

Article

Design and Experiment of the Mold for the Production Process of Natural Arc-Shaped Bamboo Laminated Lumber

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Abstract

Natural arc-shaped bamboo laminated lumber (ABLL) is an engineering material made from recyclable and rapidly renewable bamboo. Objectives: to enhance processing mechanization by (i) establishing a fixed-arc dimensional model for bamboo splits, (ii) designing an integrated mold capable of simultaneous shaping and drying, and (iii) validating its performance through simulation and experiment. Methods: numerical modeling simulated the operational process, and physical tests measured split length, thickness, inner and outer chord lengths, and moisture content. Results: after the mold completes the arc-fixing and drying of bamboo splits, parameters including the splits' length, chord length, thickness, and moisture content are suitable for subsequent processing. Based on simulation results, the working mechanism of load application and deformation of bamboo during the equipment's arc-fixing process was analyzed. The cylindrical arc geometry causes uneven material deformation and stress distribution during arc-fixing. Arc-fixing of bamboo splits results in irreversible edge densification. Thus, gluing should be performed promptly to prevent warping. Evaluation metrics for arc length data—including $RE \leq 8.46\%$, $R^2 \geq 0.71$, and $RMSE \leq 3.61$ —confirm the reliability of the dimensional model and virtual prototype simulation model. The proposed method was expected to provide a reference for the development of devices specifically designed for ABLL.

Keywords: natural arc-shaped bamboo laminated lumber (ABLL); concurrent fixed-arc shaping and drying; integrated mold; performance test



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1. Introduction

Bamboo is a fast-growing, renewable, sustainable biomass material with energy advantages [1]. In recent years, the utilization of bamboo has tended to be diversified, refined, and efficient, creating huge economic and ecological values [2]. Due to the material properties such as strength and toughness of bamboo products, they can replace wood, plastic, and concrete in the fields of daily life, construction, vehicles, etc. [3].

To improve the utilization rate of bamboo, it is often processed into small units and then reconstructed into standardized materials [4,5]. However, this processing approach not only damages the original structure and texture of bamboo but also increases costs and time [6]. The reconstruction process requires the application of numerous adhesives and

thermal energy, which is detrimental to environmental protection [7]. To address these issues, arc-shaped laminated bamboo materials have achieved the raw-state utilization of bamboo, emerging as a bamboo engineering material worthy of in-depth development [3,8–11]. When bamboo tubes with different diameters at breast height (DBH) are split into bamboo splits, each split exhibits a unique arc shape [10]. Uniformly transforming these diverse arcs into similar ones is a key step in the fabrication of novel arc-shaped bamboo split raw-state laminated materials [12]. This critical manufacturing process must be achieved by designing molds with specific arc profiles, where determining the mold radius, i.e., the fixed-arc radius, is of paramount importance [13].

In the traditional preparation of ABLL, it is necessary to first obtain bamboo splits with uniform arc shapes [14,15]. The milling method is commonly used to obtain standard arcs, but it suffers from issues of reduced material utilization rate and severe deformation [16–18]. Therefore, an improved production process for arc-shaped bamboo split laminated materials has been proposed, namely the integrated drying and fixed-arc operation [7,19]. This process enhances production efficiency and reduces bamboo waste. The key device for transforming diverse arcs into similar ones is the fixed-arc mold [8,13,20]. There are few relevant reports on the design and application–effect research of fixed-arc molds.

To tackle the low mechanization issue in the aforementioned ABLL production process, this study aims to design and investigate the operational performance of processing molds. First, a mathematical model for bamboo split arc-fixing was developed, and key performance indicators for mold functionality were defined. Subsequently, the equipment's working mechanism was examined using virtual prototype simulation techniques. Finally, the operational performance of the ABLL equipment was assessed through physical prototype testing.

2. Materials and Methods

2.1. The Mold of Arc-Shaped Bamboo Split

2.1.1. The Fixed-Arc Model of Arc-Shaped Bamboo Split Mold

As shown in Figure 1, a schematic diagram illustrates the process of obtaining plates via a fixed-arc device. The direct gluing of bamboo splits represents a flawed approach: the natural arc of bamboo splits creates gaps between stacked layers, preventing close adhesion, while the elasticity of individual splits weakens adhesive force. To address this, the new process employs a mold to simultaneously hot-air dry bamboo splits and fix their arc precisely [7]. Bamboo fibers exhibit gradient distribution in the radial direction from the wall to the axis, with the outer layer (epidermis side) featuring more stable microstructure—thus, the outer arc is designated as the reference [8,9,20].

The key to processing bamboo splits into standard arcs with consistent inner (inner membrane side) and outer diameters lies in optimizing the arc structural parameters of the mold.

Assume that the bamboo tubes are a regular circular cylinder. It is uniformly divided into four parts along the axial direction, as shown in Figure 1. Taking the change in the inner arc as an example, the following analyzes the mathematical and geometric relationship between the arc radius after shape modification and the original radius.

Figure 2 illustrates the geometric relationship analysis of bamboo arc transformation during fixed-arc processing. The red arc denotes the original arc of the arc-shaped bamboo split, with radius R_1 and central angle α . Point A is its rightmost edge point. The blue arc represents the post-modification arc (radius R_2 , central angle β), where Point A' corresponds to Point A, and the segment AA' measures the displacement of the apex point during arc change.

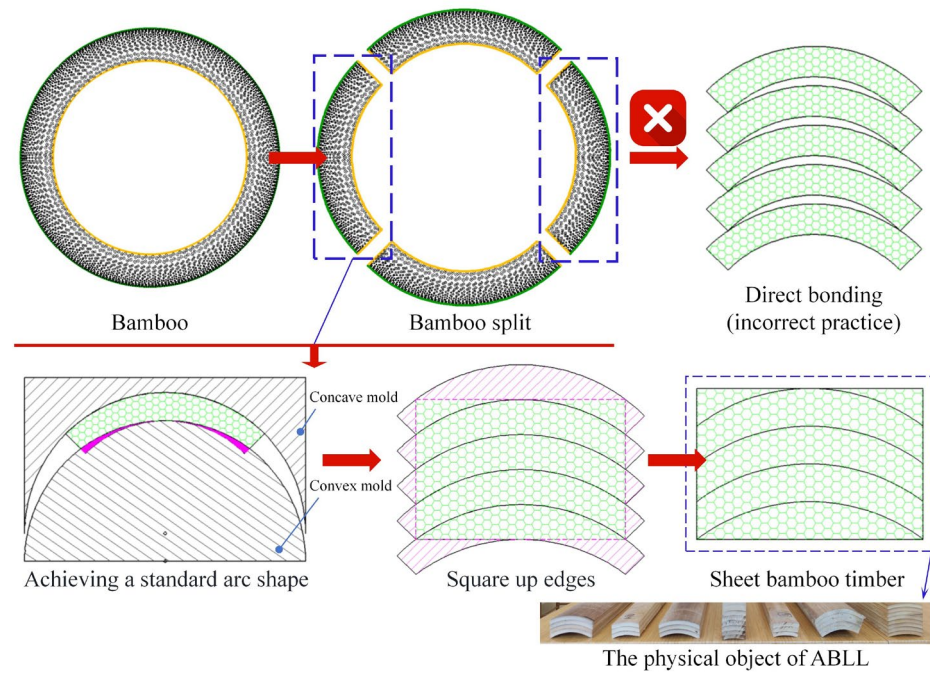


Figure 1. Schematic diagram of the plate obtaining process via fixed-arc operation.

