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Bamboo Scrimber as a Sustainable Material for Chairs: A Property Study Based on the Finite Element Method

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Abstract: Bamboo scrimber is a sustainable biomass composite with physical and mechanical properties that has potential applications in furniture. However, its performance across different furniture needs evaluation considering the specific requirements for furniture with different functions. In this study, we simulated a traditional armchair model with bamboo scrimber, ash, or beech as the substrate. Using the finite element method, we analyzed stresses and deformations under six working conditions. The results show that bamboo scrimber had a lower maximum deformation and higher maximum stress under the vertical loading of the seat, backrest, legs, and armrests. Under armrest lateral loading, ash exhibited a higher maximum stress and lower maximum deformation. For selecting furniture material, we propose a strategy that optimizes furniture design by combining the advantages of traditional and new materials according to the structural characteristics and stresses of different parts of the furniture. The results confirm that bamboo scrimber has a good deformation resistance and structural stability and can be used as a substitute for traditional wood in furniture manufacturing, especially for chairs subjected to complex loads. Our findings will help to improve sustainable development by promoting the application of bamboo scrimber in the furniture manufacturing industry.

Keywords: bamboo scrimber; traditional armchair; finite element method; furniture design

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1. Introduction

Wood has long been the primary material used for furniture manufacturing, but its acquisition often involves clearing large swathes of forests, which not only destroys ecosystems but also exacerbates carbon emissions, contrary to the goal of sustainable development. As awareness of environmental protection increases and ecological projects such as forest protection are implemented, countries are gradually restricting the export of wood materials. Limiting timber supply has a detrimental effect on the rapidly developing furniture industry [1].

Bamboo can provide highly sustainable resources given its rapid growth rate. The growth cycle of bamboo is generally 3–5 years, much faster than the decades required for the trees traditionally used for wood. China is rich in bamboo species, with a bamboo forest area covering 641.16 million km^2, accounting for approximately 20% of the world's total bamboo forest area [2]. The Chinese scholar Professor Zhang Qisheng was the first to propose the idea of "replacing wood with bamboo" in the late 1970s and early 1980s [3]. Bamboo is a natural material with desirable mechanical properties, making it increasingly valued by businesses, developers, and users [4]. However, natural bamboo is hollow, thin-walled, and small in diameter, limiting its utility. At present, raw bamboo is typically converted into artificial boards, such as bamboo-oriented strand boards, bamboo-integrated materials, and bamboo particleboards. With in-depth research in the bamboo industry, new bamboo materials are gradually being developed.

Bamboo scrimber is a composite material made from small-diameter bamboo, branch wood, and other low-quality materials processed into horizontally and longitudinally loose, interlocked bundles [5]. It is produced through drying, gluing, billeting, hot pressing, and other processes, utilizing the residue of bamboo processing as raw material [5]. This restructured bamboo timber expands the scope of bamboo applications and increases the utilization rate of bamboo materials to 90% [6]. From the perspective of sustainable development, restructured bamboo timber reduces the need for new resources, minimizes industrial waste, and lowers raw material cost, showing great potential for environmental protection and sustainability. Bamboo scrimber has a dense and uniform structure, with an air-dry density of 1.00–1.20 g/cm^3, surface hardness of 174.5 MPa, thickness swelling of 1.64%, modulus of rupture of 130–185 MPa, dry shrinkage of 2.23% in the width direction, and impact strength of 175 kJ/m. It also exhibits high physical and mechanical strength, corrosion resistance, and drying shrinkage performance [7]. Bamboo scrimber is versatile and can be machined through chipping, sanding, drilling, sawing, and finishing [8]. Currently, it is widely used in flooring, construction, landscapes, and decorative materials [9].

