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Review

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Review on the Application of Bamboo-Based Materials in Construction Engineering

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Abstract: Due to the continuously increasing demand for building materials across the world, it is necessary to use renewable materials in place of the existing nonrenewable materials in construction projects. Bamboo is a fast-growing flowering plant that may be used as a renewable material in construction. The use of bamboo in the construction of buildings can improve its long-term carbon fixation capacity and economic benefits. Although bamboo has the advantages of superior performance, low carbon content, high energy-saving and emission-reducing capacity, bamboo is an anisotropic material, which has many factors affecting its material performance, large variability of material performance, lack of systematic research, and the use of bamboo as the main building material is not always limited. This paper systematically summarizes the research status of bamboo as a building material from the aspects of bamboo composition, gradation, material properties, bamboo building components, connection nodes, and use of artificial boards. On this basis, some constructive suggestions are put forward for the further study of bamboo in the field of architecture.

Keywords: Bamboo; building element; connection node; glue-laminated bamboo; bamboo scrimber; binderless plywood

1 Introduction

Bamboo is a fast-growing flowering plant species that may be used as a renewable material in construction. Bamboos achieve their full growth in 4–5 years, and the coefficient of variation of their mechanical properties is small. Bamboo plantations can be harvested at intervals between raw bamboos. After interval harvest, bamboo plantations can recover quickly to their original appearance, and the bamboo has high mechanical properties. Bamboo is generally used in construction projects, furniture, and paper-making [1]. The use of bamboo in the construction field can improve its long-term carbon sequestration ability [2].

The construction industry accounts for a large percentage of the gross domestic product (GDP) of almost all countries, and is thus a pillar of their economies. The total energy consumption of buildings is continuously increasing worldwide. For example, the total output of the construction industry in China in 2019 was 24.84 trillion Yuan, which accounted for 25.07% of its GDP [3]. It is estimated that by 2030,

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the building energy consumption in China will account for about 35% of the total energy consumption [4]. However, the existing construction materials, such as steel, concrete, and masonry, are all nonrenewable resources [5]; hence, the use of such construction materials will have a great adverse impact on the environment.

Wood and bamboo are both renewable resources; however, compared with bamboo, wood has a longer growth cycle and slower recovery after harvesting, thus causing irreparable damage to the environment. As the forest area per capita and the overall forest coverage in China are lower than the world average values [6], since 1998, China has implemented natural forest resource protection projects in key state-owned forest areas to resolutely stop the logging of ecological public welfare forests and reduce the logging of general ecological public welfare forests. The growth of wood in fast-growing forests is relatively poor, which results in a gap between the supply and demand of timber in China.

Bamboo is a natural building material. There are 1575 species of bamboo out of which 1200 are woody [7]. Bamboo grows naturally in tropical, subtropical, and mild temperate regions of Africa, Asia, the Americas, and Oceania [8]. Apart from being an alternative and supplementary resource for wood, bamboo has found several uses because it is green, energy-saving, emission-reducing, and highly renewable. Trujillo et al. [9] pointed out that *Guadua angustifolia Kunth*, *Dendrocalamus asper*, *Phyllostachys edulis*, and *Bambusa blumeana* are the main bamboo species that can be used in structural applications. Bamboo has the potential to replace existing building materials such as steel and concrete [10]; however, it is currently suitable for temporary buildings, small civil buildings, and decorative applications [11,12]. Bamboo can also be used to build affordable houses and post-disaster reconstruction houses in disaster-stricken areas [8,13]. *P. edulis* is used in the soil nailing of soft soil foundation pits [14]. Bamboo and bamboo scrimbers are used in making furniture [15,16]. Moreover, the bamboo industry is an industry with cultural appeal and ecological benefits [17].

Although bamboo has been used as building materials for thousands of years and yields superior mechanical performance, it is still not being used as the main resource in construction projects due to the lack of reliable design standards. This paper systematically summarizes the research status of bamboo-based materials and puts forward research suggestions pertaining to construction engineering.

2 Composition of Bamboo

Bamboo as a plant has a composition similar to that of natural plants. According to Cai et al. [18], the plant cell walls of bamboo are mainly composed of cellulose, hemicellulose, and lignin. Cellulose and hemicellulose can be degraded into lignin, which encapsulates cellulose microfibers. Shu et al. [19] found that the lignin, cellulose, and hemicellulose contents of *P. edulis* cultivated in the Xiashu Forest Farm of the Nanjing Forestry University were 30.40%, 40.05%, and 19.93%, respectively.

