 3); electric constant temperature convection drying oven (Fig. 4; DHG-9626A, Shanghai Jinghong Experimental Equipment Co., Ltd., power: 2 kW, processing temperature: 30 to 300 °C); microcomputer controlled electro-hydraulic servo pressure testing machine (YAW-3000A, Jinan Times Gold Testing Instrument Equipment Co., Ltd., maximum load: 3000 kN); hydraulic jack (Haiyan Haiding Machinery Co., Ltd., 30 kN, Pressure sensor HSTL-BLY, 10 kN, XMT604 digital intelligent controller); and Vernier scale, electronic balance, steel ruler, *etc*.


Fig. 3. The horizontal molding fixture


Fig. 4. Electric thermostatic drier

Method

An orthogonal analysis method was used to design the experiments. The relationship between the longitudinal compressive strength and the process parameters of the glued HexBam prepared by the cold press shaping and hot press curing processes was investigated, and the transverse molding process suitable for the preparation of the material was explored.

Step 1: Cold press setting and hot press solidification forming of glued HexBam, with material specifications ≤ 300 mm × 300 mm × 500 mm;

Step 2: The glued HexBam was then aged at room temperature for 24 h to prepare mechanical performance specimens with a height of 460 mm;

Step 3: The longitudinal compressive strength and mechanical properties of glued HexBam were tested;

Step 4: The range and variance analysis methods were used to analyze the relationship between process factors and material properties.

At the Quality Testing Center of the Wood Industry Research Institute of the Chinese Academy of Forestry Sciences, mechanical performance tests were conducted on glued HexBam small sample specimens in accordance with the GB/T50344 (2004) standard, with specimen specifications ≤ 300 mm × 300 mm × 460 mm.

Experimental Design

The test focused on the influence of four process factors: adhesive type, sizing amount, hot pressing time, and hot pressing temperature on the mechanical properties of HexBam. The main performance index is the longitudinal compressive strength. Three levels were selected for each process factor, as shown in Table 1.

According to the setting of the above factors and levels, The Orthogonal Table L9 (3^4) (Table 2) was selected, which involved four factors and three levels. Variance and range analysis were used to determine the significance of each process factor on the mechanical properties of glued HexBam strength and the level difference between the factors and determine the optimal preparation process for mechanical properties.

Table 1. Variable Factors and Levels for Glued HexBam

Factors / Levels	Adhesive Type	Quantity of Adhesive (g/m^2)	Heat Pressing Temperature (°C)	Heat Time (min)
1	UF	200	110	10
2	PF	250	130	20
3	API	300	150	30

Table 2. The Experiment Design of Glued HexBam

Number	Adhesive Type	Quantity of Adhesive (g/m^2)	Heat Pressing Temperature (°C)	Heat Pressing Time (min)
1	UF	200	110	10
2	UF	250	130	20
3	UF	300	150	30

4	PF	200	130	30
5	PF	250	150	10
6	PF	300	110	20
7	API	200	150	20
8	API	250	110	30
9	API	300	130	10

Note: each condition was repeated 4 times

The lateral compressive strength of the glued HexBam was ≥ 3.38 MPa (Han 2014), and the optimal pressure parameter was judged to lie between 1.0 and 1.5 MPa. In the experiment, considering the variability and safety of bamboo (preventing the lateral crushing of the original multi-party recombination unit of bamboo from excessive cutting) and cost issues, a fixed pressure of 1.5 MPa was selected for this experiment. The roughness measurement (R_a) shows that the arithmetic mean deviation R_a of the contour of the glued HexBam was 2.79 μm. The average R_z of the ten point height of micro unevenness was 26.51μm. These findings indicated good quality and meeting the requirements of multi-party recombination material roughness $R_a \leq 80$ μm requirements.

Cold Press Setting and Hot Press Curing Process

The experiment focused on the glued HexBam, which exhibits typical central symmetry and axial symmetry.

Fig. 5. Glued HexBam cross section diagram

Process Route

Because the glued HexBam is a new type of material, the corresponding cold pressing and thermosetting forming equipment is under development. This experiment completed the preparation of small samples of glued HexBam through a two-step method. The first step is to apply stress through self-made transverse forming fixtures and obtain pressure by fixing the fixture position. The second step is to place the HexBam sample and fixture together in a constant temperature drying oven for heating and curing. The preparation process route of cold-pressing and thermosetting forming of glued HexBam is shown in Fig. 6.