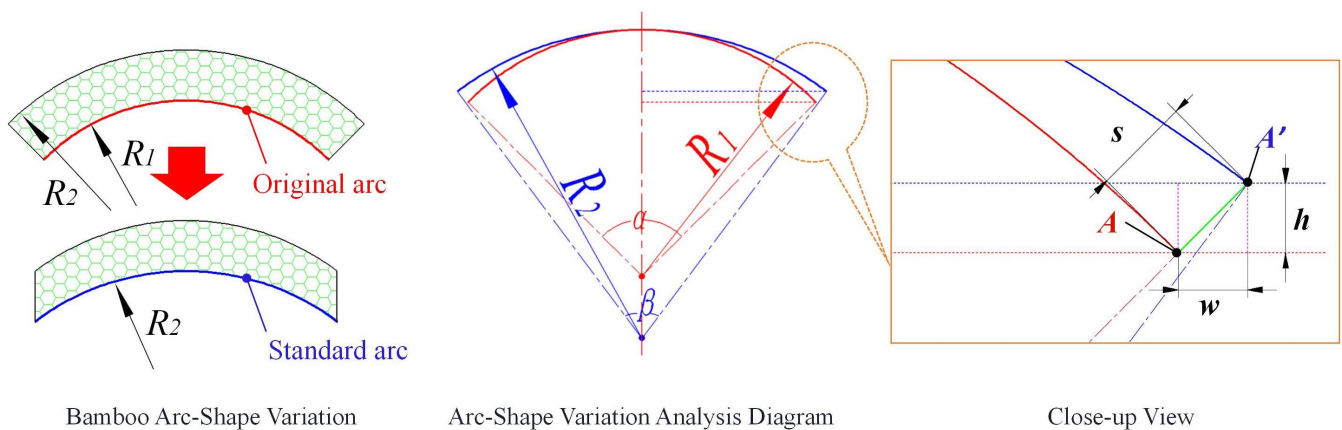


Figure 2. Geometric relationship analysis diagram of bamboo arc change.

As shown in the geometric relationships of Figure 2, the above variables can be expressed by the following Equations (1)–(3):

$$s^2 = h^2 + w^2 \quad (1)$$

$$h = R_2 \cos \frac{\beta}{2} - R_1 \cos \frac{\alpha}{2} \quad (2)$$

$$w = R_2 \sin \frac{\beta}{2} - R_1 \sin \frac{\alpha}{2} \quad (3)$$

By combining Equations (1)–(3), the length of line segment AA' can be derived as shown in Equation (4).

$$s = \sqrt{R_1^2 + R_2^2 - 2R_1 \times R_2 \cos \frac{\alpha - \beta}{2}} \quad (4)$$

According to the formula analysis, the displacement of a certain point on the bamboo split during the fixed-arc process can characterize the degree of arc change in the arc-shaped bamboo split. The larger the displacements, the greater the arc change until the

arc is completely flattened into a plane; the smaller the displacements, the smaller the arc change. When the displacement s is zero, it indicates that the arc has not changed. The displacement during the fixed-arc process is difficult to measure. The fixed-arc effect of the mold can be verified by analyzing the change in chord length before and after fixed-arc processing and the relative error between theoretical and actual values.

The arc length L of a standard circular arc is expressed by Equation (5). The chord length Q_1 of the original bamboo split is expressed by Equation (6). By combining Equations (5) and (6), the chord length Q_2 of the bamboo split after fixed-arc processing is obtained as Equation (7).

$$L = \frac{\alpha \times \pi \times R_1}{180} = \frac{\beta \times \pi \times R_2}{180} \quad (5)$$

$$Q_1 = 2R_1 \sin \frac{\alpha}{2} \quad (6)$$

$$Q_2 = 2R_2 \sin \left[\frac{R_1 \arcsin \left(\frac{L}{2R_1} \right)}{R_2} \right] \quad (7)$$

Owing to the unique material properties of bamboo, excessive arc deformation during fixed-arc processing with molds may cause cracking at the arc apex, thereby compromising product quality. Thus, the design principle for the mold's fixed-arc radius in this study is twofold: to adapt to the DBH of most bamboo culms while minimizing the radius.

2.1.2. Materials Tested

Literature review [21] indicates that the DBH of *Phyllostachys edulis* predominantly falls within the 9.5–11.5 cm range, comprising 79.2% of the total samples and exhibiting a normal distribution pattern. This study designates this interval as the primary diameter class for the mold fixed-arc radius design. Meanwhile, the mold's fixed-arc radius is set at 75 mm based on pre-experiments, a value which ensures process compatibility for most bamboo tubes post-splitting. Beyond chord length, maintaining stable dimensions (length and thickness) of the bamboo splits is crucial for material utilization and processing standardization. Given the mold's integrated fixed-arc drying capability, the bamboo split moisture content is included as a drying efficiency indicator. According to the above formula, the equipment performance evaluation in this study incorporates length and thickness of bamboo split, chord length, and moisture content as key metrics.

2.1.3. Experimental Platform

As shown in Figure 3, there are two types of molds: concave molds and convex molds (steel). The dimensions illustrated in the figure correspond to the mold's virtual prototype model and are not fixed. In practical production, the mold type and dimensions should be adjusted based on bamboo splits of varying specifications. Both the concave and convex molds are provided with through-long slots for air flow during the drying process. The positions of the slots are arranged in a staggered manner, which can not only prevent the bamboo strips from being pressed with marks at the long slots, but also increase the ventilation area of the upper and lower surfaces of the bamboo strips to improve the drying effect. An experimental prototype based on this mold is manufactured as shown in Figure 3.