Wang et al. [20] used the cellulose/dilute acid treatment method to separate lignin from natural bamboo cultivated in the Zhejiang Province. The optimal reaction conditions were as follows: during enzymatic hydrolysis, the enzyme/substrate ratio was 1:8, the substrate concentration was 0.025 g/ml, and the reaction temperature was 50°C for 48 h; the pH value was 0.82 after dilution with dilute acid. Zhang et al. [21,22] carried out the formic acid fractionation of bamboo under high pressure to obtain relatively pure lignin. This method used automatic hydrolysis to pretreat bamboo chips and promote oligosaccharide production, followed by formic acid to lower the liquid/solid ratio (7:1); finally, rapid delignification and fractionation were performed within 60 min to obtain cellulose (36.8%), hemicellulose sugar (7.0%, mainly oligosaccharides), and lignin (25.9%). Li et al. [23] used a solvent system consisting of 45 vol.% EtOH and 55 vol.% H_2O (containing 5 vol.% formic acid catalyst) at 190°C to fractionate bamboo into highly pure (84 wt%) solid cellulose, very pure (>95 wt%) organosolv lignin, and rich water-soluble hemicellulose (27 wt% oligomer, 56 wt% sugar, and 14 wt% carboxylic acid). Hao et al. [24] studied the mechanical responses of bamboo cellulose, hemicellulose, and lignin under uniaxial stretching and observed that hemicellulose is a branched polymer with short chains and lignin is a crosslinked polymer with a network structure. They also observed that amorphous lignin had higher stress than amorphous hemicellulose, and that hydrogen bond breaking and linear polymer chain sliding were the main causes of cellulose failure. The normal stress-dominated fracture mechanism was the key to hemicellulose failure, and the fracture mechanism of lignin was dominated by shear stress. He et al. [25] expounded that the microstructure of bamboo is mainly composed of longitudinal vascular bundles (VBs) and parenchyma cells (PCs). Each VB was found to have a triangular structure with two hollow vessels and a phloem, which were surrounded by fiber bundles. The density of the fiber bundles decreased from outside to inside along the stalk wall, and the VBs may be regarded as fiber-reinforced materials embedded in PCs. Xiang et al. [26] studied the main anatomical characteristics of the four clustered bamboo species (*Bambusa chungii, Dendrocalamus minor, Bambusa textilis*, and *Bambusa pervariabilis*) in the Guangxi Province and asserted that the radial VB density of the bamboo walls gradually decreased as the bamboo turned from green to membrane. The radial width was the largest in bamboo yellow, and the chord width gradually decreased as bamboo turned from membrane to green. The fiber length, width, and the cavity diameter were the largest at the middle of the bamboo wall diameter.

The microstructural composition and characteristics of bamboo reveal that the main components are lignin, cellulose, and hemicellulose; however, the variation in the content of these main components among bamboo species in different regions has not yet been studied. It is, therefore, recommended to divide the bamboos into multiple plots based on their distribution, study each plot as a unit, and further study the differences in the composition between the bamboos and the slubs.

3 Grading of Bamboo

Sharma et al. [27] proposed the concept of engineered bamboo, and divided bamboo-based materials into raw bamboo and engineered bamboo. Raw bamboo refers to bamboo-based materials that are used directly without material reorganization or modification after felling. Engineered bamboo refers to bamboo-based materials processed by reorganizing or modifying raw bamboo. Xiao et al. [28] invented a new type of engineered bamboo, called the laminated bamboo, which is a cost-effective option to be used in structural applications.

The bamboo grading referred to in this article is based on raw bamboo, researching the segmentation and standardization of bamboo segments, trying to find a solution to the sharpness of bamboo materials, so as to realize the standardized application of raw bamboo.

Wu et al. [29] pointed out that at the meter scale the external shape of the bamboo tube, when viewed externally, was composed of hollow tubes with a circular cross-section, and consisted of rod-like structures with stepped up variable cross-sections connected to each other at the bamboo joints; at the centimeter scale, the quantity and quality of vascular bundles in the original bamboo decreased from bamboo green to bamboo membrane; at the millimeter scale, the original bamboo was a composite material reinforced with a thin-walled tissue matrix and bamboo fiber bundles; at the micrometer scale, bamboo fibers were bonded to various tissues in the intercellular layer to form vascular bundles with unblocking tissues; at the sub-micrometer scale, bamboo fibers and thin-walled tissue cell walls formed by the multi-layering of cell wall sublayers were composed of a layered nanocomposite structure; at the nanometer scale, the cell wall layer possessed a nanocomposite structure of cellulose-reinforced lignin and hemicellulose.

