

Article

Manufacturing Process and Performance Experiment of Natural Arc-Shaped Bamboo Laminated Lumber

Guofu Wang ¹, Rui Gao ², Hu Miao ^{3,4,*} , Yong Wang ¹, Changhua Fang ^{3,4}  and Huanrong Liu ^{3,4}

¹ Department of Mechanical and Electrical Engineering, University of Technology, Qingdao 266520, China

² Fujian Academy of Forestry, Fuzhou 350012, China

³ Department of Biomaterials, International Center for Bamboo and Rattan, Beijing 100102, China

⁴ Key Laboratory of National Forestry and Grassland Administration, Beijing for Bamboo & Rattan Science and Technology, Beijing 100102, China

* Correspondence: miaohu@icbr.ac.cn

Abstract

Natural arc-shaped bamboo laminated lumber (ABLL) represents an eco-friendly advanced material. This study introduces an innovative preparation method and manufacturing process to enhance production efficiency and reduce costs. Full-scale processing experiments were conducted to evaluate the feasibility and performance of the innovative integrated fixed-arc and drying process. Bonding integrity was assessed through glue-line shear strength and soak-delamination resistance. The maximum dry glue-line shear strength and delamination length achieved were 8.19 MPa (>traditional value of 3.5 MPa) and 21.8 mm (<traditional value of 25 mm), respectively. Comparative analysis of material utilization of eight-layer natural arc-shaped bamboo laminated lumber demonstrated a rate of 77.9% (<traditional value of 60%). This optimized process significantly contributes to elevated production efficiency and material yield in natural arc-shaped laminated lumber manufacturing.

Keywords: natural arc-shaped bamboo laminated lumber; concurrent fixed-arc shaping and drying; performance experiment; technology and equipment



Academic Editors: Benedetto Pizzo and Angela Balzano

Received: 27 September 2025

Revised: 31 October 2025

Accepted: 5 November 2025

Published: 7 November 2025

Citation: Wang, G.; Gao, R.; Miao, H.; Wang, Y.; Fang, C.; Liu, H. Manufacturing Process and Performance Experiment of Natural Arc-Shaped Bamboo Laminated Lumber. *Forests* **2025**, *16*, 1699.

<https://doi.org/10.3390/f16111699>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Against the backdrop of global forest resource crises, momentum is growing for replacing plastics and timber with bamboo. As a biomass resource, bamboo shares comparable properties with wood while exhibiting superior growth rates and lower cultivation costs [1]. In recent years, bamboo-based products have generated substantial economic and ecological value across the construction, food service, piping, and automotive industries. The development of engineered bamboo materials represents a significant step toward resolving the conflict between timber demand and forest conservation [2,3].

Manufacturing pure bamboo panels typically necessitates sectioning bamboo into dimensional units for subsequent recombination and adhesion [4–6]. This approach compromises bamboo's intrinsic grain and structural integrity while generating environmental contamination, elevated costs, and material wastage [7]. ABLL, recognized as an optimal dimensional unit for preserving bamboo's natural grain and gradient structure, achieves utilization rates exceeding 60% [8,9].

The standard manufacturing process for ABLL comprises the following sequential stages: preparation of reconstituted bamboo elements, drying, adhesive application, assembly, high-frequency heat pressing, post-processing, and secondary processing. Among

these, the bamboo units, which originally have unequal outer (R_1) and inner (R_2) diameters, are processed into uniform dimensions (R_3). This integrated workflow produces finished arc-shaped bamboo products and value-added derivatives, as shown in Figure 1 [10–15].

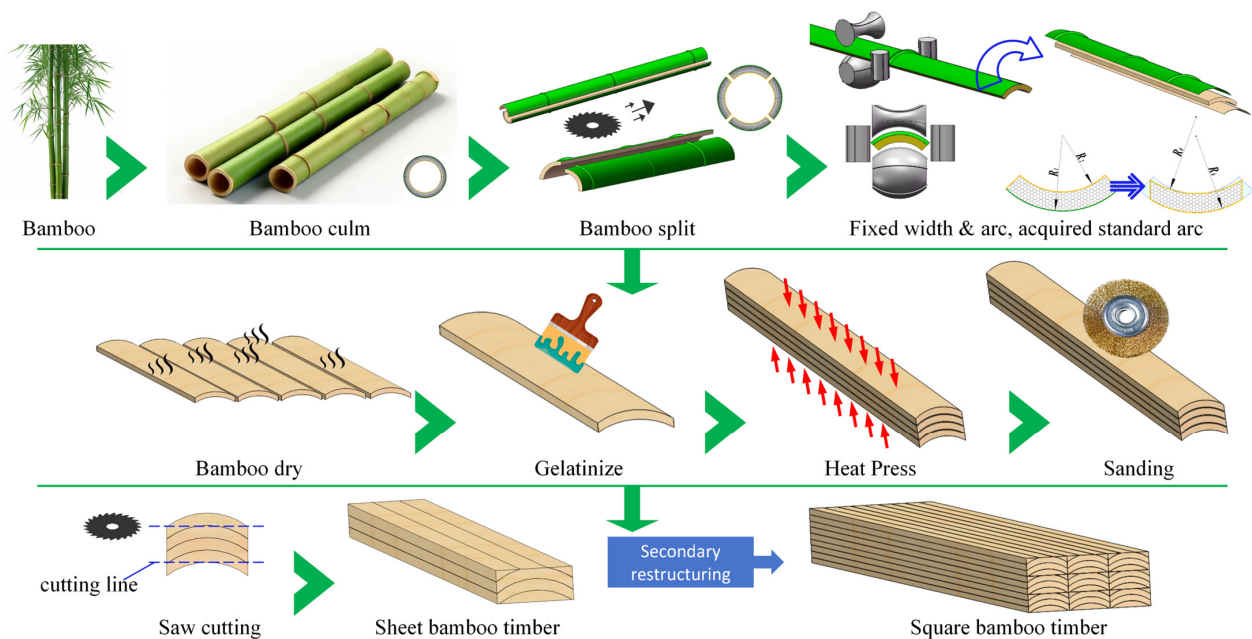


Figure 1. The traditional production process of processing bamboo stems into arc-shaped bamboo laminated lumber.