In recent years, bamboo scrimber has attracted increasing attention in the field of furniture design [10]. The materials used considerably influence the shape, structure, and manufacturing of furniture [11,12]. Guan investigated the dry-shrinkage and wet-swelling characteristics of bamboo scrimber, noting its strong directionality at densities similar to those of common furniture wood [13]. Huang and Wu studied the joint structure of bamboo scrimber furniture [14], while Fu et al. compared the deformation of bamboo scrimber to other wood types under stress [15]. These studies have highlighted the desirable properties of bamboo scrimber for furniture manufacturing.

However, the performance requirements for different types of furniture vary considerably owing to their functional differences. Zheng proposed a design strategy for outdoor furniture by investigating the adaptability of bamboo scrimber to existing product problems [16]. Liu et al. analyzed the mechanical and visual properties of bamboo scrimber to optimize the structural form and functional characteristics of folding furniture [17]. Wang and He studied the modeling design of Chinese furniture, focusing on both the morphological and decorative aspects of bamboo scrimber [18]. To determine the suitability of a material for specific furniture types, it is essential to analyze the materials' characteristics in relation to the specific structure of that furniture type.

A chair is a piece of seating furniture with a backrest and is one of the most frequently used furniture products [19]. Traditional Chinese armchairs generally use a mortise and tenon structure, with upper armrests being rounded and the lower seat cushion being square, reflecting the concept of "heaven is round and earth is square" in traditional Chinese culture [20]. The structural design of such armchairs considers the principle of ergonomics, with the backrest and armrests linked by a smooth curved design, providing good support and increased comfort when reclining (Figure 1a).

(a) (b)

Figure 1. (**a**) Common Traditional armchair shapes (**b**) Traditional armchairs in different scenarios.

Modern designers have simplified the traditional armchair design by removing complex decorations while retaining its basic form, aligning it with modern aesthetics and usage requirements. This improved armchair design is widely used in public spaces, offices, and homes (Figure 1b) [21].

Owing to its unique cultural connotations and practical functions, we selected a traditional armchair as the research object for this study. We compared the mechanical properties of bamboo scrimber with those of commonly used wood to explore the feasibility of applying bamboo scrimber in chair manufacturing. Our study provides an effective method for furniture design that promotes sustainable development through the application of bamboo scrimber in furniture manufacturing.

2. Materials and Methods

Traditional furniture mechanical property assessments are destructive, leading to inefficiency and material and energy waste [22]. The finite element method (FEM) has become the primary method for analyzing furniture performance [23]. The FEM facilitates the numerical simulation of physical objects and is commonly used in engineering. This method decomposes a complex continuum structure into several small finite elements, each regarded as a simple structure, and simulates its force state and deformation. The performance of the entire structure can be determined by calculating the displacement, stress, and deformation of each finite element under a particular applied force [24].

Many scholars have used the FEM to study the performance of chair structures and have reported that, as long as the method is appropriate, the difference between the results of the FEM and those from physical verification is generally less than 30% [25]. Thus, the FEM is an effective method that can replace traditional physical furniture verification methods. In this study, we analyzed the performance of a traditional armchair based on the FEM using ANSYS 2021R1.

2.1. Comparison of Material Parameters

Beech and ash are currently the most commonly used wood types in traditional armchairs [26]. Beech is a hardwood material in the olive family with a fine, uniform texture and an average density of approximately 0.6–0.7 g/cm^3; ash has a relatively high density, averaging approximately 0.7–0.9 g/cm^3. Both types of wood have high flexural strength, compressive strength, abrasion resistance, and durability, as well as good machinability and ease of cutting, drilling, and gluing.

In this study, we compared the properties of beech and ash with those of bamboo scrimber for manufacturing traditional armchairs. The standards and specifications for testing the mechanical properties of bamboo scrimber are not well developed. Therefore, we applied the same tests used to assess wood properties to our bamboo scrimber. The compressive strength perpendicular to the grain of bamboo scrimber was tested according to the GB/T1939-2009 standard [27]. The tensile strength parallel to the grain of bamboo scrimber was tested according to the GB/T1938-2009 standard [28]. The compressive strength parallel to the grain of the bamboo scrimber was tested according to the GB/T1935-2009 standard [29]. The modulus of elasticity and Poisson's ratio in compression parallel to the grain of the bamboo scrimber were tested using the strain gauge method (GB/T1943-2009) [30].