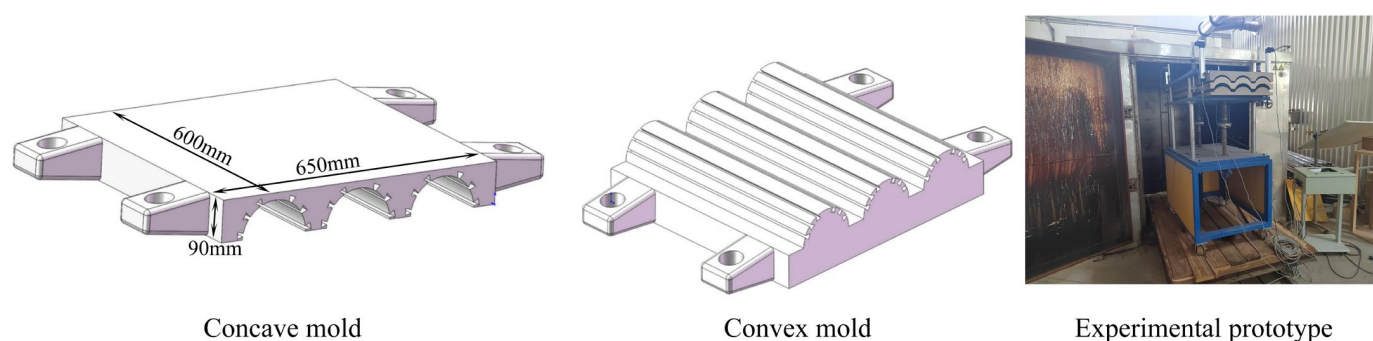


Figure 3. Fixed-arc mold and its experimental prototype.

2.2. Experimental Scheme

Moso bamboo specimens with a diameter at breast height exceeding 10 cm were harvested from Huangshan City, Anhui Province. Five moso bamboo culms with similar dimensional specifications were selected for the experiment. Prior to testing, each bamboo culm was cut into four segments, as illustrated in Figure 1. Three of these segments were used for the experimental process, resulting in a total of 15 bamboo split samples. The fourth segment was used to measure the moisture content of its parent bamboo culm. According to the reference standard [22], the moisture content of bamboo is tested using the drying method [16–18]. Five sets of experiments were conducted under identical conditions, with three samples randomly selected per set. Each mold layer on the test prototype featured three pairs of concave–convex structures distributed horizontally; thus, during testing, the bamboo splits were numbered sequentially from left to right (e.g., A1, A2, A3; B1, B2, B3; etc.), as shown in Figure 4. This numbering system facilitates subsequent data tracing and analysis. In subsequent sections, the data labeled A1, A2, and A3 represent the average values of the corresponding samples across the five experimental sets. Outliers in the five datasets were excluded, and the mean value was adopted as the test result. Data analysis was conducted using error analysis, variance analysis, and other statistical methods to assess data precision, stability, and variation trends.

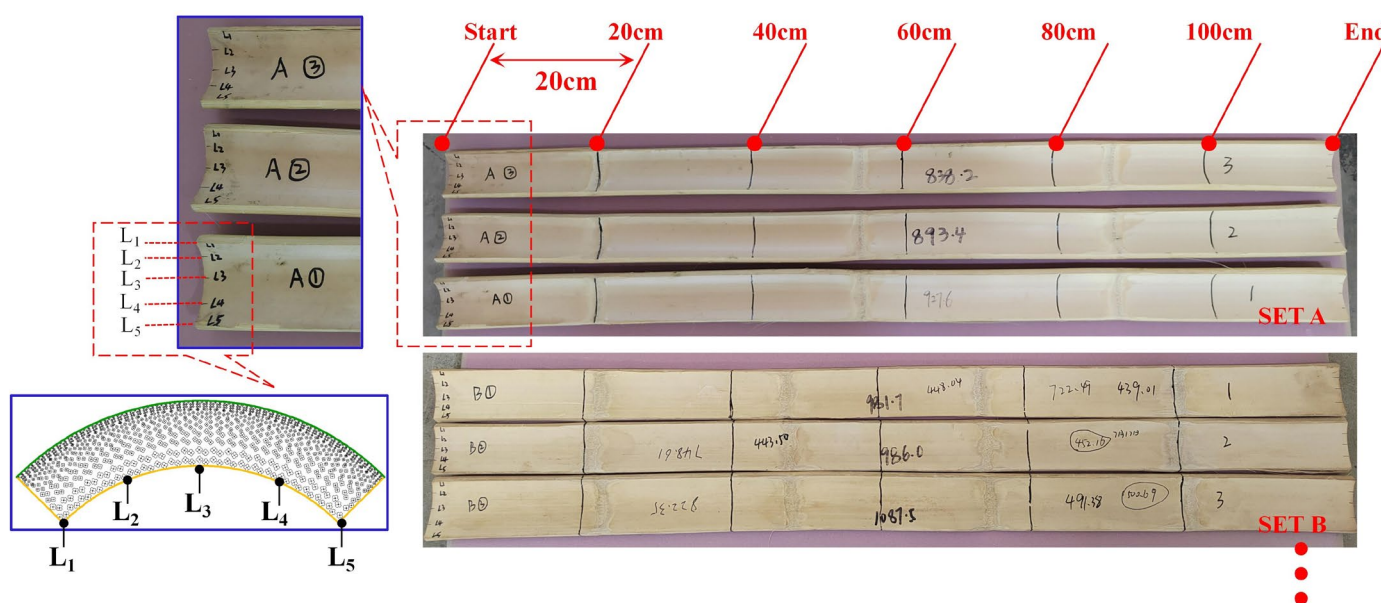


Figure 4. Schematic diagram of experimental data collection points.

The main testing equipment includes laboratory-developed integrated production process testing equipment for fixed-arc drying (Tianyu Hengchuang, China, 30 kN Pressure), a drying kiln (Research Institute of Wood Industry, Chinese Academy of Forestry, 140 °C temperature; 3 h), a vernier caliper (Mitutoyo, Japan, accuracy 0.01 mm), an electronic balance (Dongmei, China, accuracy 0.001 g), a tape measure, etc.

Based on the analysis of Equations (1)–(7), the evaluation indicators for the mold's fixed-arc effect were selected as the length of arc-shaped bamboo splits before and after arc modification, wall thickness, inner and outer chord lengths, and moisture content. Experimental procedures are described as follows. As shown in Figure 4, five points (L1 to L5) are evenly spaced along the inner circumferential arc, starting from the apex of the arc surface. Point L3 lies at the arc midpoint. As depicted in Figure 4, seven measurement points are evenly positioned along the axial length of the arc-shaped bamboo split, starting from one end at 20 cm intervals to the opposite end.

The data were measured at three temporal stages: the initial state before fixed-arc drying, final state upon drying completion, and the 40-day (28 to 35 °C temperature and 30 to 50% humidity) post-storage data, which are selected to monitor dimensional stability.

2.3. Virtual Simulation

Owing to the observational challenges in the fixed-arc process, rigid–flexible coupling multibody dynamics was employed to simulate the mold's fixed-arc operation. Three-dimensional models of bamboo splits and molds are first created using SolidWorks 2016, then imported into RecurDyn for real-time virtual prototyping. The entire bamboo split is flexibly treated in the simulation, with pertinent parameters tabulated in Table 1 [9,23–25].