Arc-shaping bamboo splits constitute the critical technical challenge in manufacturing ABLL [4]. To match the inner and outer arc radii, conventional techniques use milling. This method requires partial removal of the bamboo green and bamboo yellow parts. Such removal lowers material utilization [16,17]. Furthermore, equal-arc bamboo splits are made by milling warp and shrinking during drying. They also show varying deviations in curvature radius [15]. Existing flattening techniques are effective for turning curved bamboo into flat laminates. However, they often sacrifice the natural arc geometry. This geometry is a key structural advantage of ABLL. The sacrifice occurs because these techniques forcefully suppress bamboo's intrinsic curvature. This suppression leads to residual stresses and reduced mechanical performance [16]. Similarly, traditional laminate processes divide arc-setting and drying into separate sequential steps. First, pre-shaped arcs are formed. Then, these arcs are dried independently. This two-step approach often causes rebound or uneven shrinkage. Such issues compromise arc consistency during subsequent bonding [4]. Consequently, advancing arc-shaped original-state recombined bamboo faces a critical challenge. The challenge is to develop novel arc-setting techniques for arc-shaped bamboo splits. These techniques should meet three goals: minimize material loss, enhance utilization efficiency, and preserve arc stability before gluing. Our work addresses these limitations by combining arc-setting and drying into one process. This integrated process has multiple advantages. First, it avoids excessive material removal. In contrast, milling techniques often involve excessive material removal. Second, it retains the natural arc geometry. Flattening techniques, by comparison, usually lose this key structural feature. At the same time, the integrated process controls moisture content and curvature synchronously during drying. This feature helps overcome the arc instability that is inherent in sequential laminate techniques.

To tackle issues of inadequate bonding performance, low material utilization, and inefficient production in ABLL manufacturing, this research developed innovative improve-

ments to the production process of ABLL. To validate the effectiveness of this improved process, a full-cycle production trial of ABLL was conducted using self-developed integrated arc-setting and drying equipment. A critical aspect was testing the adhesive layer shear strength and dip peel performance of the ABLL to evaluate its bonding quality and yield rate. This research aims to provide optimized solutions for enhancing the production efficiency of arc-shaped natural scrimber and minimizing resource waste.

2. Materials and Methods

2.1. Novel Production Process for ABLL

To address limitations in the production processes and equipment of traditional ABLL, this study proposes a novel fabrication method and technology for arc-shaped bamboo splits and their laminates. The process begins with the light sanding of the bamboo green and bamboo yellow surfaces on arc-shaped splits. It then proceeds to precise arc-setting via a mold, which adjusts the inner and outer arc radii to match. Concurrent drying during arc-setting ensures a uniform moisture content, yielding arc-shaped split units that are ready for subsequent processes such as gluing and bonding. The final step involves fabricating novel arc-shaped original-state bamboo laminates through cold-press bonding. The production workflow for this novel laminate preparation is presented in Figure 2, where processes in the red and blue dashed boxes are interchangeable. Some dimensions in the figure are exaggerated for clarity.

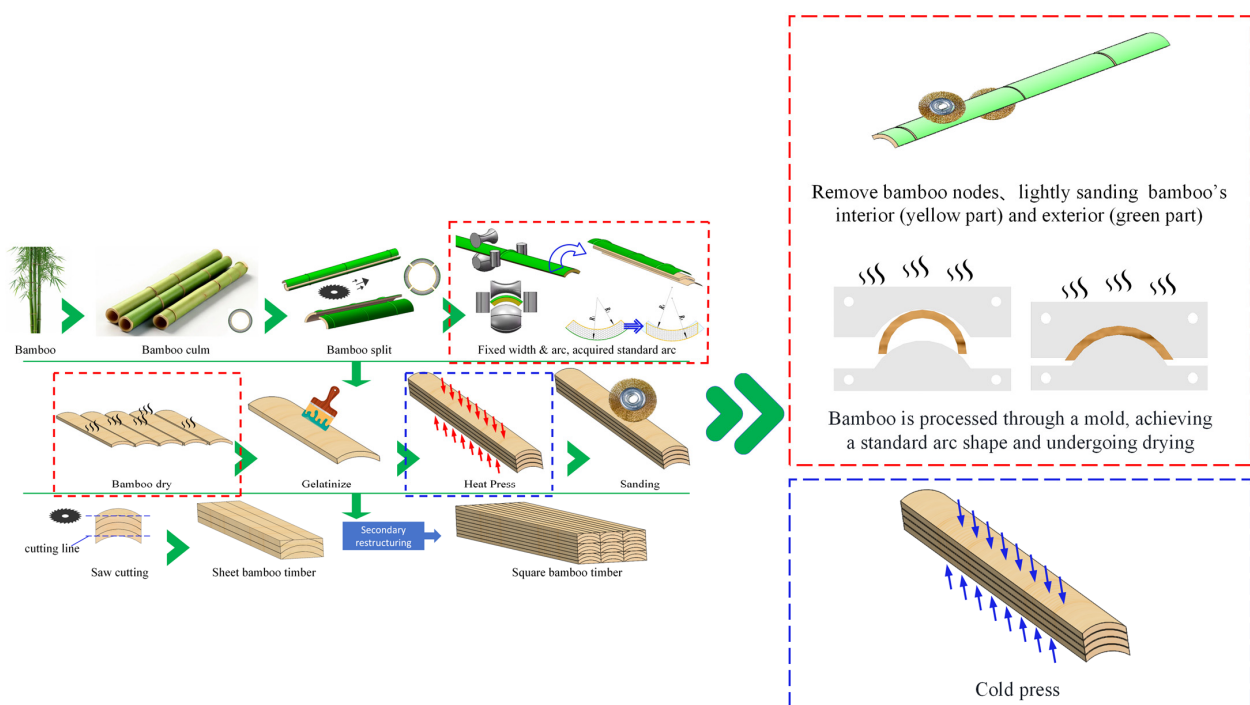


Figure 2. Novel production process for ABLL.

The production workflow for novel ABLL differs most significantly from that of traditional arc-shaped original-state recombined materials in two aspects: the method of obtaining arc-shaped bamboo split units, and the synchronization of the arc-setting and drying processes. Below is an elaboration of the design rationale for these two critical process stages.

Preliminary studies by our research team [18–21] demonstrate that phenolic resin penetrates the bamboo's yellow part via pits and cell wall layers of its stone cells, forming glue nails and cross-linked interlocking structures that generate bonding force in the

bamboo's yellow part. This finding provides a critical theoretical foundation for the present study's process of lightly sanding the bamboo's green and yellow surfaces and performing arc-conforming gluing of these layers.

Bamboo exhibits mechanical viscoelasticity characterized by time-dependent stress–strain behavior [22–24]. As the temperature increases, bamboo's plasticity enhances: applying controlled pressure to arc-shaped splits during gradual heating induces gradual arc deformation. When the temperature reaches the glass transition temperature, sufficient pressure can drive irreversible arc changes in the splits. Thus, a theoretically viable solution has been proposed for altering the original arc of arc-shaped bamboo splits. First, the arc-shaped bamboo splits are clamped using a mold with a specific curve. Next, the clamped bamboo splits are placed in an environment where the temperature increases gradually. Throughout the entire process, sustained pressure is maintained on the mold. This solution leverages the intrinsic properties of bamboo, which ultimately allows the original arc of the bamboo splits to be altered [25].