The results show that the longitudinal compressive strength of bamboo scrimber is significantly greater than the transverse compressive strength. Bamboo scrimber exhibited similar fiber structure characteristics to wood. When comparing the three materials, the longitudinal compressive strength of bamboo scrimber was comparable to that of ash but significantly better than that of beech. Additionally, the transverse compressive strength of bamboo scrimber was significantly stronger than that of the other two wood materials, indicating higher stability under bidirectional composite forces. The simulation parameters for the three materials are listed in Table 1.

Table 1. Mechanical properties of bamboo scrimber, ash, and beech.

Materials	Density (g/cm^3)	E_L (MPa)	E_R (MPa)	E_T (MPa)	μ_{RT}	μ_{LR}	μ_{LT}	G_{LT} (MPa)	G_{LR} (MPa)	G_{TR} (MPa)
Bamboo scrimber	1.11	15,466	3007	1204	0.440	0.304	0.336	1347	823	567
Ash wood	0.67	15,790	1516	827	0.71	0.46	0.51	896	1310	269
Beech	0.75	13,700	2240	1140	0.75	0.45	0.51	1060	1610	460

E_L, E_R, and E_T are the moduli of elasticity in three directions; μ_{RT}, μ_{LR}, and μ_{LT} are the Poisson's ratios in three directions; and G_{LT}, G_{LR}, and G_{TR} are the shear moduli in three directions.

2.2. Chair Load Analysis

In general, furniture is subjected to three types of loads: static, cyclic, and impact. Chairs primarily experience static loads during use, and the location, intensity, and mode of action of these loads directly affect the structure of the chair. In this study, we investigated the performance of a traditional armchair made from three types of wood by creating a 3D geometric model based on ergonomic criteria in furniture design. We then applied various loads to simulate furniture usage in different situations. Finally, we imported the model into the FEM software ANSYS 2021R1 for calculations.

2.2.1. Geometric Modeling

The most common traditional armchair on the market was selected, and its basic structure was divided into four parts: seat surface, backrest, armrests, and legs (Figure 2a). The dimensions of the chair were determined according to the national standard GB10000-88 [31]. The width was 570 mm, depth was 430 mm, height was 750 mm, and seat surface height was 407 mm. The legs were spindle-shaped with a thick middle and two thin ends. The diameters of the thickest and thinnest parts of the chair legs were 40 mm and 25 mm, respectively (Figure 2b–d). SolidWorks (R) Premium 2020 SP5.0 was used to construct the 3D geometric model.

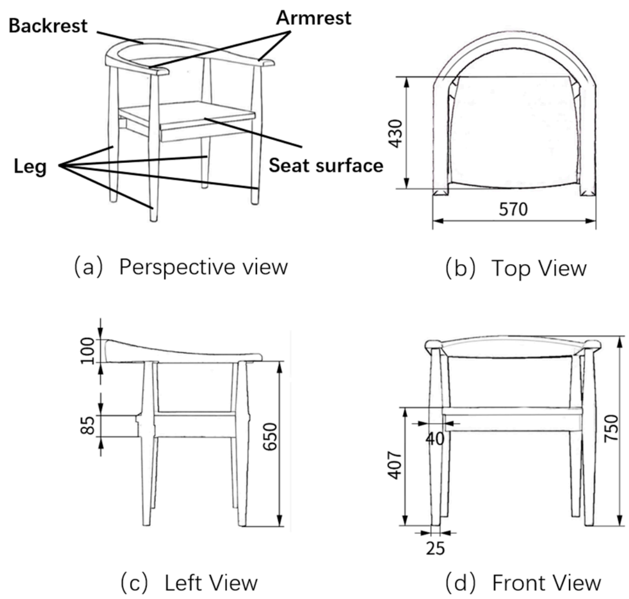
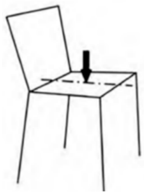
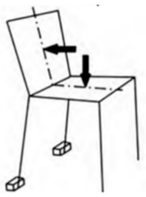
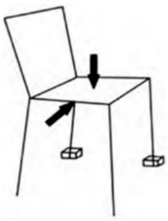
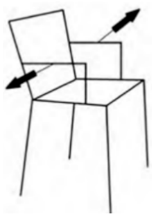
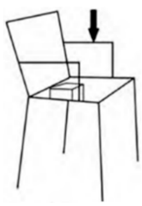