Yang et al. [30] divided *P. edulis* into three sections: root (ground to 0.9-m height), trunk (0.9-m height to branch height), and branch part (abovebranch height). Yang et al. [31] took the chest diameter as the grading index for bamboo stalks, 1 m as the truncation length, and 5 mm as the grading modulus; they then divided the bamboo stalks into nine grades in which the chest diameter of 95–115 mm was the main diameter grade area. Nurmadina et al. [32] studied the structural classification of large-leaf bamboo based on its bending characteristics and propounded that the structural classification of bamboo is useful in capacity classification rather than strength classification. The combination of linear mass and diameter square (qd^2)

is used in estimating bamboo stiffness, and qd alone in estimating the bearing capacity of bamboo. Yan et al. [33] found that the air-dry density, flexural strength, and elastic modulus of *P. edulis* increased from the base to the tip. The air-dry density value was the same for the pole height range of 3–9 m, and the mechanical properties in pole height ranges 1–5 m and 5–9 m were very close. Liu et al. [34] compared the polarized light microscopy images of *P. edulis* fiber cells with the electron microscopy images of the wall structure of *P. edulis* and classified the species based on the number of thick-walled layers.

Lorenzo et al. [35] described the details of a nondestructive three-dimensional scanning and modeling workflow developed to capture and process the relevant digital information that describes the geometric properties of bamboo poles, and pointed out that the effective digitalization of bamboo poles and its integration with modern platforms can provide the necessary support to the construction industry.

The grading study on bamboo was conducted from different angles; however, since the studies were carried out only in local areas, they cannot be used to propose a standardized solution.

4 Properties of Bamboo

The distribution density, morphology, composition, and mechanical properties of VBs vary greatly among the different bamboo species. Density is the most reliable index to evaluate the compressive strength and compressive modulus of bamboo along grains [36].

4.1 Physical Properties of Bamboo

According to Guan et al. [37], the basic density of *P. edulis* between 4 and 10 years of age increases with the age of the bamboo, the difference shrinks in different parts decreases, and the crack resistance of the bamboo increases. The older the bamboo, the better the crack resistance. According to Awoyera et al. [38], the best age for using bamboo in construction is 3–4 years. Bamboo less than 3 years or more than 5 years should not be used in construction projects. The preferred density of the bamboo is 520–820 kg/m^3. Within this range, both strength and stiffness increase with the increase in density. The drying process of bamboo should be carried out in air and in the absence of sunlight to prevent the drying speed from being too fast, which may cause cracks on the bamboo walls. Ribeiro et al. [39] calculated the modulus of rupture (MOR) of the *Bambusa vulgaris* to be 48–132 MPa, modulus of elasticity (MOE) to be 6.1–14.2 GPa, and the dynamic modulus of elasticity (Ed) to be 13.7–22.3 GPa. It was observed that the regional average density of the bamboo did not vary much and was around 630–680 kg/m^3. Ma et al. [40] found that the MOE of the bamboo gradually decreased from the periphery to the center. He [41] pointed out that the total dry shrinkage and density of the bamboo gradually decreased and increased, respectively, from the base to the top, while the compressive strength and the flexural strength gradually increased along the grains.

Cai et al. [42] observed that the bamboo shrinkage ratio was the largest in the chord direction (chord > radial > longitudinal). Chen et al. [43] found that bamboo with high moisture content had good tensile properties. Bamboo generally experiences three kinds of breaking behavior: matrix (multi-walled and thin-walled tissue cells) destruction, interface (fiber/fiber or fiber/thin-walled tissue cell wall) dissociation, and fiber breakage. While elongation mainly depends on matrix destruction and interface dissociation, strength mainly depends on fiber breakage and interface dissociation. Jakovljević et al. [44] exposed bamboo to an environment with a relative humidity of 100% ± 2%. As the number of days increased, the quality, buckling characteristics, and toughness of the bamboo also increased. Tan et al. [45] noticed that the water content in *P. edulis* gradually decreased with increasing age and that the stalks possessed the highest water content at their bases (base > middle > tip). Huang et al. [46–48] asserted that the correlation between moisture, heat transfer characteristics, and open porosity of bamboo was higher than their bulk density. Bamboo exhibits good heat storage and steam resistance; however, its heat transfer performance is poor. The moisture performance of bamboo fibers can be improved by arranging the bamboo charcoal upstream of the moisture flow, which weakens the flow of moisture and heat through the outer wall. Huang et al. [49,50] posited that density was the most critical parameter that affected the transient temperature distribution in bamboo. The outside of the bamboo stalk walls could be used to minimize the relative humidity change in the panel, and the inside could improve the thermal insulation performance of the panel. The water vapor diffusion resistance factor manifested a decreasing trend from the outer surface to the inner surface in the radial direction, and its value in the longitudinal direction was significantly lower than those in the radial and tangential directions. The resistance factors of the nodes in the radial and tangential directions were lower than those between the nodes. Zhang et al. [51] performed a double cantilever beam test to study the feasibility of linear vibration welding of bamboo and calculated the bamboo VB concentrations on the outside and inside to be 85% and 45%, respectively. They also observed that the parenchymal parenchyma was mainly composed of PCs surrounded by VBs. The average density of the entire bamboo wall was calculated to be 0.68 g/cm^3 (outside = 1.02 ± 0.6 g/cm^3 and inside = 0.57 ± 0.5 g/cm^3). A low VB concentration indicates a better welded joint performance, with the moisture content of the bamboo welded joints being less than 18.1%. Zhang et al. [52] noticed that the welding strength of *P. edulis* increased first and then decreased with the increase in the welding pressure, and the maximum average welding strength reached 7.15 MPa. The welding and bonding interface layer was wrapped with the frictional heat melting bamboo cell intercellular material (mainly lignin) and intertwined with bamboo fibers. Due to the frictional temperature, hemicellulose degraded, the amount of lignin in the welding layer increased, and cellulose remained almost unchanged.