To investigate the variation patterns of the aforementioned dimensional parameters, three equiangular points are positioned on both the inner and outer arcs of as-received bamboo splits (Figure 5). Tracking point trajectories and intra-bamboo stress evolution informs the subsequent physical experiments.

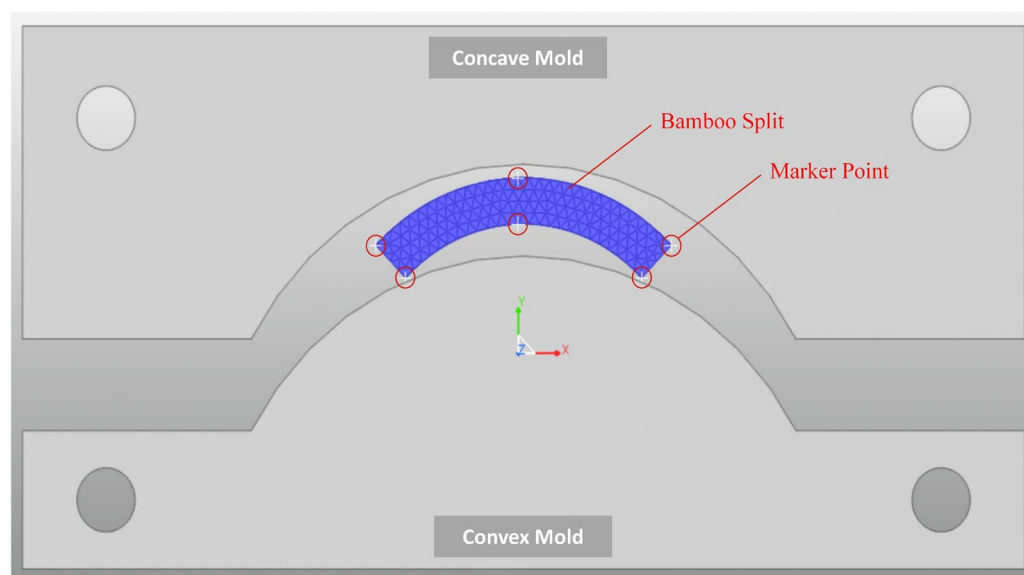


Figure 5. Virtual prototype of bamboo split fixed-arc device.

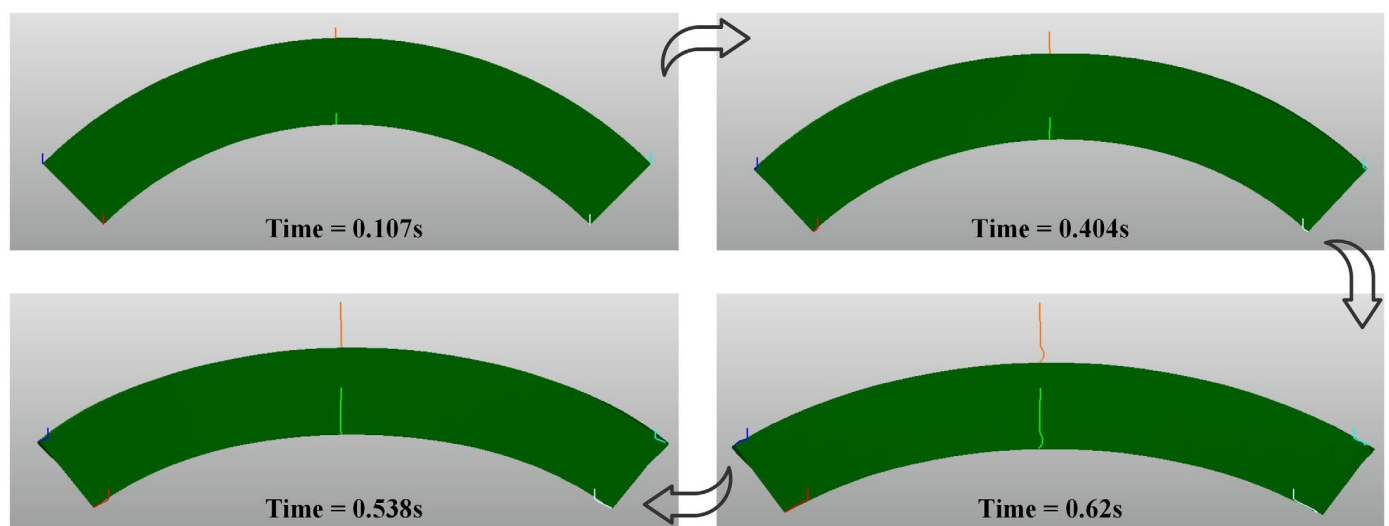
Table 1. Parameter of simulation.

Parameter	Value
Young's modulus of bamboo	9.6 GPa
Poisson's ratio of bamboo	0.3
Density of bamboo	0.75 g/cm ³
Mesh Type	Shell 3 (Tria 3)
Nodes in total	44,013
The number of elements after division	88,022

3. Results and Discussion

3.1. Analysis of the Fixed-Arc Process

After fixed-arc processing by the mold, the motion trajectories of marked points and stress nephograms of bamboo split cross-sections are shown in Figures 6 and 7. The size variation patterns of bamboo splits during mold compression can be predicted by utilizing the motion trajectories of each point and the stress characteristics of bamboo splits.

**Figure 6.** The shape variation in bamboo splits during fixed-arc process.

Simulation results categorize the fixed-arc process into three phases. The first is the steady-state phase, where the bamboo split remains undeformed. As the concave mold descends to compress the split, the arc apex and two inner-arc endpoints bear initial load. The second phase is deformation, where downward mold movement increases loading on the inner-arc apex beyond the outer-arc apex. Here, maximum stress localizes at inner-arc endpoints and the outer-arc apex. The outer-arc endpoints trace an oblique downward-then-upward trajectory, while inner-arc endpoints slide downward along the convex mold. When both arc surfaces conform to the mold, the pressure-holding phase begins: cross-sectional stress forms uniform contour patterns, with minimum stress at the geometric center and maximum stress at inner-arc endpoints. Lateral material extrusion during pressure-holding induces global deformation, with inner-arc endpoints exhibiting greater displacement than outer-arc endpoints throughout the process. This finding is consistent with the results reported in Reference [8].