Figure 2. Perspective view and three views of a traditional armchair.

2.2.2. Loading Mode

According to the GB/T10357.3-2013 standard ("Test of mechanical properties of furniture-Strength and durability of chairs and stools") [32] and previous studies [33,34], the mechanical strength of the simplified traditional armchair model was analyzed considering the mechanical requirements of the 3rd test level. Based on the "Report on Nutrition and Chronic Disease Status of Chinese Residents (2020)" [35] released by the State Council Information Office, 95% of Chinese adult males aged 26–35 years weigh 74 kg, and those aged 36–60 years weigh 78 kg. Therefore, a load of 75 kg was selected for the chair in this study. The national standard for testing chair mechanical strength includes six working conditions (Table 2). Considering potential misuse under special circumstances and international practice standards, the load value was increased to 1500 N.

Table 2. Test of chairs under different working conditions.

Condition	Load	Load View	Exert Load	Balance Load	Chair Leg Restraint
1	Seat surface		1500 N vertical load applied to seat surface		Frictionless confinement
2	Backrest		500 N load applied to backrest	1100 N vertical load applied to seat surface	Two rear chair legs set with fixed restraints
3	Front legs		500 N forward horizontal load applied to seat panel rear	1100 N vertical load applied to seat surface	Two front chair legs set with fixed restraints
4	Lateral legs		500 N horizontal load applied to right side of seat panel	1100 N vertical load applied to seat surface	Left two chair legs set with fixed constraints
5	Lateral load on armrests		400 N load applied outward horizontally and vertically from both armrests		Frictionless confinement
6	Vertical load on armrests		800 N vertical load applied to one armrest	800 N load applied to seat surface on opposite side	Frictionless confinement

Condition 1: Seat surface loading: The chair was supported by the ground and chair legs without friction constraints. A 1500 N vertical load was applied to the seat surface,

with the loading point positioned 100 mm away from the front edge of the chair at the center line of the seat surface.

Condition 2: Backrest loading: The two rear chair legs formed a fixed constraint with the ground. The longitudinal axis of the backrest at 300 mm was selected as the loading point. A 500 N horizontal load was applied, and simultaneously, a 1100 N vertical load was applied to the seat surface.

Condition 3: Front leg loading: The two front legs formed a fixed constraint with the ground, and a vertical load of 1100 N was applied to the center of the seat surface. A horizontal forward load of 500 N was applied to the middle of the back edge of the seat surface.

Condition 4: Lateral leg loading: The two left chair legs formed a fixed constraint with the ground, and a vertical load of 1100 N was applied to the center of the seat surface. A horizontal load of 500 N was applied to the right side of the seat surface.

Condition 5: Armrest lateral loading: The chair legs and ground were without friction constraints. An outward lateral load of 400 N was applied to both armrests.

Condition 6: Armrest vertical loading: The chair legs and ground were without friction constraints. A downward vertical load of 800 N was applied to one armrest. A balanced load of 800 N was applied to the seat surface on the opposite side.