Xiao et al. [53] conducted a fire simulation experiment study on the full-scale room unit model, examining the temperature history records of several points on the wall and floor, the fire behavior of the overall structure, and the damage to the components. Numerical simulation was conducted using the fire-driven fluid dynamics software Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology (NIST). Fire design measures using gypsum boards and rock wool insulation suggested for new bamboo buildings were found to be adequate from this research.

The physical properties of bamboo, such as shrinkage ratio, density, stability, water content, heat storage, and steam resistance, have been extensively investigated; however, the bamboo wood welding technology does not solve the problem of moisture resistance at the nodes.

4.2 Mechanical Properties of Bamboo

Chen et al. [54] studied the mechanical behavior of bamboo during fracture using acoustic emission (AE) and found three different types of fracture behavior: matrix (parenchymal cell) destruction, interface (fiber/fiber or fiber/parenchymal cell wall) dissociation, and fiber breakage. The mechanical properties were found to be greatly affected by the water content, with wet bamboo having higher fracture energy than dry bamboo. Moisture-enhanced microfiber bridging (wart flexion), multiwall fiber pullout, and crack deflection ensured high strength and toughness.

Chung et al. [7] asserted that the mechanical properties of bamboo were superior to those of ordinary wood, and that bamboo had excellent compression and bending resistance. Gottron et al. [55] advocated that the fibrous structure of bamboo made its mechanical properties better than those of other natural materials. The fiber density increased from the inner walls of the rods (10%) to the outer walls (60%). The wall thickness was the largest at the base and decreased with increasing height. The fiber volume increased with increasing height to compensate for the loss of strength and stiffness caused by the decrease in the top diameter and wall thickness.

Askarinejad et al. [56] pointed out that *P. edulis* could withstand higher stresses during deformation. Lo et al. [57] calculated the compressive strength of *P. edulis* to be 45–65 N/mm^2, and found that the amount of VBs at the top of the bamboo was higher than that at the bottom, thus making the compressive strength at the top higher than that at the bottom. Krause et al. [58] observed that the strength and stiffness of *P. edulis* gradually increased from the inner layer to the outer layer. Verma et al. [59] advocated that the mechanical properties of the bamboo increased from the inside to the outside, and that it increased with the increasing height of the bamboo stem. The average strength of the bamboo is better than that of softwood and comparable to that of hardwood.

Monteiro et al. [60] conducted a Weibull analysis of the tensile strength of giant bamboo fibers and asserted that the tensile strength was inversely proportional to the fiber diameter, and that the tensile strength of fine fibers was greater than 300 MPa. Song et al. [61] noticed that a low fiber density resulted in a high fatigue life and high fatigue limit. Akinbade et al. [62] observed that the silica-rich epidermal layer greatly affected the MOR and stiffness of the entire stem. They further observed that the parenchyma tissue near the outer stem wall destroyed the interface between the PCs, and the parenchyma tissue near the inner stem wall destroyed the cells passing through the parenchyma.

Jakovljević et al. [63] advocated that humidity significantly reduced the tensile, compression, and bending strengths of bamboo. Askarinejad et al. [64] studied the effect of humidity on the mechanical properties of bamboo under torsion and observed that the shear modulus was the highest when the humidity was 60%. Similarly, the highest shear strength was obtained when the humidity was 60%–80%, and observed that the ductility of bamboo improved with the increase in humidity. Mo et al. [65] carried out a high-temperature, rapid, hot-pressing treatment on *P. edulis* slices for 4–6 years and obtained the maximum compressive strength of 80.19 MPa along the grains at 300°C and the minimum compressive strength of 63.78 MPa at 375°C; the maximum flexural strength of 151.00 MPa at 250°C and the minimum flexural strength of 61.85 MPa at 375°C; and the maximum flexural elastic modulus of 10487.44 MPa at 300°C and the minimum flexural elastic modulus of 7071.14 MPa at 375°C. Kadivar et al. [66] asserted that the density and bending properties of the bamboo could be improved using an open hot press. All samples of *D. asper* were compressed following the same procedure at 140°C and 4.34 MPa for 15 min. *D. asper* was found to have the best bending performance when the water content was 10%, and the average MOR, MOE, and Ed were calculated to be 318 MPa, 27754 MPa, and 34120 MPa, respectively. Salvati et al. [67] studied the effects of five different NaOH concentrations (5%, 10%, 15%, 20%, and 25%) on the elastic properties of bamboo. A high NaOH concentration was used to eliminate lignin and destroy the bonding between fibrils. Fiber elastic modulus and stiffness were found to be the highest at 20% NaOH, and the increment of stiffness was assessed to be 59% with the respect to the pristine materials. The fiber toughness and crack resistance were the highest at 25% NaOH. Sharma et al. [68] pointed out that bleaching and caramelization increased the compressive and shear stresses, reduced the tensile properties, increased the flexural modulus by 20%, and made the bamboo brittle, resulting in longitudinal splitting failure.