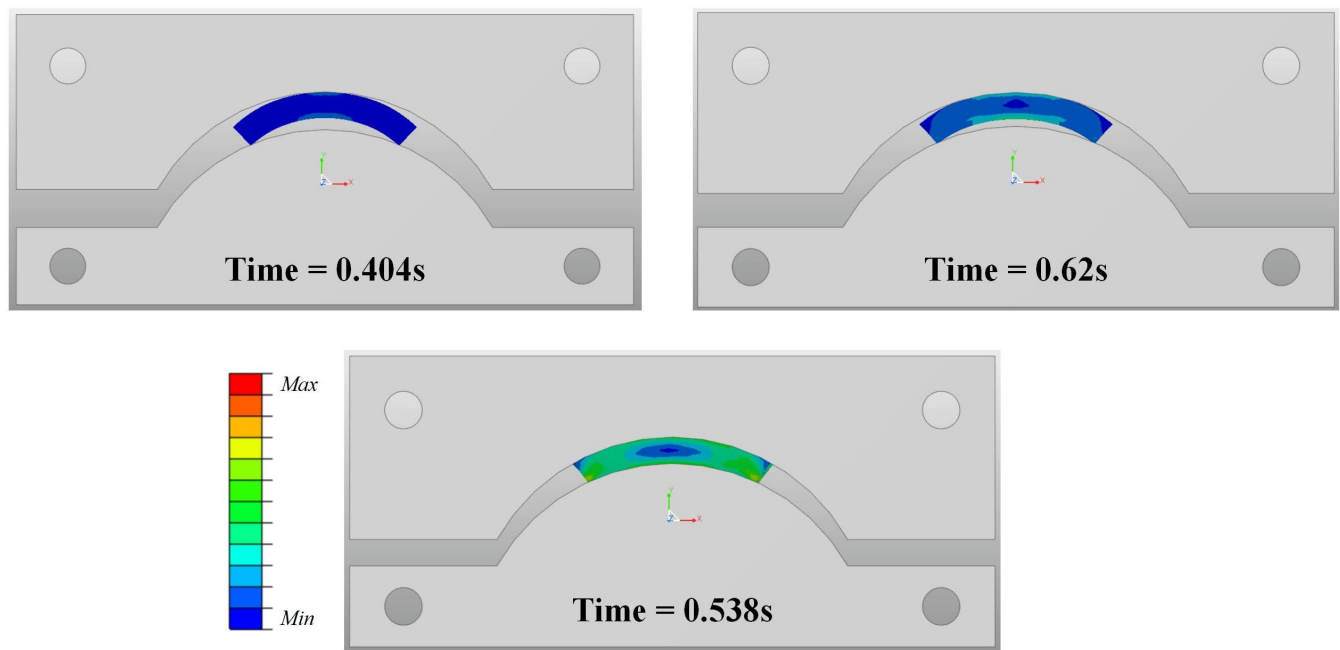


Figure 7. The stress variation in bamboo splits during fixed-arc process.

3.2. The Length of Bamboo Split

Length variations in bamboo splits before/after arc modification are depicted in Figure 8. In this figure and the subsequent ones, “Time” represents the time of data collection, and “Position” indicates the data testing position on the bamboo splits.

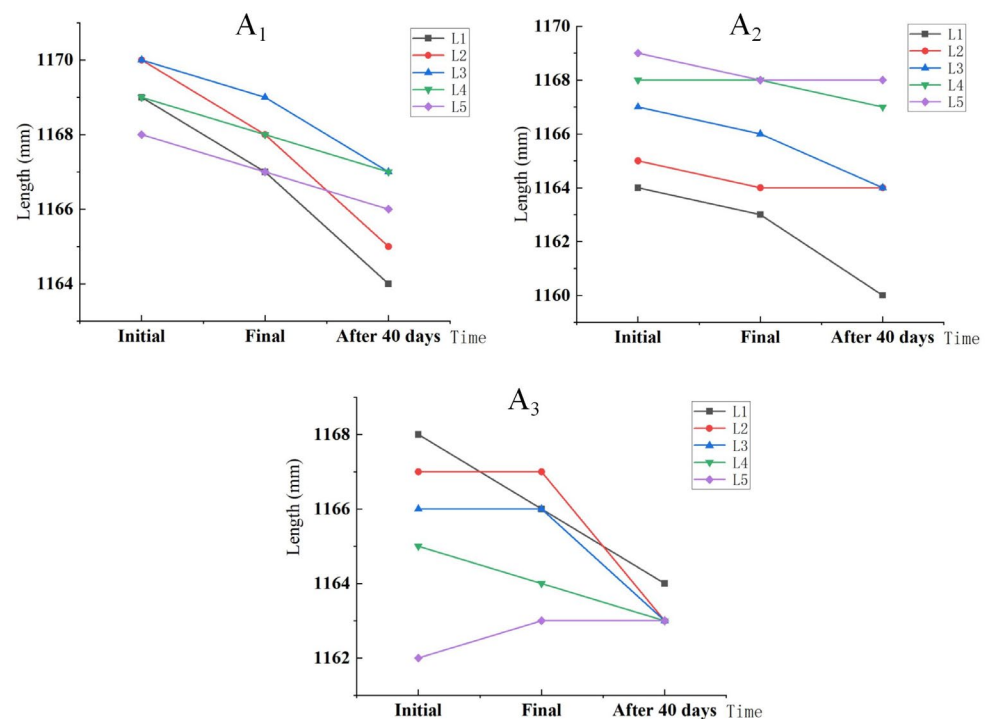


Figure 8. Length variation trends of specimens.

Notably, the arc-shaped specimens exhibited an overall longitudinal shortening (1–5 mm) during arc-fixing drying in the mold. An analysis of variance (ANOVA) was conducted on the bamboo split length data, with results presented in Table 2. Experimental results indicated no significant difference in bamboo split length before and after arc-fixing. In other words, while individual variations (1–5 mm) existed, these variations likely lacked

a strong systematic correlation with the process itself. This phenomenon can be attributed to the combined effects of mechanical deformation and drying shrinkage experienced by the bamboo [26–28]. Simulation results show the arc surface sustains significant compressive stress in the deformation and pressure-holding phases, inducing material redistribution that counteracts drying-induced shrinkage [25,29,30]. Additionally, based on the overall results, the bamboo split lengths remained within the standard range. It complies with the requirements for dimensions and tolerances specified in [31–33], imposing no impact on subsequent processing or material utilization

Table 2. ANOVA for the lengths of the bamboo split.

Source of Variance	SS	df	MS	F	<i>p</i> -Value	F Crit
Between-group	11.48	2	5.74	1.7×10^{-5}	0.99	4.26
Within-group	3.05×10^6	9	338,518.8			
Cor Total	3.05×10^6	11				

Specimens with standardized arcs develop pronounced midsection warpage after 40-day storage in an indoor ambient environment, as illustrated in Figure 9. This indicates that the equipment mainly completes the shaping of physical form but fails to completely change the natural properties of bamboo [27,28]. In particular, post-fixed-arc drying bamboo splits require prompt gluing to prevent warpage.