3. Results and Discussion

Figure 3 illustrates the material orientation of each chair component, with millimeters as the unit and megapascal as the unit for the elastic modulus. The model mesh size was 10 mm, with 36,068 mesh cells and 66,019 nodes. Tables 3–8 detail the stresses of the three materials under the six tested conditions.

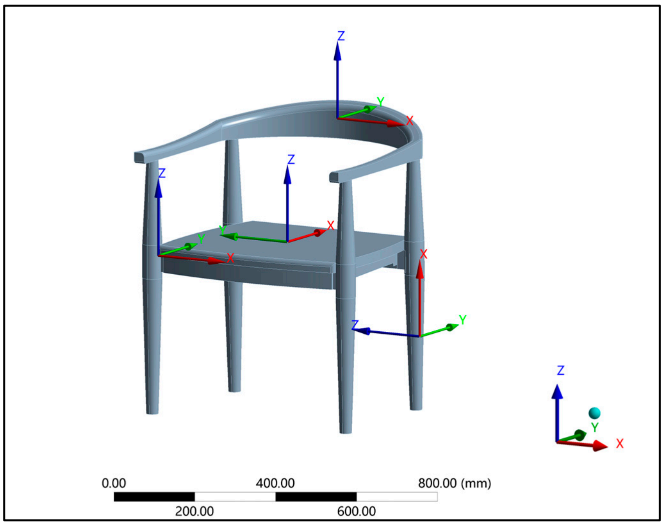


Figure 3. Material orientation of each component of the chair.

The maximum deformation and stress under seat surface loading are detailed in Table 3. The maximum deformation for all three materials occurred at the end of the chair legs (0.69 mm for bamboo scrimber, 0.80 mm for beech, and 1.13 mm for ash). The maximum stress was observed in the middle of the front edge of the seat (5.07 MPa for bamboo scrimber, 5.53 MPa for ash, and 5.28 MPa for beech). Bamboo scrimber exhibited a superior deformation resistance and load-bearing capacity under this condition.

The maximum deformation and stress under backrest loading are detailed in Table 4. The maximum deformation for all three materials was observed in the middle of the backrest (16.43 mm for bamboo scrimber, 18.20 mm for beech, and 24.57 mm for ash). The maximum stress was also in the middle of the backrest (24.69 MPa for bamboo scrimber, 23.64 MPa for beech, and 23.60 MPa for ash). Bamboo scrimber exhibited a superior deformation resistance and load-bearing capacity under backrest loading.

Table 3. Results for seat surface loading (condition 1).