Mannan [69] observed that the internal toughness of bamboo was higher than the external one, a trend that was opposite to that of rigidity. Zou et al. [70] advocated that bamboo nodes and VBs were the main factors that affected bamboo energy absorption. The energy absorption of the nodal was better than the internode.

Hu et al. [71] conducted the quasi-static and dynamic Split Hopkinson pressure bar (SHPB) compression experiment at strain rates ranging from 500 and 2200 to investigate the effect of strain rate on the mechanical properties of bamboo. The yield stress for the specimens crushed along the longitudinal direction of the fibers increased from 38.59 to 94.25 MPa, as the strain rate varied from 1.85×10^{-3} to 2200 s^{-1}, while it increased from 7.18 to 42.04 MPa for the specimens crushed in the direction perpendicular to the fiber.

Rua et al. [72] performed compression, three-point bending, Charpy impact and SHPB tests on *G. angustifolia Kunth*. The impact test showed than the impact energy is similar to that of stainless steel

410. The SHPB test shows that the yield point for the *Guadua* species is around 4 MPa. It was also observed that samples could handle up to 6.4% deformation, after which the material tends to fail.

Zhou et al. [73] used a universal testing machine to perform quasi-static tests on glue-laminated bamboo (GluBam), and an expressly designed aluminum SHPB apparatus to perform dynamic tests on GluBam. Two types of GluBams were tested to characterize their quasi-static and high-strain rate compressive characteristics. The results showed that GluBam is strain rate-sensitive and that the sensitivity highly depends on the loading direction.

The longitudinal mechanical properties of bamboo and the mechanical properties after modification treatments have been extensively investigated; however, very few studies have researched the differences between the radial and tangential mechanical properties of bamboo and the difference in the mechanical properties of slubs and bamboo. There are very few studies on the cracking mechanism of bamboo and the factors that affect bamboo cracking. The mechanical properties of different parts of bamboo stalks have not yet been systematically studied. The on-site, rapid, nondestructive inspection of the properties of bamboo must be further strengthened.

4.3 Functional Research on Bamboo

After heat treatments, the contact angle of the bamboo increased (not more than 90°), wetting performance decreased, hydrophobicity increased significantly, and the water wetting contact angle of the bamboo pith was higher than that of the bamboo skin [74,75]. Li et al. [76] used a micro-nano binary structure of the TiO_2 film and low surface energy fluorinated components to form a superhydrophobic surface on bamboo and wood substrates (contact angle was more than 150° and sliding angle was less than 10°). The as-prepared structure had good mechanical and chemical stability, durability, and anti-corrosion and self-cleaning performances. Fei et al. [77] advocated that rutile nano-TiO_2 can interact with bamboo fiber molecular chains and improve their thermal stability and reduce their thermal oxidation aging, in turn acting as a light-shielding agent and ultraviolet absorber to hinder the photocatalytic oxidation of bamboo fibers. Rao et al. [78] observed that the benzotriazole (BTZ) coating achieved the best light stability on the bamboo surfaces. BTZ-NZnO and BTZ-$NTiO_2$ had a strong synergistic effect, while BP-$NTiO_2$ and BP-NZnO had an antagonistic effect. Chen et al. [79] pointed out that the fire and burnout temperatures of bamboo samples pretreated with NOE-7F natural organic enzymes were higher than that of raw bamboo.

Sun et al. [80] asserted that both the bamboo and wood preservatives were dominated by copper-containing compounds. It was necessary to strengthen or add anti-mold ingredients to wood preservatives in order to prevent attack by fungi. Inorganic boron salts, organic fungicides, and natural extracts are generally used to achieve the antiseptic effect. Li et al. [81] noticed that ZnO-treated bamboo had better resistance to *Aspergillus niger* and *Penicillium digitatum*; however, they showed poor resistance to *Trichoderma viride*. Wei et al. [82] studied the effects of the silica-alumina inorganic antiseptic treatment on the color of the bamboo surfaces and the distribution of the antiseptic solution in the bamboo cell cavity.