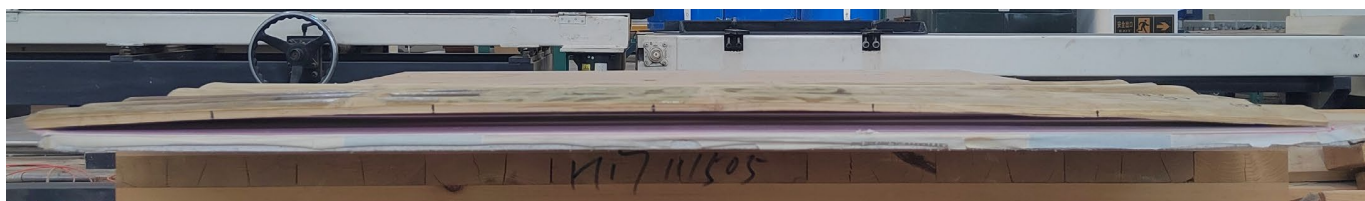


Figure 9. Warpage of fixed-arc specimens after 40-day indoor storage (five samples).

3.3. Wall Thickness of Bamboo Splits

Wall thickness variations in arc-shaped bamboo splits before/after arc modification are depicted in Figure 10. It can be observed that during the fixed-arc process using molds, the wall thicknesses on both sides of specimen A generally exhibit a decreasing trend. Left-side variations range from 0.13 to 0.59 mm, and right-side from 0.26 to 0.95 mm, both <1 mm. The thicknesses of the processed bamboo strips have changed by less than 80% compared to their original sizes and meet the minimum size requirement of 5 mm. Compliant with the provisions of [34,35]. Five repeated simulations reveal a maximum thickness variation of 1.2 mm, with close agreement between physical and simulation results. Two-way ANOVA with replication was conducted for the wall thickness of bamboo splits, with results presented in Table 3. The analysis indicates that both measurement time and measurement position have statistically significant effects on bamboo split wall thickness. No interaction effect was observed between the two factors. In other words, this suggests that, under these experimental conditions, the thickness of the entire bamboo strip was relatively consistent.

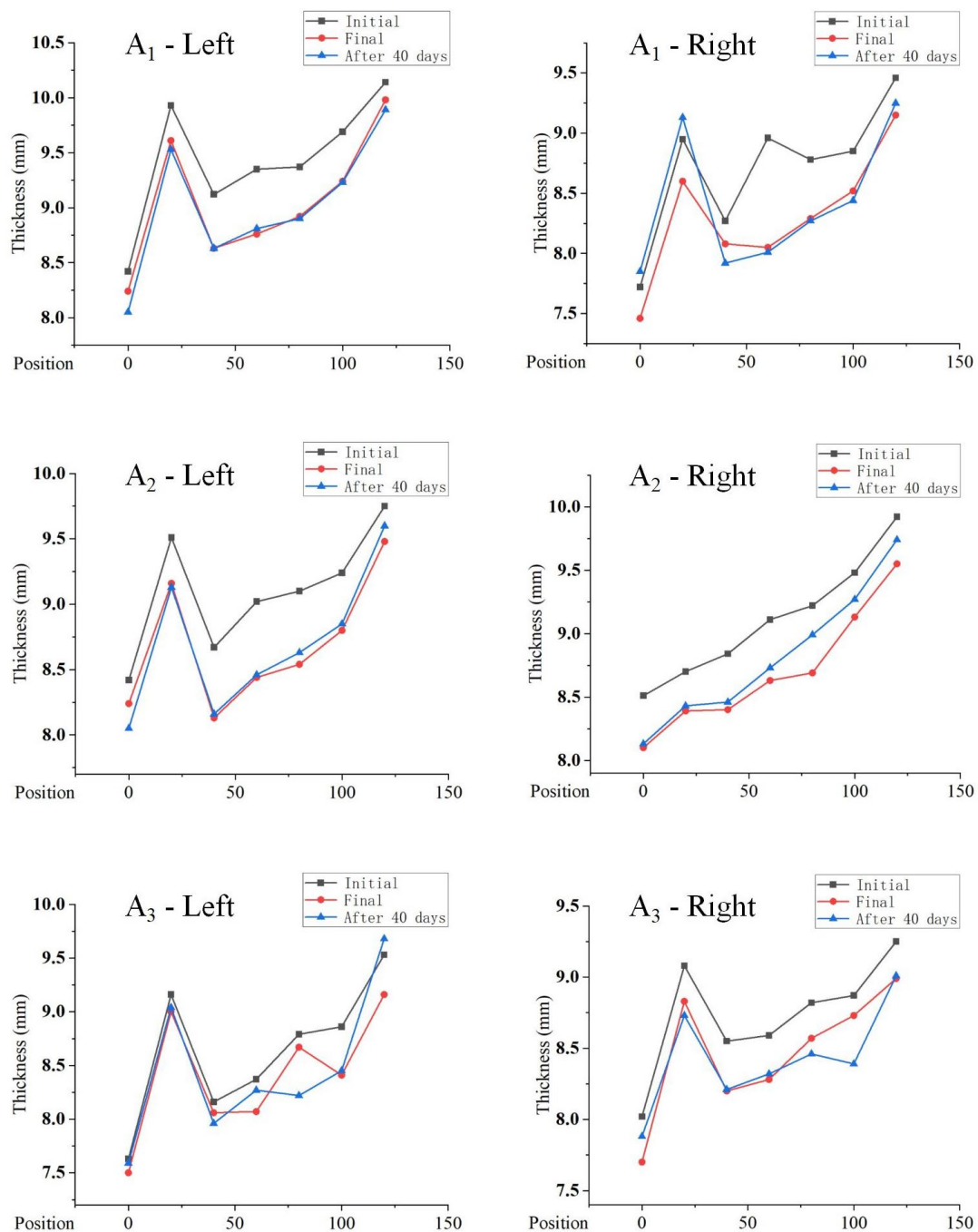


Figure 10. Wall thickness variation trends of specimens.

Table 3. ANOVA for the wall thickness of the bamboo split.