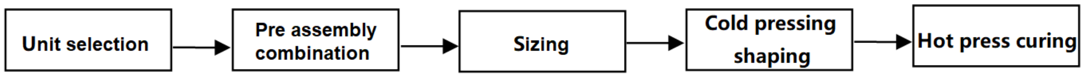

Fig. 6. Hot pressing preparation process of glued HexBam

Preparation Process

Preassembly and combination

The first step is to classify and organize the materials with different diameter classes based on the preparation units of HexBam. Then the materials with diameter class differences within 5 mm are arranged and combined according to the original multi-party recombination technology to determine the bonding interface. The next step is to pre-assemble the reconstituted material using iron wire clamping. The preforms are then sorted according to the diameter grade of the bamboo material, and their positions are marked. Observing the contact between units, and if the contact is good, the relative position is marked and then glued as the basic unit of glued HexBam. If the interface contact effect is poor, then there will be gaps or mismatches between them, and another suitable raw bamboo should be selected for pre splicing, as shown in Fig. 7. The purpose is to determine the relative position of the bonding interface, remove gaps caused by material mismatch, improve the bonding performance of the HexBam, and maximize its bonding contact area.

Fig. 7. Pre-assembled

Applying adhesive

According to the process parameters determined in Table 2, the adhesive and the application amount were selected. The adhesive was applied manually, with the central raw bamboo having the glue applied on six sides and the remaining peripheral raw bamboo being used as contact surfaces, that is, having glue applied on three sides. After applying the adhesive, the cold pressing and shaping were carried out to avoid rapid curing of the two component isocyanate adhesive.

Cold press setting

The cold press setting was completed using self-made transverse forming fixtures and auxiliary equipment, as shown in Fig. 8. The procedure was to apply 1.5 MPa of pressure to both ends of the specimen using fixtures. The pressure was completed by hydraulic jacks above and on the side. Strain type pressure sensors were placed below the jacks to control the pressure application value. A beginning force load of approximately 100 N was applied to ensure that the transverse hydraulic jack did not fall in the system, and the end size of the glued HexBam was measured. When applying pressure, attention should be paid to slowly pressurizing horizontally and longitudinally to prevent the pressure equipment on one side from falling off due to excessive displacement on the other side. When the pressure reached the selected pressure (with an allowable error of 100 N), the fixing nut was tightened and the end size of the glued HexBam was measured and recorded. The operation of the other end was the same, and when applying pressure, the front and rear ends of the bamboo material were kept level, in order to avoid experimental errors caused by the self weight of the fixture and material.

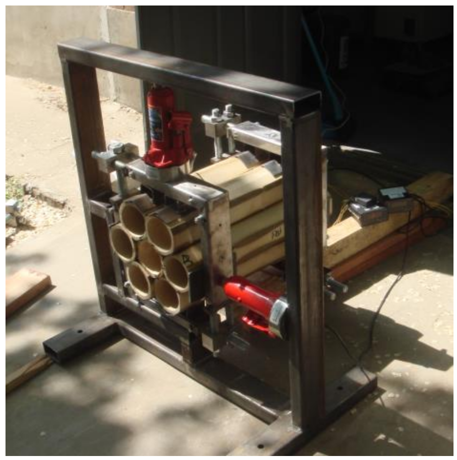

Fig. 8. Cold pressing shaping of glued HexBam

Hot pressing curing

After cold pressing and shaping, the glued HexBam and the self-made transverse forming fixture were placed in an electric convection drying oven (Fig. 9), and the temperature was set according to the process plan designed in Table 2 to achieve hot pressing curing. To prevent the impact of sudden cooling on material properties, after the hot press curing was completed, the material was placed in the drying oven for 5 min, and the door of the convection oven was opened. After natural cooling at room temperature for 120 min, the material and fixtures were taken out of the oven. The end size of the glued HexBam was measured and recorded, and the fixtures are disassembled. The material was stored for 24 h before use. At the same time, the end size of the glued HexBam was measured and recorded. Its elastic recovery performance was tested. This experiment uses thermosetting adhesives and obtains HexBam through hot pressing curing. Compared with materials prepared by cold pressing in the past, the bonding interface was found to be firm and there were basically no gaps.

Post processing

There can be a dimensional error in the cross section of the glued HexBam units, and the assembly of the cold pressing and setting process can also result in uneven ends. Therefore, it was necessary to perform cross cutting treatment on the material to ensure that the end faces of each recombination unit were in the same horizontal plane, with a processing allowance of 20 mm.

Fig. 9. Hot forming of glued HexBam

Testing of Material Mechanical Properties

To test the corresponding physical and mechanical properties of the materials, this experiment was conducted at the Engineering Quality Testing Center of Hunan University of Science and Technology. Referring to the "Technical Standards for Building Structure Testing" (GB/T50344-2004), the main mechanical properties of bamboo such as glued HexBam were tested. The experiment is shown in Figs. 10 and 11.