In order to realize the new process, this study developed an experimental setup and its corresponding control system. With reference to the methodology reported in the existing literature [26,27], the performance of the process and associated equipment was evaluated by investigating the bonding layer properties of cold-pressed ABLL and calculating the bamboo utilization rate. Specifically, the bonding performance parameters include shear strength and peeling length.

2.2. Design of the Prototype for the Experiment

The pressing capacity of the test prototype is critical to the arc-setting performance. The equipment's pre-stored release force determines its maximum pressing capacity. Based on reference [28] and verified with test bamboo materials, the formula for calculating the pre-stored release force of the mold that is required for a single arc-shaped bamboo piece is given in Equation (1).

$$F_s = lcSk \quad (1)$$

where F_s is the force of mold pre-stored release; l is the length of the bamboo split; c is the length of the bamboo split chord; and S is the radial direction ring stiffness of Moso bamboo (150 kN/m^2) [4,7]. Given the significant variation in radial ring stiffness of round bamboo from the base to the top, a correction coefficient k is introduced. Pre-experimental data and references indicate that k ranges from 0.5 to 1.5, enabling the fine adjustments required in practical production [4,8,28].

The self-designed test prototype is illustrated in Figure 3, with key structural parameters being presented in Table 1. The operating principle of the mechanical structure for the integrated fixed-arc drying process is as follows: A compression spring is fixed to the top of the guide rail, with the concave mold and convex mold being mounted sequentially beneath it. The lead screw mechanism is installed at the base of the convex mold. It drives the convex mold upward along the guide rail. This upward movement reduces the gap between the concave and convex molds. As the movement continues, the gap keeps decreasing until the two molds close completely. Once closed, the lead screw continues to lift, compressing the spring. The compression degree of the spring is measured by a displacement sensor. The required deformation amount of the spring is obtained using Equation (1) and Hooke's Law. Additionally, a pressure sensor was installed on the base of the lead screw to measure the pre-stored release force. The two signals serve as each other's references. When the compression deformation and pre-stored release force reach the required value, the lead screw stops lifting and remains in position. The experiment prototype is housed in a drying kiln. Heated airflow permeates the mold cavity. As this occurs, the arc-shaped bamboo

splits soften. The spring, already deformed, rebounds to release stored energy. This ensures that the bamboo split's arc conforms to the mold geometry.

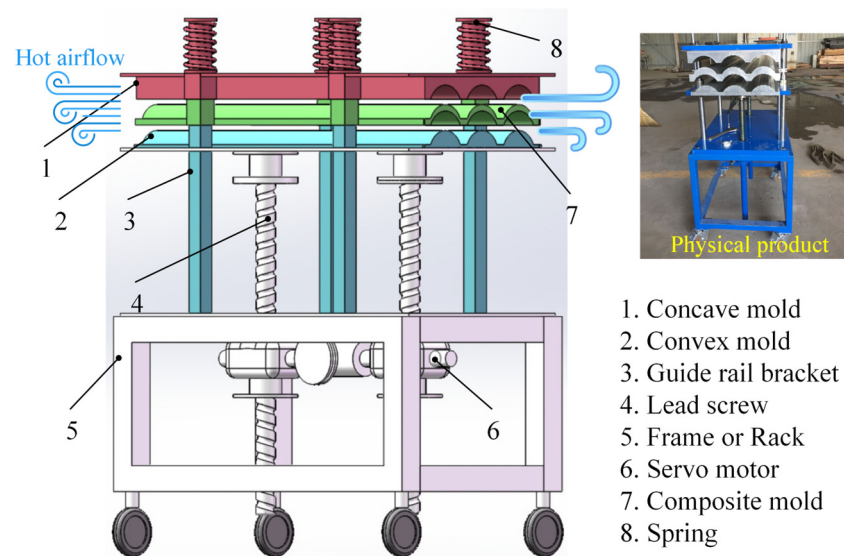


Figure 3. Schematic diagram of the prototype machine.

Table 1. Parameters of the experimental prototype.

Parameter	Value
Maximum loading capacity	10 t
Length	1200 mm
Width	800 mm
Height	Determined by pressing layers
Stroke of mold	75 mm
Layers of mold	2

2.3. Design of the Information Acquisition and Control System

An information acquisition and control system was designed to monitor and record process parameters in real time during the integrated fixed-arc drying process. It requires the following functionalities:

- (1) Real-time temperature acquisition in the drying kiln and associated data storage;
- (2) Real-time acquisition of the mold's pre-stored release force and data storage;
- (3) Real-time gap measurement between concave and convex molds and data storage;
- (4) Real-time display of acquired parameters, system operation monitoring, and sampling frequency configuration.

To fulfill these functionalities, this study deploys a pressure sensor (piezoresistive pressure sensor, 0–20 kN) for real-time measurement of the mold's pre-stored release force, a temperature sensor (online infrared temperature measurement sensor, 0–200 °C) for real-time acquisition of the drying kiln temperature, and a displacement sensor (linear position sensor; the precision is 0.01 mm) for real-time measurement of the compression distance of the spring and the gap between concave and convex molds. A Siemens PLC serves as the main controller, responsible for sensor signal acquisition, analysis, and storage. A human-machine interface (HMI) is developed using WEINVIEW touchscreen and Visual Studio 2017 software, enabling real-time display of acquired parameters, sampling frequency configuration (30 s in this experiment), and more. These components collectively constitute the information acquisition and control system, with its structure and experiment setup being presented in Figure 4.