Source of Variance	SS	df	MS	F	<i>p</i> -Value	F Crit
Time	9.511283	6	1.585214	43.29495	9.35×10^{-11}	2.572712
Position	1.071461	2	0.53573	14.63173	0.000105	3.4668
Interaction	0.121028	12	0.010086	0.275457	0.987409	2.250362
Internal	0.7689	21	0.036614			
Cor Total	11.47267	41				

Based on simulation results, this was attributed to the fact that the stress distribution during the bamboo split arc-fixing process adheres to a fundamental principle: stress increases with proximity to the outer surface and decreases as it approaches the central (neutral) layer [8]. The bamboo green side sustains extremely high tensile stress, whereas

the bamboo yellow side endures extremely high compressive stress. Consequently, when considering bending behavior alone, the maximum thickness variation naturally occurs at the two sides of the stressed bamboo split. Based on simulation analysis and the aforementioned data, the underlying mechanisms are as follows. During arc-fixing, downward compression by the mold forces bamboo splits to flow along the width and length directions under approximately constant volume [36]. Consequently, the cross-sectional wall thickness is generally reduced. Meanwhile, bending induces a combined tension–compression effect (tension on the outer arc and compression on the inner arc) and the Poisson effect, which further thins the wall thickness. At the two endpoints of the inner arc, stress and displacement reach maximum values, making cells prone to collapse. This leads to greater thinning and structural densification. During the pressure-holding stage, bamboo undergoes slow creep and extrusion, resulting in a slight additional reduction in wall thickness. Additionally, the internode structure of bamboo splits causes variations in wall thickness across different positions [37,38]. After 40-day storage in an indoor ambient environment, wall thickness remains unchanged from post-fixed-arc drying values. Combined with stress simulation results, this indicates densification and microstructural alteration in the arc-shaped splits [27,36,38].

3.4. Inner/Outer Chord Lengths of Bamboo Splits

Figure 11 depicts inner/outer chord length variations in arc-shaped bamboo split specimens before/after fixed-arc processing. During mold-based fixed-arc processing, outer chord lengths decrease by 1.5 mm on average, while inner chord lengths increase by 3.3 mm. The findings are in full agreement with both theoretical predictions and simulated dimensional trends, according to Equation (6). In constrained forming, the final dimensions of the material are the combined result of the joint action of external loads, constraint conditions, and the material's own flow behavior [39–41]. The shortening of the outer chord confirms the dominant role of vertical compressive stress, which overcomes the bending tensile effect and causes a slight net compression even in the high-strength bamboo green layer. The elongation of the inner chord is not true tension; instead, it is a macroscopic manifestation of the plastic flow of the low-strength bamboo yellow-side material under high pressure, which is forced to redistribute to fill the mold space [26,42].

The inner and outer chord lengths serve as sensitive indicators for characterizing the geometric accuracy of curved components. Their variations simultaneously reflect both global and local deviations in the combined bending-compression process, making them suitable for verifying the accuracy of the simulation and theoretical models. Table 4 is a reliability analysis table for the theoretical values, actual values, and simulated values of the inner and outer chord lengths of bamboo splits. The evaluation metrics include relative error (RE), coefficient of determination (R^2), and root mean square error (RMSE). In particular, a residual analysis was conducted on the actual values and simulated values of the inner and outer chord lengths of bamboo splits, as shown in Figure 12. The standard residuals are concentrated within the interval (2, −2). Analysis of the coefficient of variation (CV) for the specimen chord lengths confirms the stability of the data, as shown in Table 5. These results confirm the validity of both the simulation model and the mathematical model. Following 40-day storage in an indoor ambient environment, chord lengths show no significant deviation from post-fixed-arc drying values. This indirectly evidences that irreversible mold-conformed changes occur on both sides of the arc-shaped bamboo splits during the process.

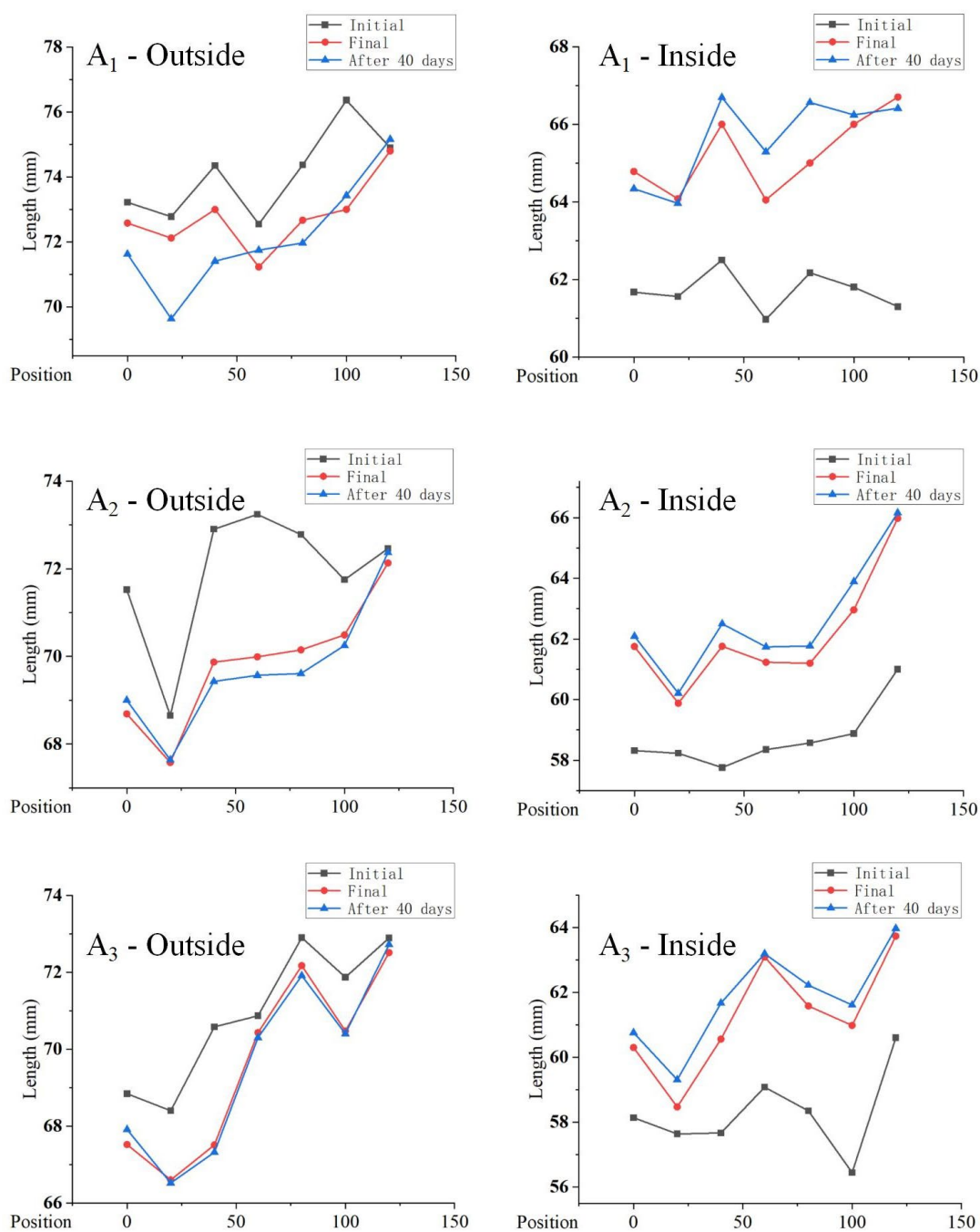


Figure 11. Inner/outer chord length variation trends of specimens.