Fig. 10. Longitudinal compressive strength test

Fig. 11. Transverse bending strength test

RESULTS AND DISCUSSION

Cross Section Deformation Analysis

Bamboo is a biomass material, which has the joint effect of dry shrinkage, wet expansion, and thermal expansion during autoclave curing. To grasp the size changes of bamboo raw materials during the hot pressing process and determine the design pressure and stroke of the cold pressing and hot setting molding machine, a random sample was taken from four materials under each process condition to measure the changes in the transverse and longitudinal dimensions of the initial, cold pressing and setting, hot pressing and curing, and 24 h of aging. After 24 h of aging, the material was considered to have reached its final size. The initial size was defined with the material under compression, based on the application of about 100 N of pre-stress to ensure that the hydraulic jack can be fixed on the frame. The size after hot setting was defined as the size before the specimen is removed from the electric constant temperature convection oven without removing the fixture. The length (plane to plane, horizontal in Fig. 6) and height were measured before and after the test. The changes in lateral dimensions are shown in Tables 3. The changes in longitudinal dimensions are shown in Tables 4.

As shown in Tables 3, there was no significant change in the horizontal size of the glued HexBam. The average horizontal size at the initial stage was 288.1 mm, while the average size after thermosetting molding was 284.5 mm, a decrease of 3.61 mm compared to the initial value, with a relative size change of approximately 1.25%. After cold pressing, the average size decreased by 2.11 mm, and after thermosetting forming, the size decreased by 1.50 mm compared to after cold pressing. During hot pressing curing, there was a dual effect of dry shrinkage, wet expansion, and hot expansion and cold shrinkage, with dry shrinkage being the main result. After 24 h of aging, the average size showed an elastic recovery of 0.39 mm, with a proportional recovery of 10.8%.

Table 3. Transverse Size of HexBam

Number	Initial Size (mm)	Size after Press (mm)	Size Increased after Press (mm)	Size after Heat Press (mm)	Size Increased after Heat Press (mm)	Final Size (mm)	Size Increased after Final Size (mm)
1	293.00	292.00	-1.00	289.50	-3.50	290.00	-3.00
2	296.00	294.00	-2.00	294.00	-2.00	294.00	-2.00
3	296.50	294.50	-2.00	292.00	-4.50	292.00	-4.50
4	289.00	287.00	-2.00	285.50	-3.50	286.00	-3.00
5	282.50	280.00	-2.50	278.00	-4.50	278.50	-4.00
6	280.50	277.50	-3.00	276.00	-4.50	276.00	-4.50
7	296.00	294.00	-2.00	293.50	-2.50	294.00	-2.00
8	274.50	272.00	-2.50	271.00	-3.50	271.50	-3.00
9	285.00	283.00	-2.00	281.00	-4.00	282.00	-3.00
Mean	288.11	286.00	-2.11	284.50	-3.61	284.89	-3.22
Size					-1.50		
Size							0.39

The longitudinal size variation pattern of the HexBam did not have a significant effect. Overall, the average longitudinal size at the initial stage was 271.8 mm, and the average size after thermosetting forming was 269.1 mm, which was 2.7 mm less than the initial value, with a size change of approximately 0.98%. After cold pressing, the average size decreased by 1.69 mm. After thermosetting molding, the size decreased by 0.98 mm compared to after cold pressing. After 24 h of aging, the average size showed an elastic recovery of 0.31 mm, with a proportional recovery of 11.5%.

Comparing Tables 3 and 4, the horizontal size change of the glued HexBam was greater than the vertical size change, with an average decrease of 3.61 mm in the horizontal direction and 2.67 mm in the vertical direction. This is because the fixtures were connected horizontally and longitudinally. When applying pressure in the experiment, to prevent the bamboo unit from breaking, the horizontal pressure parameter was used as the standard, resulting in the longitudinal pressure not reaching the required pressure value for design.