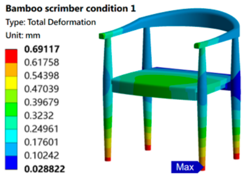
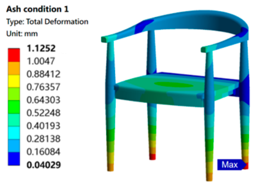
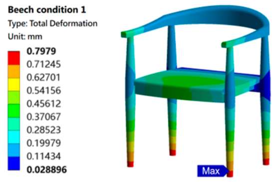
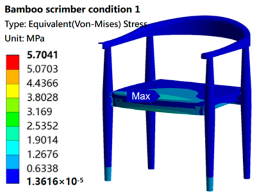
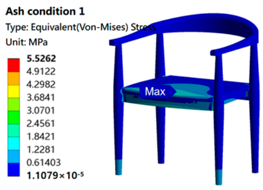
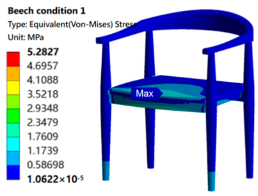
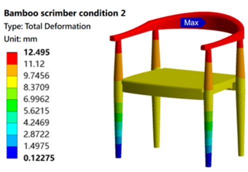
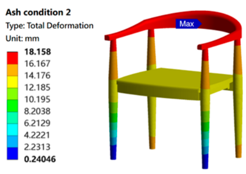
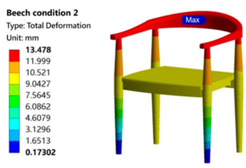
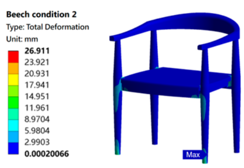
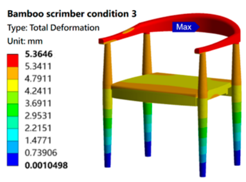
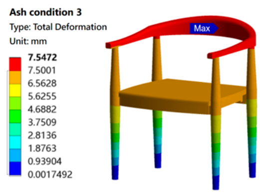
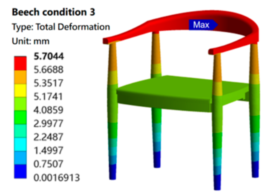
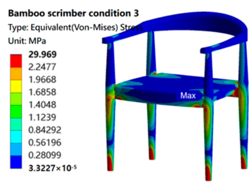
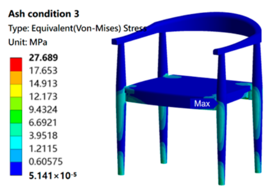
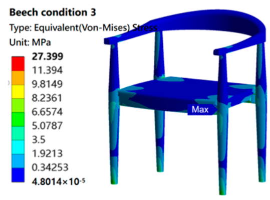
Material	Bamboo Scrimber	Ash	Beech
Maximum deformation (mm)	0.69	1.13	0.80
Maximum deformation position	Chair leg extremity	Chair leg extremity	Chair leg extremity
Maximum stress (MPa)	5.70	5.53	5.28
Maximum stress position	Seat surface	Seat surface	Seat surface
Deformation			
Stress			

Table 4. Results for backrest loading (condition 2).

Material	Bamboo Scrimber	Ash	Beech
Maximum deformation (mm)	12.50	18.16	13.48
Maximum deformation position	Backrest	Backrest	Backrest
Maximum stress (MPa)	29.98	28.15	26.91
Maximum stress position	Chair leg	Chair leg	Chair leg
Deformation			
Stress			

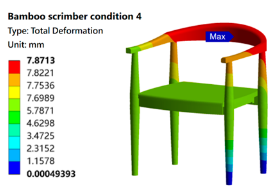
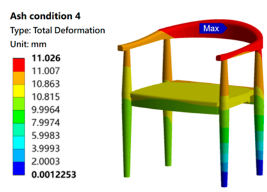
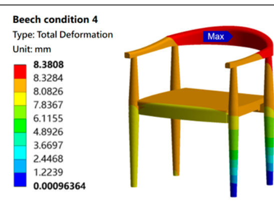
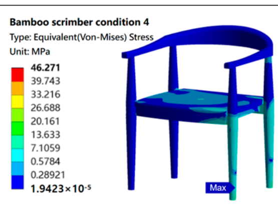
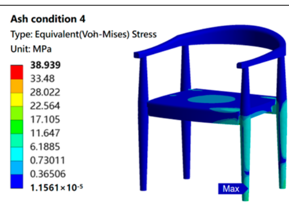
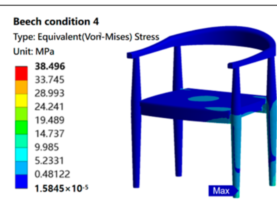
The maximum deformation and stress of the chair legs under forward loading are presented in Table 5. The maximum deformation for all three materials occurred at the backrest (5.36 mm for bamboo scrimber, 5.70 mm for beech, and 7.55 mm for ash). The maximum stress was at the connection between the chair legs and the seat surface (29.97 MPa for bamboo scrimber, 27.69 MPa for ash, and 27.40 MPa for beech). Bamboo scrimber exhibited a superior deformation resistance and load-carrying capacity under front leg loading.

Table 5. Results for front chair leg loading (condition 3).