Table 4. The reliability analysis table for the theoretical values, actual values, and simulated values of the inner and outer chord lengths of bamboo splits.

Evaluation Indicator	Inner Chord Length (mm)			Outer Chord Length (mm)		
	a-b	a-c	b-c	a-b	a-c	b-c
RE	8.46%	1.92%	7.16%	2.07%	5.89%	7.91%
R ²	0.78	0.89	0.79	0.93	0.82	0.71
RMSE	3.61	1.59	2.51	1.38	2.01	2.93

Note: a denotes the theoretical value; b denotes the actual value; and c denotes the simulated value.

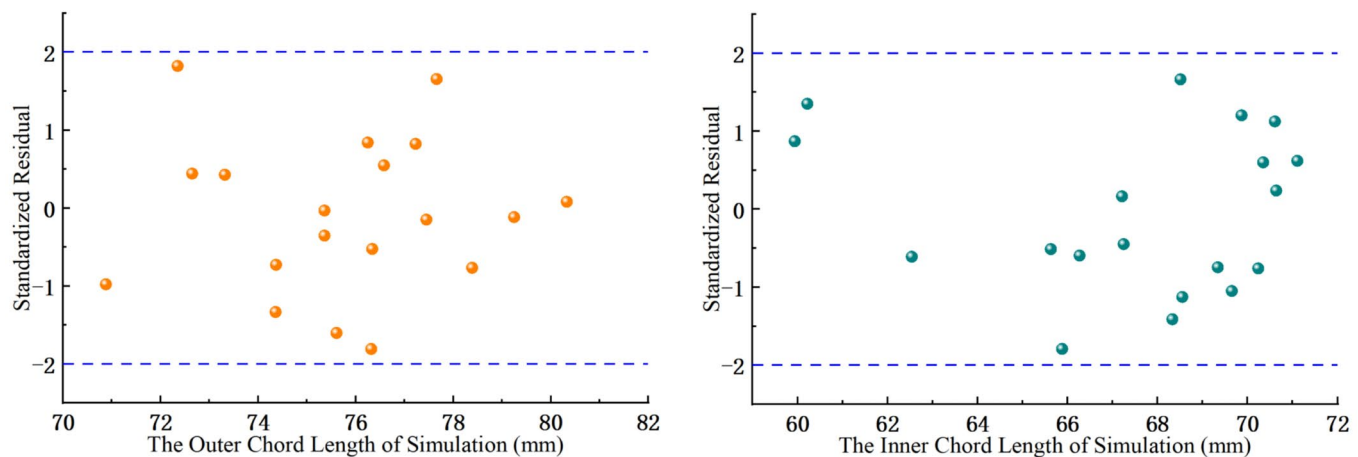


Figure 12. Standardized residual plot of simulated values versus actual values.

Table 5. The coefficient of variation (CV) for the specimen chord lengths.

Measurement Position	Inner Chord Length			Outer Chord Length		
	Initial	Final	After 40 Days	Initial	Final	After 40 Days
0	3.10%	3.81%	2.75%	3.35%	3.67%	2.90%
20	3.52%	4.28%	2.33%	3.57%	4.80%	4.03%
40	2.62%	3.93%	2.95%	4.66%	4.55%	4.23%
60	1.69%	0.89%	1.57%	2.27%	2.28%	2.81%
80	1.21%	1.86%	1.89%	3.59%	3.34%	4.16%
100	3.58%	2.04%	2.51%	4.54%	3.99%	3.62%
120	1.77%	1.97%	2.07%	0.58%	2.37%	2.05%

3.5. The Moisture Content of Bamboo Split

Moisture content variations in arc-shaped bamboo splits before/after arc modification as shown in Table 6.

Table 6. The value of the moisture content of arc-shaped bamboo splits.

Specimen Position	Weight (g)				Moisture Content (%)		
	Oven-Dry Weight	Initial State	Final State	After 40 Days	Initial State	Final State	After 40 Days
A1	530.06	770.98	629.58	570.28	45.45	18.78	7.58
A2	510.51	741.23	601.9	542.56	45.19	17.9	6.28
A3	478.97	690.62	563.91	510.39	44.18	17.73	6.55
CV	0.0509	0.0553	0.0551	0.0554	0.0149	0.0311	0.1008

The data of Table 6 reveal significant moisture content decreases in arc-shaped bamboo split specimens during mold-based fixed-arc processing, confirming concurrent fixed-arc drying. Moisture content in specimens decreased by 26.67% (45.45%→18.78%), 27.29% (45.19%→17.9%), and 26.45% (44.18%→17.73%), respectively, during fixed-arc processing. The result is slightly higher than the upper limit of 15% for the optimal moisture content of bamboo sheet gluing as stipulated in [31,43]. Under the experimental conditions, the placement of bamboo splits in the mold had no significant effect on the drying result (CV of final moisture content < 0.11%). The feasibility of the integrated fixed-arc drying process is validated by consistent moisture content reduction ranges and uniform final values across specimens. Significantly, storing specimens for 40 days in an indoor ambient environment led to additional moisture loss, which directly influenced subsequent gluing operations.

4. Conclusions

Experimental and numerical results confirm that the integrated fixed-arc drying mold can conform ABLL bamboo splits to the required geometry while simultaneously reducing their moisture content. After one pass, split length shortened by only 1–5 mm—well within industrial dimensional-stability limits—while wall thickness decreased uniformly on both sides (left 0.13–0.59 mm, right 0.26–0.95 mm, all <1 mm). The reliability of the data derived from the theoretical and simulation models for the inner and outer chord lengths was validated using evaluation metrics, including relative error (RE), coefficient of determination (R^2), root mean square error (RMSE), and standardized residual plots. Specifically, the metrics yielded the following values: $RE \leq 8.46\%$, $R^2 \geq 0.71$, and $RMSE \leq 3.61$. Moisture content dropped consistently from $27.12\% \pm 0.67\%$ to $18.26\% \pm 0.5\%$, demonstrating that arc-forming and drying can be completed in a single energy-efficient step. Together, these outcomes indicate that the mold delivers dimensional accuracy, bonding-ready surfaces, and process consolidation, providing a feasible approach to draw upon for scaling ABLL production.

Notable limitations include potential batch inconsistency from material heterogeneity, asymmetric thickness variation, and post-storage warping. Future efforts should focus on optimizing mold pressure distribution to balance material flow, refining simulations with bamboo's anisotropic properties and integrating real-time moisture monitoring. These improvements will enhance the technology's industrial scalability and sustainability, addressing the current constraints for broader adoption.

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