Table 4. Longitudinal Size of Glued HexBam

Number	Position	Initial Size (mm)	Size after Press (mm)	Size increased after press (mm)	Size after Heat Press (mm)	Size increased after heat press (mm)	Final Size (mm)	Size increased after Final size (mm)
1	h1	283.00	281.00	-2.00	281.00	-2.00	281.00	-2.00
	h2	286.00	285.00	-1.00	285.00	-1.00	285.00	-1.00
2	h1	278.00	276.00	-2.00	274.50	-3.50	275.00	-3.00
	h2	279.00	277.00	-2.00	275.00	-4.00	275.50	-3.50
3	h1	281.00	281.00	0.00	279.50	-1.50	279.50	-1.50
	h2	279.00	280.00	1.00	278.50	-0.50	279.00	-0.00
4	h1	280.50	280.50	0.00	277.50	-3.00	277.50	-3.00
	h2	279.00	275.50	-3.50	276.00	-3.00	277.00	-2.00
5	h1	257.50	255.50	-2.00	253.00	-4.50	253.50	-4.00
	h2	250.00	248.00	-2.00	247.50	-2.50	247.50	-2.50
6	h1	276.50	274.00	-2.50	274.00	-2.50	274.00	-2.50
	h2	278.00	276.00	-2.00	275.50	-2.50	276.00	-2.00
7	h1	272.00	269.00	-3.00	267.50	-4.50	268.00	-4.00
	h2	277.50	275.50	-2.00	274.00	-3.50	274.00	-3.50
8	h1	258.00	256.00	-2.00	254.50	-3.50	255.00	-3.00
	h2	258.00	255.50	-2.50	255.50	-2.50	256.00	-2.00
9	h1	264.00	262.00	-2.00	262.00	-2.00	262.00	-2.00
	h2	255.00	254.00	-1.00	253.50	-1.50	254.00	-1.00
Mean		271.78	270.08		269.11	-2.67	269.42	-2.36
Size						-0.98		
Size								0.31

There was a common maximum size reduction of 4.5 mm in both the horizontal and vertical directions for the original state of glued HexBam. During the thermosetting process, the size change of the glued HexBam was mainly attributable to drying shrinkage. After 24 h of aging, there was an elastic recovery of approximately 0.3 to 0.4 mm, with a proportional recovery of 11%. At the same time, the horizontal size of the glued HexBam was larger than the vertical size. This was because bamboo is an elastic-plastic material. After cold pressing and shaping, the material undergoes a reduction in plastic deformation size under pressure, and on the other hand, the bonding between units becomes more compact, resulting in a reduction in size. After hot pressing and curing, the size of the glued HexBam shrank further, mainly due to the evaporation of free water and bound water in the cell walls during the thermosetting process, as well as the drying shrinkage of hemicellulose, starch, and other pyrolysis products. The plate spring is set in the self-made fixture, which will deform after the drying shrinkage occurs, to compensate for the pressure loss caused by the size reduction and ensure the stability of the applied pressure during the thermosetting process. After 24 h of aging, the material exhibited partial elastic recovery, manifested by a slight increase in size. The bamboo material is circular on the side, and there is instability in the process after splicing. Additionally, there is a wax layer on the surface of the bamboo material, which prevents splicing.

Stress Relaxation and Pressure Determination

Glued HexBam is an elastic-plastic material, similar to wood, with a relaxation creep phenomenon. After applying a load, its value will change over time, as shown in Fig. 12. When applying a load, due to the structural characteristics of the material, the longitudinal load should be approximately 2.3 times the transverse load. In actual tests, due to the correlation between the longitudinal and transverse loads applied to the same fixture, the transverse load was applied at the predetermined pressure of 200 kg as the basis.

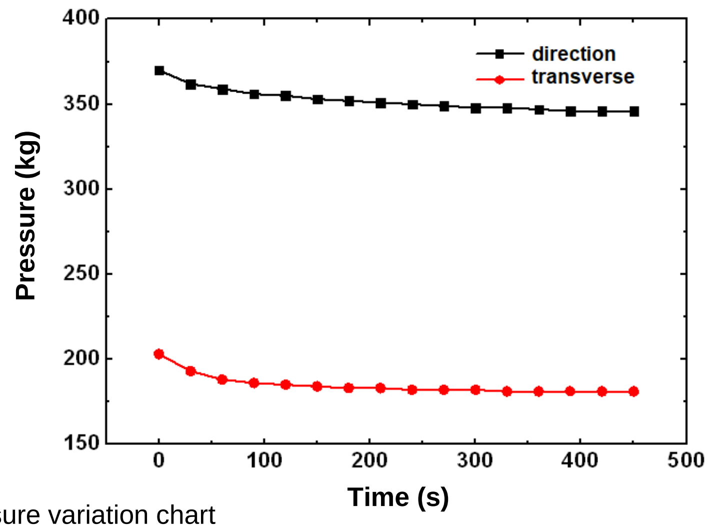

Fig. 12. Pressure variation chart

Under the condition of constant strain, the gradual decrease of pressure with time is a stress relaxation phenomenon. Figure 12 shows that the pressure reduction decreased with time, which was caused by the elastic-plastic nature of the glued HexBam. In pressure testing, the pressure loss caused by stress relaxation mainly occurred in the first 180 seconds, with a high inclination rate of the pattern. The middle changed slowly, and after 360 seconds, it was basically in a straight line. This part of pressure was the final load applied to the glued HexBam.