Material	Bamboo Scrimber	Ash	Beech
Maximum deformation (mm)	5.36	7.55	5.70
Maximum deformation position	Backrest	Backrest	Backrest
Maximum stress (MPa)	29.97	27.69	27.40
Maximum stress position	Junction of seat surface and legs	Junction of seat surface and legs	Junction of seat surface and legs
Deformation			
Stress			

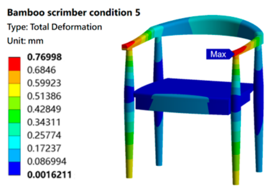
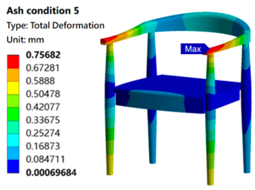
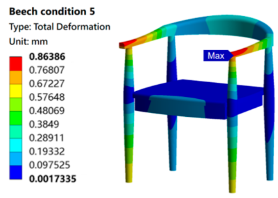
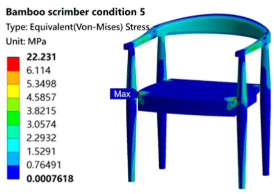
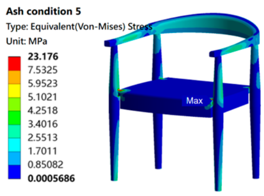
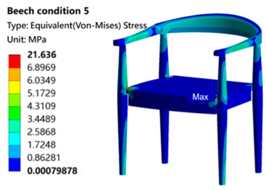
The maximum deformation and stress of the chair legs under lateral loading are presented in Table 6. The maximum deformation for all three materials occurred in the middle part of the backrest (7.87 mm for bamboo scrimber, 8.38 mm for beech, and 11.03 mm for ash). The maximum stress was observed in the lower part of the left side of the chair leg (46.27 MPa for bamboo scrimber, 38.94 MPa for ash, and 38.50 MPa for beech). Bamboo scrimber demonstrated a superior deformation resistance and load-bearing capacity under lateral leg loading.

Table 6. Results for lateral chair leg loading (condition 4).

Material	Bamboo Scrimber	Ash	Beech
Maximum deformation (mm)	7.87	11.03	8.38
Maximum deformation position	Backrest	Backrest	Backrest
Maximum stress (MPa)	46.27	38.94	38.50
Maximum stress position	Lower half of the left seat leg	Lower half of the left seat leg	Lower half of the left seat leg
Deformation			
Stress			

The maximum deformation and stress of the armrests under lateral loading are presented in Table 7. The maximum deformation for all three materials occurred at the front part of the armrest (0.76 mm for ash, 0.77 mm for bamboo scrimber, and 0.86 mm for beech). The maximum stress was observed at the connection between the front chair legs and the chair surface (23.18 MPa for ash, 22.23 MPa for bamboo scrimber, and 21.64 MPa for beech). Bamboo scrimber demonstrated a slightly lower deformation resistance and load-bearing capacity compared to ash but outperformed beech under lateral armrest loading.

Table 7. Results for armrest lateral loading (condition 5).

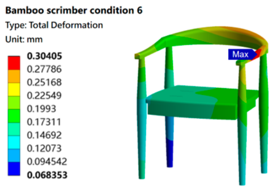
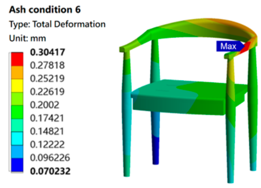
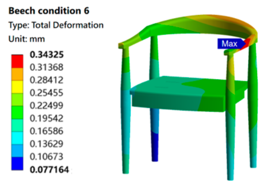
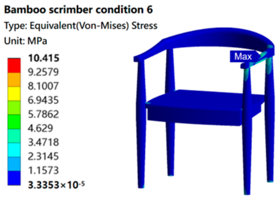
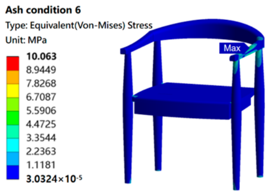
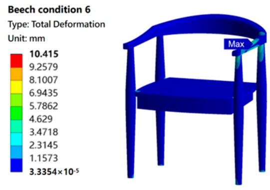
Material	Bamboo Scrimber	Ash	Beech
Maximum deformation (mm)	0.77	0.76	0.86
Maximum deformation position	Armrest front	Armrest front	Armrest front
Maximum stress (MPa)	22.23	23.18	21.64
Maximum stress position	Junction of seat surface and front legs	Junction of seat surface and front legs	Junction of seat surface and front legs
Deformation			
Stress			