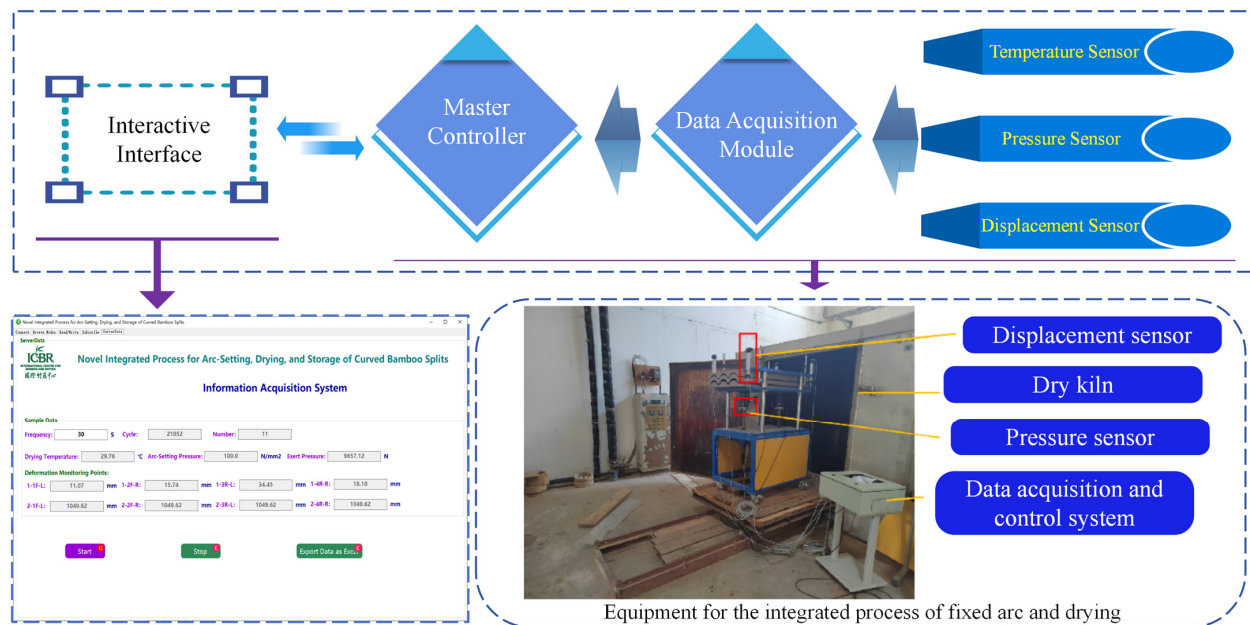


Figure 4. Experiment equipment, information acquisition, and control system.

2.4. Experimental Materials and Scheme

The experimental materials used in this study consisted of 4-year-old Moso bamboo (Latin name: *Phyllostachys edulis*), sourced from Huangshan City, Anhui Province, China. Dimensions include an average breast diameter of 10–12 cm, with lengths selected within the range of [0.5 m, 1.3 m] relative to the bamboo's cutting line. Raw harvested bamboo was quartered, with nodes being removed and surfaces lightly sanded, as shown in Figure 1. Three of the bamboo splits were used for the experiment, while the fourth segment was reserved for calibrating moisture content parameters and replacing abnormal samples [27]. To control variables, 15 bamboo splits with similar dimensions were selected for fabricating three-layer laminates (ABLL-3), and 40 bamboo splits were used for eight-layer laminates (ABLL-8). Ten samples of 150 mm were taken along the ABLL-3 axis for the experiment. Destructive tests, including horizontal shear strength and immersion peeling performance evaluations, were conducted on the ABLL-3 to assess bonding quality [27–29]. For the shear test, the specimen was mounted on a universal testing machine (UTM), as shown in Figure 5 [30]. The loading roller gradually applied a downward load until the material failed. Based on pre-experimental results, this load was insufficient to cause damage to the bamboo splits. However, it was sufficient to induce cracking in the adhesive layer of the bamboo sheets. A compressive load was gradually applied axially to the specimen to induce shear failure in the adhesive layer, and the maximum shear force was measured. For the immersion peeling performance test, the intact specimens were subjected to the following cyclic procedure: First, a specimen was submerged in boiling water for 4 h. After removal, it was transferred to a 63 °C drying oven and dried for 20 h. Next, the specimen was re-submerged in boiling water for another 4 h. Upon removal, it was placed in the 63 °C drying oven again for a 3 h drying period. Finally, the maximum continuous peeling length of the adhesive layer was measured. For each of the above two tests, 5 original samples were selected. The material utilization rate of ABLL-8 was calculated using Equation (2) [31]. These samples can also be used for other purposes. After excluding outliers from the five datasets, the mean was adopted as the test outcome. To assess the data's precision, stability, and variation tendencies, data analysis was performed utilizing statistical methods including error analysis and variance analysis. Post-treatment, the test

bamboo splits had dimensions of approximately 1260 mm (length) $\times$ 150 mm (width) $\times$ 10 mm (thickness).

$$\Phi = \frac{M_1 - M_2 - M_3}{M_0} \times 100\% \quad (2)$$

where Φ denotes the bamboo utilization rate; M_1 represents the absolute dry weight of bamboo splits after the arc fixing process; M_2 is the weight of the applied glue; M_3 refers to the weight that was removed via sawing; and M_0 stands for the initial absolute dry weight of bamboo splits.

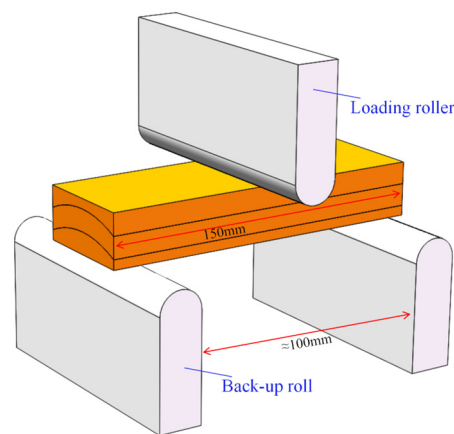


Figure 5. Schematic diagram of horizontal shear strength test.

The key equipment includes an in-house-developed integrated test rig for arc-setting, drying, and storage processes, along with a drying kiln, vernier calipers (Mitutoyo, Kanagawa, Japan; ± 0.01 mm), an electronic balance (± 0.001 g), and a tape measure, as shown in Figure 4. Following the pre-experiment, this study adopted Henkel LOCTITE HB S109 PURBOND (Henkel LOCTITE Co., Ltd., Shanghai, China), a one-component liquid polyurethane adhesive. Based on the adhesive's performance specifications and the unique properties of bamboo, the process parameters for gluing and cold-press forming are presented in Table 2.

Table 2. Gluing and cold-press forming process parameters for arc-shaped bamboo splits.

Parameters	Value
Adhesive application amount	200 g/m ² (single-sided application)
Curing time	≤ 10 min (20 °C, air humidity: 65%, bamboo moisture content: 12%)
Pressurization time	45 min
Ambient temperature	30 $\pm$ 5 °C
Ambient humidity	40% $\pm$ 10%
Pressurization pressure	0.8 $\pm$ 2 MPa
Post-pressurization placement time	At least 2 h of placement in a 20 °C environment after pressurization

After being formed into standard arcs, the specimens exhibited similar moisture contents. They meet the requirements for lay-up pressing into finished lumber [25,31]. In this study, the novel process employs cold-pressing. After applying adhesive to the arc-shaped bamboo specimens, they are placed into the cold-press mold to initiate the cold-press bonding process, as illustrated in Figure 6. Based on Equation (1), the press system was set to a range of 10–15 T [29].