The elastic deformation of biomass materials makes it difficult to determine the pressure of the hot pressing process. This study mainly used a plate elastic compensation mechanism to compensate for pressure loss. It is recommended that when preparing bamboo raw materials or designing and manufacturing related equipment, the load at 600 s can be positioned at the final pressure to ensure the stability and accuracy of the pressure.

Longitudinal Compressive Test Results

The test was conducted according to the process parameters designed in Table 2, which showed the design of experiments. The mechanical properties of the sample of glued HexBam were tested with reference to the Technical Standard for Testing of Building Structures (GB/T50344-2004). The fixed loading rate was 2 mm/min, the displacement target value was 50 mm, the laboratory temperature was 20 °C, and the relative humidity was 60%. The test results are shown in Table 5.

The average load of the glued HexBam sample was 758 kN, with an average mass of 5.66 kg and a compressive strength of about 72.8 MPa. Considering the impact of quality on material properties, a specific strength analysis was conducted. The specific strength is the ratio of compressive strength to the actual density of the glued HexBam.

Table 5. Performance of HexBam

Number	Load (kN)	Quality (kg)	Actual Area (mm²)	Compressive Strength (MPa)	Specific Strength (N·m/kg)
1	725.4	5.64	8806.88	70.01	0.05128
2	828.8	6.38	10362.72	67.98	0.05079
3	783.1	5.67	9585.47	69.43	0.05099
4	755.9	5.18	8147.45	78.86	0.05605
5	706.6	5.65	8491.81	70.73	0.05490
6	661.1	5.31	8382.47	67.03	0.05267
7	850.9	5.69	8631.10	83.79	0.05546
8	736.7	5.63	8444.82	74.15	0.05216
9	779.2	5.78	9051.52	73.17	0.05159
Mean	758.6	5.66	8878.25	72.80	0.05288

Analysis and Discussion

Compressive strength is one of the main performance indicators of the glued HexBam as a building material. Considering it as a load-bearing component, its factor of safety needs to be studied. The compressive strength of the material in Table 5 is the corrected compressive strength (the correction factor *k* is 0.85). The range analysis and significance test were carried out using SAS software, and the results are shown in Table 6. The significance test of material performance was conducted using range analysis, and the results are listed in Table 7. The range analysis was conducted on the specific strength of glued HexBam samples, and the results are shown in Table 8.

Table 6. Variance Analysis and Significance Test of the Process Factors

Index	Source	DF	SS	MS	F-value	Pr>F
Compressive strength (MPa)	Adhesive type	2	380.47	190.24	21.07	<.0001**
	Quantity of adhesive	2	414.68	207.34	22.96	<.0001**
	Hot temperature	2	113.82	56.91	6.30	0.0057*
	Time	3	48.87	24.44	2.71	0.0849
	Model	8	957.83	119.72	13.26	<.0001
	Error	27	243.82	9.03		
	Corrected Total	35	1201.66			

Note: a=0.001 is very significant, with * *; a=0.05 significantly, with *

Table 7. Maximum Difference Analysis of Compressive Strength

Index	Level	Adhesive Type	Quantity of Adhesive (g/m²)	Heat Temperature (°C)	Heat Temperature Time (min)
Compressive strength (MPa)	1	207.43	232.67	211.20	213.91
	2	216.63	212.86	220.02	218.82
	3	231.12	209.64	223.96	222.45
	R	23.69	23.03	12.76	8.53

Table 8. Maximum Difference Analysis of Specific Strength

Index	Level	Adhesive Type	Quantity of Adhesive (g/m²)	Heat Temperature (°C)	Heat Time (min)
Compressive strength (MPa)	1	0.15306	0.16279	0.15611	0.15777
	2	0.16362	0.15785	0.15843	0.15892
	3	0.15921	0.15525	0.16135	0.1592
	R	0.01056	0.00754	0.00524	0.00143

Table 6 shows that the type and amount of adhesive had a statistically significant impact on the compressive strength of glued HexBam. The effect of thermosetting temperature on the compressive strength of the material was significant, while the effect of thermosetting molding time on the compressive strength of the material was not significant. The range analysis of compressive strength in Table 7 and the range analysis of specific strength in Table 8 show that among various process factors, the adhesive type had the most significant impact on compressive strength. It was followed by the adhesive amount, thermosetting molding temperature, and thermosetting molding time. The analysis showed that the most significant factors affecting the compressive strength of glued HexBam were the amount of glue applied and the type of adhesive, with the type of adhesive having the most significant impact.

To express the relationship between process factors and longitudinal compressive strength, histogram 8, 10, 11, and Line chart 12 were made according to the specific strength range analysis table 8.