The maximum deformation and stress of the armrests under vertical loading are presented in Table 8. The maximum deformation for all three materials occurred in the middle of the left armrest (0.30 mm for both bamboo scrimber and ash, and 0.34 mm for beech). The maximum stress was observed in the middle of the left armrest (10.42 Mpa for both bamboo scrimber and beech, and 10.06 Mpa for ash). Under vertical armrest loading, bamboo scrimber exhibited a deformation resistance equivalent to ash but superior to beech, while its load-bearing capacity matched that of beech but exceeded that of ash.

In summary, bamboo scrimber exhibited the lowest maximum deformation and the highest maximum stress under seat, backrest, leg, and armrest loading in the vertical direction. This indicates that bamboo scrimber possesses strong structural stability and balanced load-bearing capacity, meeting the requirements for furniture materials, particularly for chairs subjected to complex loads.

In the armrest lateral load test, ash demonstrated high maximum stress and low maximum deformation. The positional cloud diagrams indicate that the maximum deformation occurred at the front end of the armrests, while the maximum stress was observed where the front legs connected to the chair surface. Therefore, we propose a material selection strategy that combines traditional and new materials. Bamboo scrimber would be utilized for the seat, backrest, and legs, while ash would be employed for the armrests and the connection between the front legs and seat. This material configuration not only optimizes the performance of each component but also improves the durability and stability of the entire product.

Table 8. Results for armrest vertical loading (condition 6).

Material	Bamboo Scrimber	Ash	Beech
Maximum deformation (mm)	0.30	0.30	0.34
Maximum deformation position	Middle of left armrest	Middle of left armrest	Middle of left armrest
Maximum stress (MPa)	10.42	10.06	10.42
Maximum stress position	Middle of left armrest	Middle of left armrest	Middle of left armrest
Deformation			
Stress			

Based on the FEM results, this paper proposes a material selection strategy for furniture design. By comprehensively analyzing the performance of multiple materials under different working conditions, the most suitable materials were selected for different parts of the furniture according to specific force conditions. In traditional armchair design, we recommend using bamboo scrimber for the chair surface, backrest, and legs, while the armrests and the parts connecting the legs and chair surface should be constructed from ash, which can effectively improve the overall performance of the traditional armchair.

Future research should continue to explore the application of bamboo scrimber to other furniture types to promote its widespread use in furniture manufacturing for sustainable development. The FEM can also be used to analyze the performance of other types of furniture to further validate and improve the material selection strategy proposed in this paper.

4. Conclusions

This study compared the performance of three materials (bamboo scrimber, ash, and beech) under six different working conditions using the FEM. The results indicate that bamboo scrimber has significant performance advantages over traditional wood materials for furniture manufacturing. First, bamboo scrimber showed excellent resistance to deformation, and its deformation in the vertical loading test of the seat, back, legs, and armrests was much lower than that of ash and beech, proving its structural stability. Second, bamboo scrimber demonstrated a stronger load-bearing capacity under most test conditions, especially in the areas of the legs and seat, which are subject to concentrated forces. These findings not only confirm the feasibility of using bamboo scrimber as a sustainable furniture material but also highlight its suitability for furniture subjected to complex stresses.

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