The resistance to water, flame, corrosion, and mildew, and the light stability of bamboo has been investigated extensively; however, these studies have mainly used heavy metals to resist corrosion and mildew, thus causing greater pollution to the environment.

5 Building Components Using Bamboo

Li et al. [83] observed that bamboo columns filled with concrete and cement mortar had a higher axial bearing capacity and initial stiffness than traditional bamboo columns, with the bamboo joints capable of increasing the bearing capacity of the members. Wang et al. [84] observed that ordinary, low-strength concrete did not have a significant effect on the compressive bearing capacity of composite materials; ductility, however, was significantly improved. Tian et al. [85] noticed that 4-year-old *P. edulis* plants in the Zhejiang Province had a tensile strength, a compressive strength, and an elastic modulus of 193.2 MPa, 63.0 MPa, and 14500 MPa, respectively, in the direction parallel to bamboo fibers whose moisture content ranged between 10% and 18%. A composite mortar was observed to improve the stability of the bamboo; however, it could not improve their compressive bearing capacity. Rahman et al. [86] observed that epoxy coatings enhanced the acid resistance of bamboo composites and improved their bond strength of their interface with concrete. The addition of sand particles on the surface of bamboo composites further increased the bond strength of the bamboo. Javadian et al. [87] used bamboo-based materials in concrete structures instead of steel bars to study their bonding properties and chemical reactions with concrete. Dey et al. [88] used a thin layer of epoxy resin to prevent bamboo from absorbing water and wrapped the bamboo with sand, steel wires, and coconut shell. It was found that the steel wire-wrapped bamboo had the best friction performance with concrete. Deng et al. [89] studied the influence of different parts of a *P. edulis* tube, a diabolo tube, and a concrete bamboo tube on the compressive bearing capacity.

Zhao et al. [90] developed a new type of thin-walled steel pipe/bamboo plywood hollow composite column with restraining rods, and found that bamboo plywood and thin-walled steel pipes could form a combined column with better stability. However, three different modes of compression failure were noticed: broken plywood at the end of the column, partial degumming, peeling and curling, and overall instability.

Li et al. [91] studied the thermal performance of a steel-bamboo composite wall structure (Fig. 1) and noticed that the thermal performance of the 170-mm-thick steel-bamboo composite wall exceeded that of common building walls. Zhang et al. [92] studied the bonding stress and slip of two types of steel-bamboo interfaces: pure adhesive bonding interface bonded by a structural adhesive and reinforced bonding interface reinforced with self-tapping screws. A theoretical model to determine the shear stress and slip at the steel-bamboo interface was proposed. Wen et al. [93] mixed discrete and randomly distributed fibers with concrete and used bamboo strips as the bio-reinforced material to make beams. It was observed that the ductility of the components increased with the addition of fibers, with the optimal fiber content being 0.3%. Mali et al. [94] advocated that grooved bamboo bands (2%) could improve the flexural strength, energy absorption capacity, ductility, and the failure mode (ductility) of the bamboo-reinforced concrete panels.

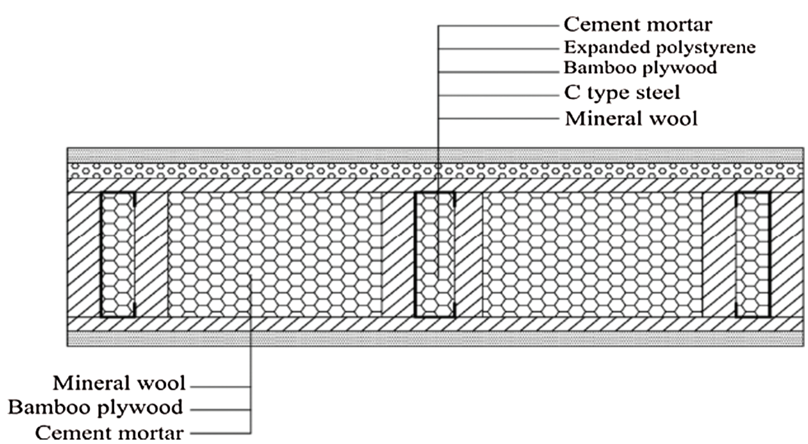

Figure 1: Steel-bamboo composite wall structure [91]

He et al. [95] used hard-headed yellow bamboo as the raw material to press an raw bamboo structure composite board and measured its physical and mechanical properties (Fig. 2). Tian [96] noticed that the

Figure 2: Raw bamboo structure composite board [95]