The Influence of Adhesive Types on Longitudinal Compressive Strength

The longitudinal compressive strength of the glued HexBam prepared with urea formaldehyde adhesive was the lowest, while the phenolic adhesive gave the highest value. The compressive strength of the glued HexBam prepared with water-based isocyanate was slightly lower than that of the phenolic adhesive. Part of the reason is that phenolic adhesive had the best wettability on the surface of bamboo, followed by urea formaldehyde adhesive. The two-component isocyanate adhesive exhibited poor wettability on the surface of bamboo, resulting in a relatively reduced bonding interface. In Table 7, the compressive strength of the glued HexBam prepared with API adhesive was significantly higher than that of the reconstituted material prepared with PF adhesive, due to quality differences. Table 6 shows that the type of adhesive had a significant impact on compressive strength.

After the longitudinal compressive test, the UF adhesive material was completely dispersed and the adhesive layer was completely torn. The PF adhesive material was not fully dispersed, and after the longitudinal compressive test, individual bamboo segments still adhered to each other. Materials prepared by API adhesive, except for the tearing of the adhesive layer at the damaged position, had good bonding at other positions, as shown in Fig. 13. This may be determined by the characteristics of the adhesive. The cured UF and PF adhesives were brittle, and after applying a load, the bonding interface underwent brittle fracture. Complete separation occurred between units. By contrast, API is a plastic adhesive with toughness. After applying load, it will undergo elastic deformation, and the bonding performance between units remains intact without damage. The price of API in the market is 2.5 times that of PF adhesive and more than 4 times that of UF adhesive. Therefore, when preparing HexBam, phenolic resin adhesive is preferred, which not only can prepare materials with the highest compressive strength, but also can save costs.

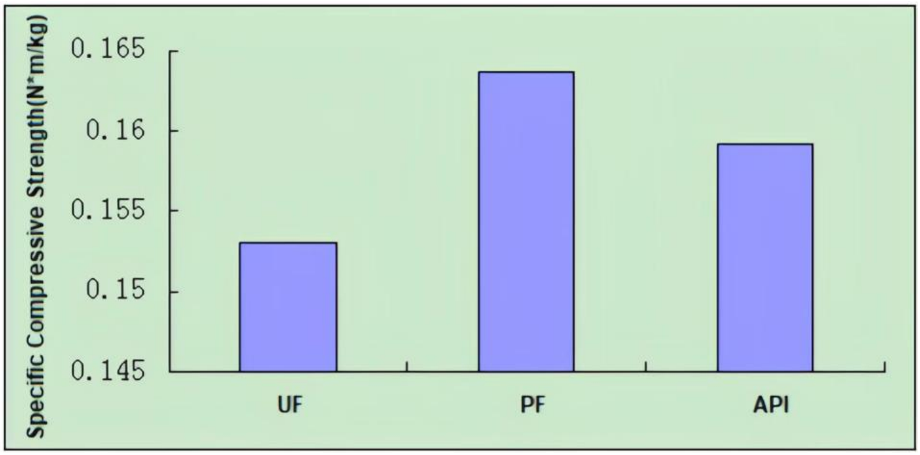

Fig. 13. The relationship between adhesive type and specific strength

Fig. 14. Longitudinal compressive test results

The Influence of Adhesive Application Amount on Longitudinal Compressive Strength

The influence of the quantity of adhesive on the compressive strength of the glued HexBam was found to be very significant. As shown in Fig. 15, the compressive strength decreased with the increase of the quantity of adhesive, and the compressive strength was the largest when the quantity of adhesive was 200 g/m^2. The influence of the quantity of adhesive in Table 7 on the compressive strength is the same as that in Table 8, because the adhesive layer was evenly distributed. At the level of 200 g/m^2, the adhesive fully penetrated into the bonding surface, and the bonding strength was the best. As the amount of adhesive increased, a multi-molecular layer structure was formed between the adhesive layers, and the bonding performance actually decreased. During the experiment, based on the initial compressive strength standard of 250 g/m^2, the optimal adhesive amount for lateral molding was established. Although the adhesive application method was the same for transverse and longitudinal bonding, the results were different. Further testing is needed to determine the changes in compressive strength when the glue dosage is below 200 g/m^2. Based on the present data, the best glue dosage process appears to be 200 g/m^2.