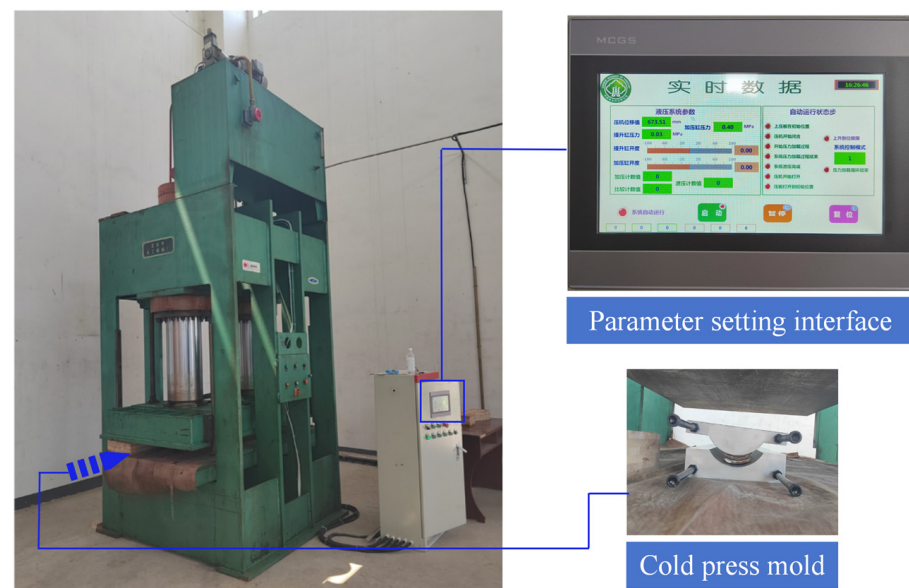


Figure 6. Equipment and operation site diagram of the cold-pressing process.

3. Results and Discussion

3.1. The Products of the Experiment

A diagram of the experimental effect of the arc-shaped bamboo laminate process is presented in Figure 7. Within the mold, it is clearly observed that the green part of the processed bamboo specimens closely conforms to the concave mold, while the bamboo's yellow part fits the convex mold tightly. Additionally, a noticeable arc modification effect is evident. Upon removal from the mold, the specimens exhibit no significant cracking on either the bamboo's green or yellow sides, confirming effective arc-setting. When the three arc-shaped bamboo pieces are stacked along their arc direction, their arcs are nearly uniform, with good conformity. After completing the cold-press bonding process, the pressed blank is removed from the mold. It is then placed in a laboratory environment for 2 h, followed by edge trimming via sawing. This resulted in the production of ABL-3 using the new process, as shown in Figure 7.

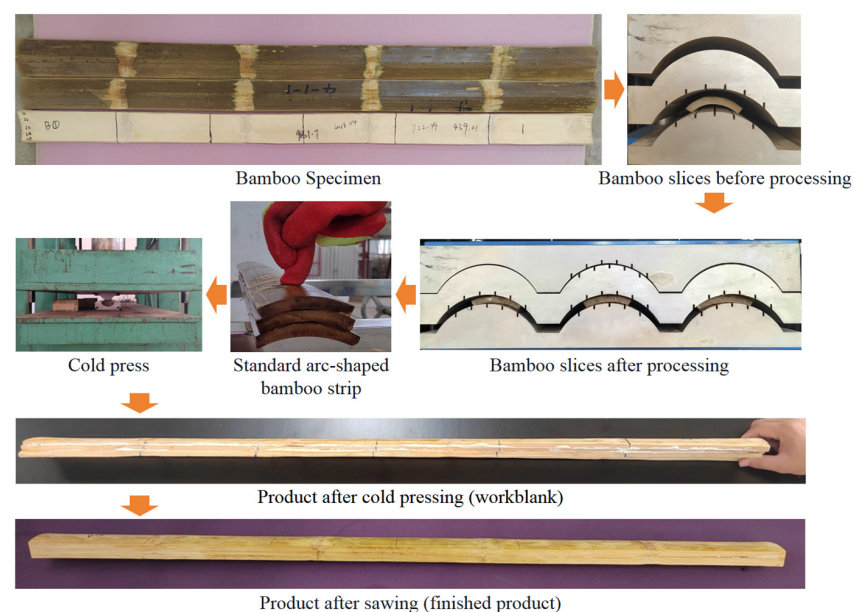


Figure 7. A diagram of the experimental effect of the arc-shaped bamboo laminate process.

3.2. The Experimental Effect on Bonding Quality

Experiments revealed that the average maximum dry adhesive layer shear strength of five sets of ABLL-3 samples was 8.19 MPa, with a coefficient of variation of 5.6%. ABLL and cross-laminated timber (CLT) have identical typical application scenarios. Specifically, one of the core objectives of ABLL research is for it to serve as an alternative to CLT [1,4,8]. Thus, CLT was chosen as the reference for shear strength comparison. The shear strength value exceeds that of CLT by 3.51 MPa and can be used as a structural material instead of CLT [1,5]. The shear strength values of ABLL meet the requirements of relevant standards [32,33], making it more conducive to further processing and application in the future. This is attributed to the high tensile strength of cellulose microfibrils, which enables effective transfer of shear stress and prevents shear stress concentration in the adhesive layer [34]. Bamboo inherently exhibits higher fiber alignment. After the arc fixing process, its density increases, and its interfacial mechanical interlocking capacity is enhanced. These two changes collectively result in a significant improvement in shear strength. Following arc fixing, the uniform and optimal thickness and moisture content of bamboo splits facilitate complete curing of the adhesive layer, minimizing adhesive layer cracking induced by local stress concentration [25,35]. Notably, adhesive failure occurred between the bamboo's yellow part and the bamboo flesh, rather than at the conventional yellow part–adhesive interface. The core reason stems from the inherent structural heterogeneity of bamboo itself and the enhancement of interfacial bonding strength by the process developed in this study [2,3]. The structure and composition of the bamboo's yellow part and flesh exhibit gradient abrupt changes, forming natural cohesive force weak zones within the bamboo substrate [7]. Specifically, the arc fixing process in this study preserves the surface integrity of the bamboo's yellow part. Meanwhile, the drying process in this study precisely controls the moisture content. These two processes collectively significantly enhance the physical anchoring and chemical cross-linking forces at the adhesive–yellow part interface. These enhanced forces exceed the cohesive force of the yellow part–bamboo flesh weak zones, resulting in bonding failure that occurs preferentially at the latter [36].

The damaged specimens after the immersion peel performance tests are shown in Figure 8, with their corresponding data being presented in Table 3. Analysis confirms low variability in the data. As shown in Table 3, the immersion peel performance of the ABLL-3 complies with the “immersion peel” requirements specified in the forestry industry standard [33], namely that the total peel length of any adhesive layer shall not exceed 25 mm. This is because the degree of cross-linking of the adhesive layer directly determines its peel resistance. Consistent with the rationale presented earlier, the integrated arc fixing and drying process maximizes the retention of the integrity of bamboo's surface fibers and pores, while simultaneously increasing the bamboo's density [25,37–39].