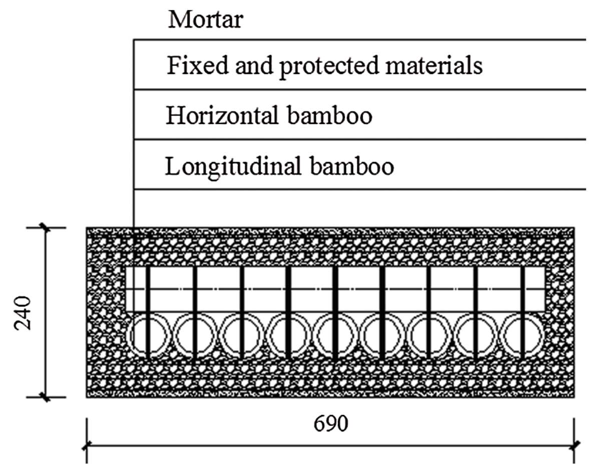

Figure 3: Hollow floor slab combined with an raw bamboo skeleton and light aggregates [96]

mechanical properties of the hollow floor slab combined with an raw bamboo skeleton, and light aggregates were controlled by deflection, and that the material strength was used as a safety reserve (Fig. 3).

Wang et al. [97] studied the thermal insulation performances of bamboo and wood shear walls in light buildings and observed that the thermal insulation performance of bamboo shear walls was slightly lower than that of the wooden shear walls. The thermal conductivity of the bamboo shear wall parallel to the fiber direction was about 40%.

Chithambaram et al. [98] studied the flexural performance of fly ash-containing bamboo-based reinforced concrete floor slabs and observed that bamboo strips had a greater influence on the ultimate bearing capacity than mortar and wire mesh, and that the floor slabs had a greater impact before bending failure.

Wang et al. [99] studied a new type of lightweight shear walls made using a GluBam stud frame and ply-bamboo sheathing panels. The test results demonstrate that the performance of the lightweight GluBam shear walls is similar to that of the conventional lightweight wood-frame shear walls, with higher initial stiffness and peak load, but lower ductility. In addition, a new uplift hold-down device and design-improved edge studs were used to increase the ductile performance of GluBam shear walls.

Li et al. [100] studied the load-bearing behaviors of self-drilling screw connections in cold-formed steel (CFS) frame shear walls sheathed with engineered bamboo panels. The performance of the CFS-bamboo connections was studied under various conditions with respect to differently engineered bamboo sheathing panels, screw features, end distances, and loading rates. The experiments showed that engineered bamboo panels can be used as efficient sheathing panels for CFS structures with good mechanical performances.

The mechanical properties of bamboo-based materials with steel, concrete, mortar, and other building materials have been studied elaborately; however, since the properties of bamboo varies across types, the industrialization of bamboo components is unable to be achieved. Furthermore, the deformation coordination between different materials is yet to be studied.

6 Connection Nodes in Raw Bamboo

According to Wang [101], raw bamboo has node connections, which include lashing connection, bucket connection, pin connection, groove connection, and burnt connection. Node-filling materials (wood, cement mortar, plaster) strengthen steel components and steel plate connections. According to Zhang et al. [102,103], defects generally occur in lashing connections, piercing joints, and steel plate connections. The key aspects that need to be focused in order to enhance the structural integrity of raw bamboo nodes are improving construction efficiency and structural reliability, and reducing the cost. Generally, gypsum and an appropriate amount of fly ash, retarder, and other additives are used as fillers to fill the cavities between the raw bamboo nodes. According to Yan et al. [104], raw bamboo node connection methods mainly include bamboo-metal composite nodes, bamboo-cement composite nodes, and bamboo-wood composite nodes (wood wedge or pole connection). According to Hong et al. [105], traditional connection methods include using tenons (the shortfalls of using tenons are large cross-section weakening and poor splitting resistance) and binding (the shortfalls of using binding are inadequate stiffness, low rope strength, and poor durability), whereas modern connection technologies include the use of bolt connections (the shortfalls of using bolt connections are open holes that easily crack and joints that easily form gaps), steel members, and steel plate joints (the shortfalls of using steel plate joints are that the steel joints are expensive), reinforced joints (the shortfalls of using reinforced joints are filler selection, construction convenience, and long-term service life must be improved), and other connection joints.

Zhang et al. [106] applied structural glue to wood after processing, put it into the raw bamboo cavity, and reinforced it with steel wires. Tenon-mortise connections were used between the wood. Paraskeva et al. [107] used steel buckle plate-type connectors to quickly assemble a simple, rural bamboo footbridge (Fig. 4). Paraskeva et al. [108] added a steel hose clamp to resist the brittle split between the raw bamboo and steel (Fig. 5). Hu et al. [109] studied the bearing capacity and failure modes of bolted joints in an assembled circular bamboo structure and asserted that the double-bolt joint design and the high-strength mortar strengthening significantly improved the bearing capacity of the bolted joints (Fig. 6).

Figure 4: Steel buckle plate connection node [107]

Trujillo et al. [110] used metal fasteners (φ3.5–5 self-tapping screws, and φ3–16 smooth pins and bolts) as bamboo joints, but observed that the compatibility of bamboo with metal fasteners needed further investigation (Fig. 7). Moran et al. [111] designed a new type of raw bamboo node connection that could transmit bending moments with two thin steel half-rings to form a steel clamp. Each node was composed of five steel clamps tightly clamped onto the stem (Fig. 8).