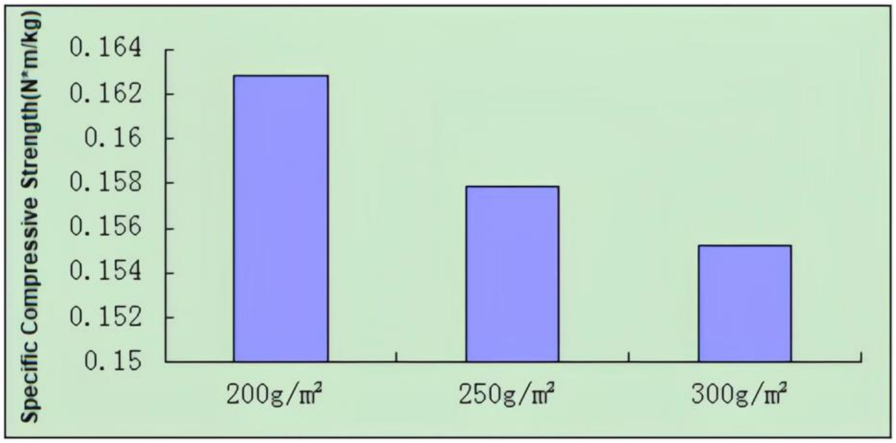

Fig. 15. The relationship between quantity of adhesive and specific strength

The Influence of Thermosetting Molding Temperature on Longitudinal Compressive Strength

The thermosetting hot-press temperature had a significant impact on the compressive strength of the glued HexBam. As shown in Fig. 16, with the increase of the thermosetting molding temperature, the longitudinal specific compressive strength of the glued HexBam increased, but the increase ratio was not large, only 5.5%. The change law of the thermosetting molding temperature on the compressive strength and specific strength of the glued HexBam was the same. Both were gradually increasing. On the one hand, with the increase of temperature, the adhesive will be fully cured, and the three-dimensional cross-linking of the adhesive will be more sufficient. The materials will be more closely bound by chemical bonds, and the bonding effect will be significantly improved. On the other hand, with the increase of temperature, the pyrolysis reaction of hemicellulose and contents in bamboo cells will occur, and this will enhance its compression resistance. At the same time, the carbonization phenomenon will occur in the HexBam, and the increase of stiffness and strength will enhance its compression resistance. As the temperature increases, the original state of bamboo material undergoes carbonization, and the increase in stiffness and strength enhances its compressive performance.

The Influence of Thermosetting Molding Time on Longitudinal Compressive Strength

The thermosetting molding time had no significant effect on the longitudinal specific compressive strength of the glued HexBam. As shown in Fig. 17, the longitudinal specific compressive strength of the material gradually increased with time, which was the same as the change rule of the compressive strength. The strength of the material was increased by 8% after 30 min of hot-pressing compared to 10 min of hot-pressing. The improvement effect was significant when hot-pressing for 20 min was compared to 30 min of hot-pressing. Extending the hot setting forming time is not ideal for improving the material’s performance. At 10 min, the adhesive had fully spread to the bonding surface, the spatial crosslinking reaction was basically completed, and a solid bonding interface had been formed. As time continued to increase, only the three-dimensional crosslinking of the adhesive was more comprehensive, showing a slight improvement in bonding performance, but not significantly. In sum, the selection of adhesive and adhesive amount for preparing glued HexBam was the most important, followed by the thermosetting molding temperature. The thermosetting molding time had the smallest impact on the longitudinal compressive performance of the material.