Table 3. Immersion peel performance data.

Parameter	Mean Value	Standard Deviation (SD)	Variance (s ²)
Peel length of the right view	0 mm	0	0
Length of the right view	148.6 mm	3.8	14.46
Peel length of the front view	0 mm	0	0
Length of the front view	148.9 mm	2.73	10.32
Peel length of the left view	21.8 mm	1.32	8.33
Length of the left view	148.6 mm	3.64	11.26
Peel length of the rear view	0 mm	0	0
Length of the rear view	148.9 mm	2.93	9.65
Peel rate	3.67%		

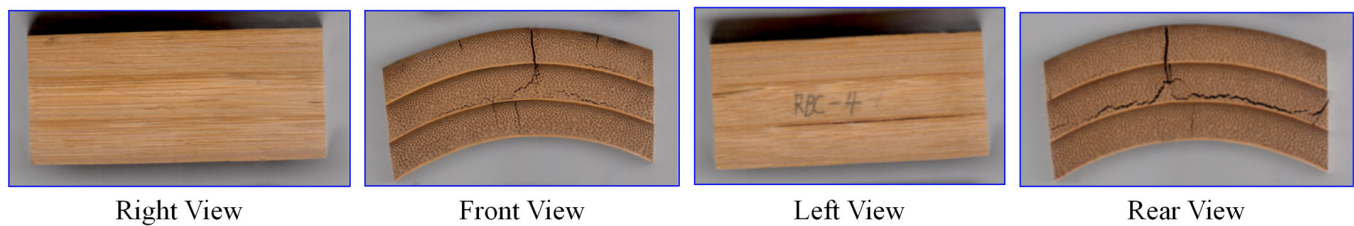


Figure 8. The results for the specimens of immersion peel performance experiments.

In conclusion, the cold-press bonding process employed herein to fabricate the novel natural arc-shaped bamboo laminate utilizes appropriate adhesives and rational process parameters, resulting in satisfactory bonding quality of the final product.

3.3. The Material Utilization Rate of ABLL

To evaluate the material utilization efficiency of the integrated arc-setting and drying process, an experiment was conducted on ABLL-8. The average value of the weights of arc-shaped bamboo splits at each experimental stage were recorded, with results being presented in Table 4. Data analysis results confirm stable performance of the drying kiln, while significant variations in weight and moisture content were observed among the eight samples. The cold-press bonding process for the ABLL-8 and the resulting finished products are illustrated in Figure 9.

Table 4. Recorded weights of ABLL from production to finished product.

Specimen Number	Oven-Dry Weight (g)	Initial Weight (g)	Initial Moisture Content (%)	Weight After Node Removal and Sanding (g)	Weight After Arc-Setting and Drying (g)	Moisture Content After Arc-Setting and Drying (%)	Oven-Dry Weight After Arc-Setting and Drying (g)	Weight of Edge-Sawing Trimmings (g)	Finished Product Weight (g)
1	483.26	705.32	45.9	641.51	562.88	16.5	470		
2	530.25	758.12	43	695.05	615.98	16.2	516.19		
3	519.61	727.98	40.1	670.98	602.9	16.0	506.44		
4	367.05	543.74	48.1	499.67	427.58	16.5	357.03		
5	407.78	617.68	51.4	556.48	476.35	16.8	396.32		
6	516.3	821.21	59.1	742.78	603.43	16.8	502.05	908.12	3774.29
7	521.17	916.4	75.8	846.32	616.12	18.2	503.99		
8	518.17	834.92	61.1	761.21	610.84	17.8	502.11		
SD	61.50	120.64	11.75	111.92	72.68	0.77	59.60		
s^2	3309.76	12,734.24	120.75	10,959.96	4621.56	0.52	3107.70		
SUM	3863.59						3754.13		

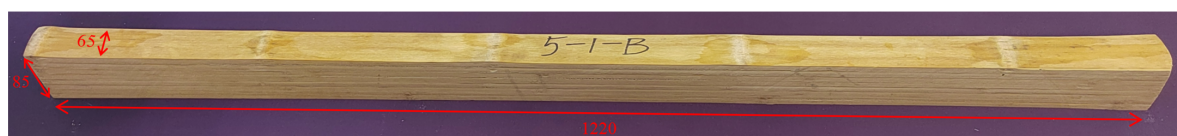


Figure 9. Cold-pressing process of 8-layer ABLL and the resulting finished products.

To exclude the influence of moisture content in arc-shaped bamboo splits, the oven-dry weight of the splits at each stage was used as the reference for calculations in this experiment [19,23]. As shown in Table 4, the total oven-dry weight of the eight-layer ABLL at the initial production stage was 3863.59 g. Following the integrated arc-setting and drying process, the total oven-dry weight decreased to 3754.13 g. After applying 166.5 g of adhesive and performing cold-press bonding, 908.12 g of trimmings was generated during edge sawing. The total oven-dry weight of the finished product was approximately

3012.51 g. Accordingly, the material utilization rate of natural arc-shaped bamboo splits processed into finished products was approximately 77.9% [3]. This is far higher than the maximum utilization rate of about 60% for similar products [19,40–43]. According to relevant standards, the product conforms to the actual production conditions [44–47].

4. Conclusions

Traditional manufacturing processes for natural arc-shaped bamboo laminated lumber (ABLL) suffer from procedural complexity, low material utilization, and excessive waste. To address these issues, this study proposed an innovative integrated process combining arc-setting and drying with purpose-built supporting equipment. Pretreated bamboo splits with consistent moisture content and standardized arc geometry were then directly cold-pressed and bonded to form ABLL blanks.

The experimental results show that the bamboo splits that were processed by the integrated arc-setting and drying equipment showed a uniform shape, consistent moisture content, and high dimensional conformity. This lays a critical foundation for stable bonding. Specifically, the ABLL-3 specimens displayed an average ultimate shear strength of 8.19 MPa, with a coefficient of variation of 5.6%. Notably, this strength surpassed the 3.51 MPa recorded for cross-laminated timber (CLT). This enhanced performance stems from the high tensile strength of bamboo cellulose microfibrils and the arc-fixing treatment, which increases the bamboo's density and strengthens interfacial mechanical interlocking. Additionally, the uniform wall thickness and optimal moisture content of the specimens ensured full curing of the adhesive layer, thereby reducing the risk of cracking. Regarding the adhesive failure mode, failure occurred at the natural weak zone between the bamboo's yellow part and its flesh, rather than at the adhesive layer interface. This indicates that the bonding strength of the adhesive–yellow part interface has exceeded the internal cohesive force of the bamboo substrate. Furthermore, the immersion peeling performance of ABLL-3 met industry standards, with a total peeling length of no more than 25 mm. This finding further confirms the effectiveness of the integrated arc fixing and drying process in improving gluing quality. The material utilization efficiency for ABLL-8 reached ~77.9%, representing a substantial improvement from the traditional process.

This research still requires further investigation and implementation in the following aspects: Experiments were conducted exclusively on Moso bamboo splits with a diameter of 8–10 cm. The process's adaptability to smaller-diameter bamboo or aged bamboo remains untested, potentially restricting its applicability to specific raw material ranges. The current equipment operates in small batches. Scaling up to industrial production may lead to an uneven temperature distribution in the drying chamber. This uneven temperature distribution could degrade the arc consistency or increase energy consumption. This issue represents a key trade-off between laboratory efficiency and industrial feasibility.

Author Contributions: Conceptualization, H.M. and G.W.; methodology, G.W.; software, H.M. and H.L.; validation, H.M. and R.G.; formal analysis, C.F. and H.L.; investigation, C.F. and Y.W.; resources, C.F., H.M. and H.L.; data curation, R.G. and Y.W.; writing—original draft preparation, H.M. and G.W.; writing—review and editing, Y.W. and G.W.; funding acquisition, G.W. and H.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Program of the Foundation of the International Centre for Bamboo and Rattan Scientific Research Projects (Grant No. 1632022021) and the basic scientific research operation funds of Qingdao University of Technology (Grant No. 20506327).

Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding author upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Chen, Q.; Fei, B.; Qi, J.; Zhang, S.; Huang, X.; Jiang, Y.; Xie, J.; Jia, S. Effect of moisture content on bamboo's mode I interlaminar fracture toughness: The competition between promoting and impeding crack growth. *Constr. Build. Mater.* **2022**, *341*, 127822. [\[CrossRef\]](#)
- Ma, Y.; Luan, Y.; Chen, L.; Huang, B.; Luo, X.; Miao, H.; Fang, C. A Novel Bamboo–Wood Composite Utilizing High-Utilization, Easy-to-Manufacture Bamboo Units: Optimization of Mechanical Properties and Bonding Performance. *Forests* **2024**, *15*, 716. [\[CrossRef\]](#)
- Arya, S.; Kumar, R.; Chauhan, S. Preparation and characterization of woven jute fabric layered composite by using bamboo fiber reinforced polymers as resin matrix. *Constr. Build. Mater.* **2024**, *411*, 134343. [\[CrossRef\]](#)
- Huang, B.; Chen, L.; Wang, X.; Ma, X.; Liu, H.; Zhang, X.; Sun, F.; Fei, B.; Fang, C. Eco-friendly, high-utilization, and easy-manufacturing bamboo units for engineered bamboo products Processing and mechanical characterization. *Compos. Part B Eng.* **2023**, *267*, 111073. [\[CrossRef\]](#)
- Dauletbek, A.; Li, H.; Lorenzo, R.; Corbi, I.; Corbi, O.; Ashraf, M. A review of basic mechanical behavior of laminated bamboo lumber. *J. Renew. Mater.* **2022**, *10*, 273. [\[CrossRef\]](#)
- Reynolds, T.P.; Sharma, B.; Serrano, E.; Gustafsson, P.-J.; Ramage, M.H. Fracture of laminated bamboo and the influence of preservative treatments. *Compos. B Eng.* **2019**, *174*, 107017. [\[CrossRef\]](#)
- Wang, X.; Chen, X.; Shang, L.; Chen, L.; Huang, B.; Ma, X.; Fei, B.; Liu, H.; Fang, C. A straightforward and efficient gradient pressure method for bamboo flattening: Strain and multi-scale deformation. *Compos. Part B Eng.* **2024**, *272*, 111232. [\[CrossRef\]](#)
- Fang, C.-H.; Jiang, Z.-H.; Sun, Z.-J.; Liu, H.-R.; Zhang, X.-B.; Zhang, R.; Fei, B.-H. An overview on bamboo culm flattening. *Constr. Build. Mater.* **2018**, *171*, 65–74. [\[CrossRef\]](#)
- Yuan, T.; Wang, X.; Liu, X.; Lou, Z.; Mao, S.; Li, Y. Bamboo flattening technology enables efficient and value-added utilization of bamboo in the manufacture of furniture and engineered composites. *Compos. Part B Eng.* **2022**, *242*, 110097. [\[CrossRef\]](#)
- State Forestry Administration Beijing Forestry Machinery Research Institute. Arc-Shaped Bamboo Original State Recombinant Material and its Manufacturing Method. CN1970254B, 7 November 2006.
- Fu, W.S.; Zhou, J.B. Study on industrial manufacturing technology of Natural Arc-bamboo Laminated Lumber. *Wood Process. Mach.* **2010**, *6*, 7–11.
- Li, W.; Zhang, Z.; Cheng, F.; Fu, W. The processing method and utilization ratio of arch bamboo pieces. *For. Grassl. Mach.* **2009**, *20*, 1–6.
- Liu, J.; Fu, W.; Zhou, J. Research on original re-combined arc bamboo board material. *For. Grassl. Mach.* **2010**, *21*, 26–29.
- Zhang, Z.; Li, W.; Peng, X.; Li, W.; Zhang, J. Development of Bamboo Shaping and Curve Milling Equipment. *For. Mach. Woodwork. Equip.* **2011**, *39*, 18–22.
- Zhou, J. Study on Adhesives Strength of A-BROS and Developing of Arc Bamboo Fine-Milling Machine. Ph.D. Thesis, Chinese Academy of Forestry, Beijing, China, 2015.
- Chen, L.; Fang, C.; Liu, H.; Ma, X.; Fei, B. Study Progress on the Forming Technology of Curved Bamboo. *China For. Prod. Ind.* **2021**, *58*, 40–44.
- Yan, W.; Zhou, J.; Zhang, B.; Fu, W.; Chen, Z.; Ma, C.; Ningxia, Y. Development design and mechanical properties of arc bamboo. *Wood Res.* **2017**, *62*, 365–372.
- Chen, L.; Huang, B.; Su, Q.; Wang, X.; Fang, C.; Zhang, X.; Chen, Q.; Yuan, J.; Fei, B. In-situ dynamic observation on the gluing process of Moso bamboo cells. *Ind. Crops Prod.* **2023**, *204*, 9. [\[CrossRef\]](#)
- Chen, L.; Luo, X.; Huang, B.; Ma, Y.; Fang, C.; Liu, H.; Fei, B. Properties and bonding interface characteristics of an innovative bamboo flattening and grooving unit (BFGU) for laminated bamboo lumber. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *676*, 132185. [\[CrossRef\]](#)
- Chen, L.; Yuan, J.; Wang, X.; Huang, B.; Ma, X.; Fang, C.; Zhang, X.; Sun, F.; Fei, B. Effect of bamboo pith ring on the stability of the gluing interface. *Ind. Crops Prod.* **2022**, *187*, 11. [\[CrossRef\]](#)
- Chen, L.; Yuan, J.; Wang, X.; Huang, B.; Ma, X.; Fang, C.; Zhang, X.; Sun, F.; Fei, B. Fine gluing of bamboo skin and bamboo pith ring based on sanding. *Ind. Crops Prod.* **2022**, *188*, 12. [\[CrossRef\]](#)
- Hu, G. Study on Dynamic Viscoelasticities of Heat-Treated Bamboo. Master's Thesis, Zhejiang A&F University, Hangzhou, China, 2012.
- Huang, M.; Zhang, W.; Zhang, X.; Yu, W.; Li, W.; Dai, C.; Wang, S. Dynamic mechanical analysis of moso bamboo timber. *J. Nanjing For. Univ.* **2016**, *40*, 123–128.
- Yu, W.; Jiang, Z.; Ye, K. Characteristics research of bamboo and its development. *World For. Res.* **2002**, *15*, 50–55.
- Miao, H.; Gao, R.; Wang, G.; Ma, X.; Fang, C.; Liu, H. Design and Experiment of the Mold for the Production Process of Natural Arc-Shaped Bamboo Laminated Lumber. *Forests* **2025**, *16*, 1452. [\[CrossRef\]](#)
- Correal, J.F.; Ramirez, F. Adhesive bond performance in glue line shear and bending for glued laminated guadua bamboo. *J. Trop. For. Sci.* **2010**, *4*, 433–439.