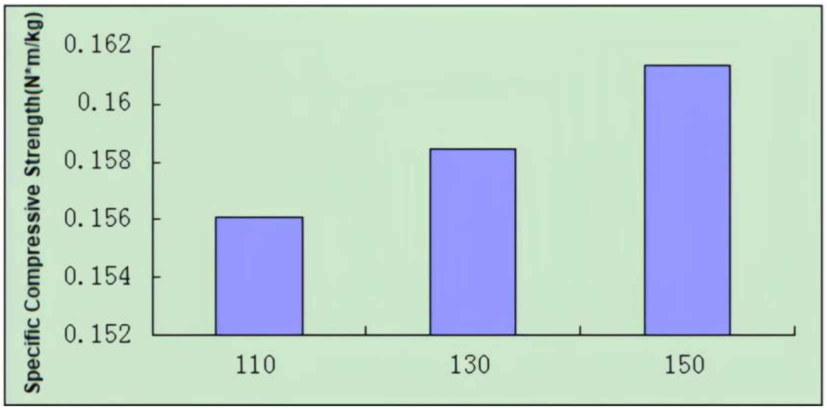

Fig. 16. The relationship between hot pressing temperature and specific strength

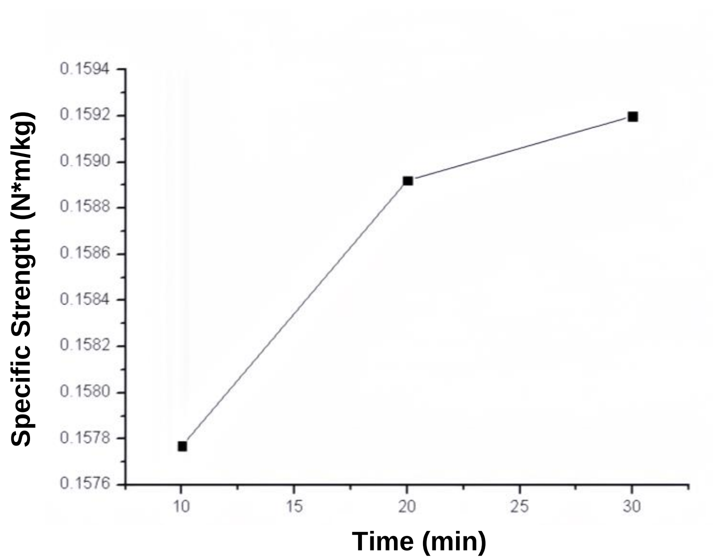

Fig. 17. The relationship between time and specific strength

Optimization and Validation of Forming Process

Taking into account various process factors, the optimized process parameters for preparing glued HexBam using the cold pressing and hot setting method were determined: The adhesive type is phenolic adhesive (PF), with an adhesive dosage of 200 g/m^2, a heat setting molding temperature of 130 °C, and a heat setting molding time of 10 minutes. Under the conditions of these hot-pressing process parameters, the glued HexBam was prepared and inspected.

Four test specimens were prepared using the optimized cold pressing and hot solidification process obtained from the analysis, and their performance was tested. The results are shown in Table 9. After optimizing the process, the specific strength of the glued HexBam was 0.0559 N • m/kg, which was better than the average value of in the experiment 0.0529N • m/kg, and slightly higher than the specific strength of steel 0.0535

N • m/kg. At the same volume, the weight of steel is 5.0 to 6.0 times that of glued HexBam, indicating that glued HexBam can be regarded as a high-strength and lightweight biomass material.

Table 9. Test Results of Process Optimization

Load (kN)	Quality (kg)	Actual Area (mm^2)	Compressive Strength (MPa)	Specific Strength (N•m/kg)	Allowable Load (kN)
793.70	5.45	9141.66	73.80	0.0559	195.00

Note: The safety coefficient is 4

CONCLUSIONS

1. The average cross-sectional size (side to side) of the glued HexBam was 288.1 mm, which was reduced by an average of 3.6 mm after hot pressing molding, for a proportional change of about 1.25%. The average longitudinal size of the cross-section (vertex to vertex) was 271.8 mm, which was reduced by 2.7 mm after hot pressing, for a proportional change of approximately 0.98%. The maximum reduction in transverse and longitudinal dimensions of the cross-section was 4.5 mm. After being aged for 24 h, an elastic recovery of about 0.3 to 0.4 mm was generated, with an elastic recovery proportion of about 11%. The lateral size change of the glued HexBam was greater than that of the longitudinal material.
2. The stress of the glued HexBam decreased with time during creep testing, and the decreasing trend tended to remain unchanged with time. In pressure testing, the pressure reduction caused by creep mainly occurred in the first 180 seconds, with a high inclination rate of the pattern. After 360 seconds, the pressure trend was basically in a straight line, which can be considered as the final load applied to the glued HexBam . It is recommended to position the load at 600 s at the final pressure when preparing bamboo raw materials or designing and optimizing related equipment.
3. The glued HexBam prepared with phenolic resin adhesive exhibited the best performance, followed by isocyanate adhesive. The phenolic adhesive gave the lowest strength. The longitudinal compressive strength of this material decreased with the increase of adhesive dosage, at 200 g/m. The maximum compressive strength was achieved by the amount of adhesive applied. As the temperature increased, it increased and reached its maximum value at 150 °C, but the proportion of increase was not high. The longitudinal compressive strength remained basically unchanged over time.
4. Optimized values were determined for the process parameters for preparing glued HexBam by cold pressing and hot setting molding method: The adhesive type was phenolic adhesive (PF), with an adhesive dosage of 200 g/m^2, a heat setting molding temperature of 130 °C, and a heat setting molding time of 10 minutes. Under these process parameters, the glued HexBam prepared had a longitudinal compressive strength of 73.8 MPa and a specific strength of 0.0535 N • m/kg, which is superior to ordinary steel.

ACKNOWLEDGMENTS

The authors are grateful for the special funds for basic scientific research business expenses of central-level public welfare scientific research institutes (Grant No. CAFYBB2021QC004).

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Article submitted: June 15, 2023; Peer review completed: July 8, 2023; Revised version received: September 19, 2023; Accepted: September 28, 2023; Published: October 6, 2023.
DOI: 10.15376/biores.18.4.7963-7980