27. GB/T 1927.4-2021; Test Methods for Physical and Mechanical Properties of Small Clear Wood Specimens—Part 4: Determination of Moisture Content. Standards Press of China: Beijing, China, 2021.
28. Zhang, W.; Jiang, Z.; Wang, G.; Cheng, H.; Zhang, D. Radial compression mechanical properties of bamboo-culm by ring stiffness. *J. Beijing For. Univ.* **2013**, *35*, 119–122.
29. Yang, F. Processing Technology of Bamboo Scrimper and OSB Composite and Its Performance Prediction. Ph.D. Thesis, Chinese Academy of Forestry, Beijing, China, 2014.
30. GB/T 20241-2021; Laminated Veneer Lumber. Standards Press of China: Beijing, China, 2022.
31. Huang, B.; Fang, C.; Chen, L.; Miao, H.; Ma, X.; Liu, H.; Fei, B. Analysis of the use rate of equal arc-shaped bamboo splits. *Constr. Build. Mater.* **2021**, *302*, 124273. [[CrossRef](#)]
32. ISO 12578:2016; Timber Structures—Glued Laminated Timber—Component Performance Requirements. International Organization for Standardization: Geneva, Switzerland, 2016.
33. LY/T 1815-2009; Non-Structural Glued Laminated Bamboo. Standards Press of China: Beijing, China, 2009.
34. Nkeuwa, W.N.; Zhang, J.; Semple, K.E.; Chen, M.; Xia, Y.; Dai, C. Bamboo-based composites: A review on fundamentals and processes of bamboo bonding. *Compos. B Eng.* **2022**, *235*, 109776. [[CrossRef](#)]
35. Azadeh, A.; de Sá, A.D.; Kadivar, M.; Gauss, C.; Junior, H.S. The effect of densification on physical and mechanical properties of bamboo *Dendrocalamus asper*. *Eur. J. Wood Prod.* **2022**, *80*, 877–888. [[CrossRef](#)]
36. Brito, F.M.S.; Paes, J.B.; da Silva Oliveira, J.T.; Arantes, M.D.C.; Vidaurre, G.B.; Brocco, V.F. Physico-mechanical characterization of heat-treated glued laminated bamboo. *Constr. Build. Mater.* **2018**, *190*, 719–727. [[CrossRef](#)]
37. Serrano, E.; Enquist, B. Contact-free measurement and non-linear finite element analyses of strain distribution along wood adhesive bonds. *Holzforschung* **2005**, *59*, 641–646. [[CrossRef](#)]
38. Müller, U.; Sretenovic, A.; Vincenti, A.; Gindl, W. Direct measurement of strain distribution along a wood bond line. Part 1: Shear strain concentration in a lap joint specimen by means of electronic speckle pattern interferometry. *Holzforschung* **2005**, *59*, 300–306. [[CrossRef](#)]
39. Maulana, S.; Gumelar, Y.; Fatrawana, A.; Maulana, M.I.; Hidayat, W.; Sumardi, I.; Wistara, N.J.; Lee, S.H.; Kim, N.H.; Febrianto, F. Destructive and Non-destructive Tests of Bamboo Oriented Strand Board under Various Shelling Ratios and Resin Contents. *J. Korean Wood Sci. Technol.* **2019**, *47*, 519–532. [[CrossRef](#)]
40. Kelkar, B.; Shukla, S.; Paul, B.; Arya, S. Effect of softening duration on physical, mechanical and microstructural properties of flattened densified *Bambusa bambos*. *J. Build. Eng.* **2023**, *74*, 106821. [[CrossRef](#)]
41. Wang, X.; Su, N.; Chen, X.; Fei, B.; Ma, X.; Liu, H.; Miao, H.; Fang, C. Impact of temperature on mechanical properties and dimensional stability in a novel gradient pressure bamboo flattening technique. *Constr. Build. Mater.* **2024**, *427*, 136258. [[CrossRef](#)]
42. Kadivar, M.; Gauss, C.; Stanislas, T.T.; Ahrar, A.J.; Charca, S.; Savastano, H., Jr. Effect of bamboo species and pre-treatment method on physical and mechanical properties of bamboo processed by flattening-densification. *Mater. Chem. Phys.* **2022**, *291*, 126746. [[CrossRef](#)]
43. Mirmehdi, M. The Effects of Bamboo Species and Adhesive Type on Mechanical Properties of Laminated Bamboo Lumber (LBL). Ph.D. Thesis, Federa University of Lavras, Lavras, Brazil, 2016.
44. LY/T 1072-2022; Bamboo Parallel Sliver Lumber. Standards Press of China: Beijing, China, 2022.
45. GB/T 26899-2022; Structural Glued Laminated Timber. Standards Press of China: Beijing, China, 2022.
46. ISO 22156:2021; Bamboo Structures—Bamboo Culms—Structural Design. International Organization for Standardization: Geneva, Switzerland, 2021.
47. ISO 7567:2024; Bamboo Structures—Glued Laminated Bamboo—Product Specifications. International Organization for Standardization: Geneva, Switzerland, 2024.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.