Quaranta et al. [112] introduced the main characteristics of an raw bamboo-steel composite truss structure. The upper chord and diagonal bars of the spatial truss structure are made up of GluBam

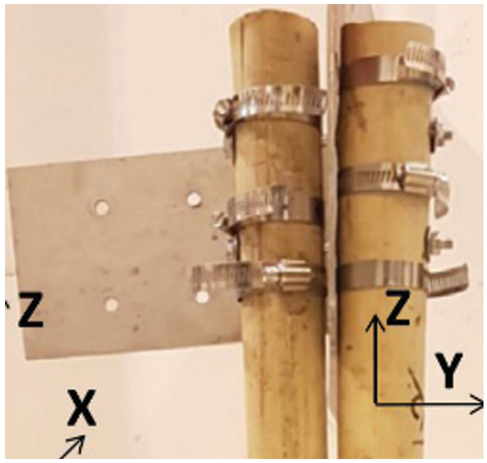

Figure 5: Steel buckle plate connection node with steel clips [108]

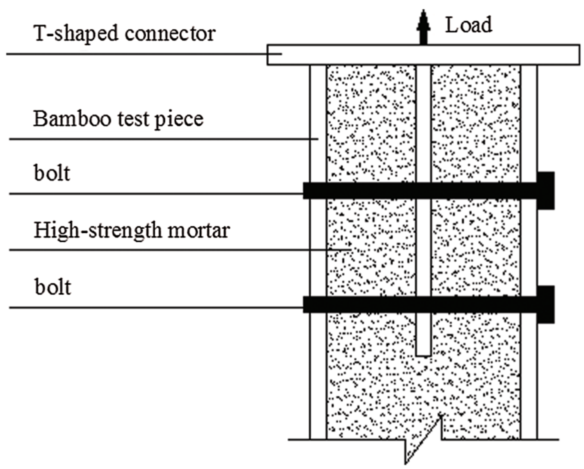

Figure 6: Double bolt grouting combined node [109]

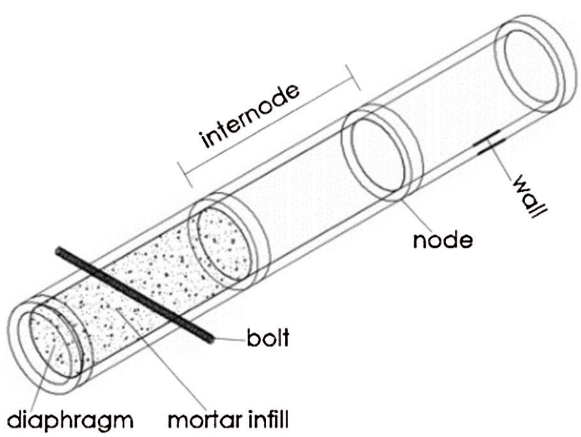

Figure 7: Metal fastener connection [110]

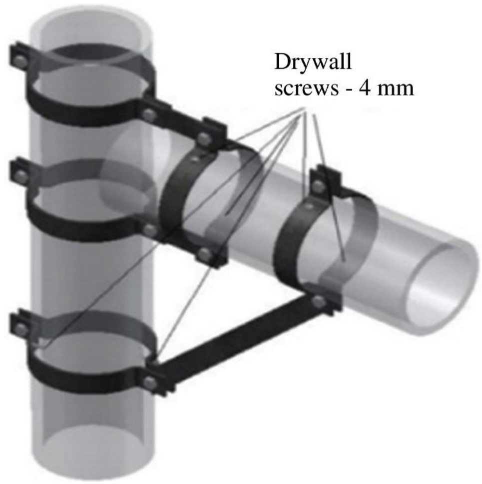

Figure 8: Steel half-rings connection [111]

elements whereas the lower chord is made up of steel members with a hollow cross-section. The truss structure uses steel connection nodes. A conservative, viscous damping ratio around 1.5% for the bending-type mode is suggested in GluBam truss structures with steel bolted connections, whereas conservative values between 0.5% and 1.5% (mean value equal to 1%) are recommended for all the modes.

Albermani et al. [113] designed a special *polyvinyl chloride* (PVC) joint designed for bamboo double layer grids (DLGs). Experimental studies have shown that the new PVC joint system can be used in practice for constructing lightweight, medium-span bamboo DLG structures with excellent structural and aesthetic aspects.

Villegas et al. [114] designed a new joint to connect *G. angustifolia* slats based on the ductile behavior of the material under compression along the thickness of the culm or the radial direction. The joint connects two *G. angustifolia* (GA) slats using two small curved steel plates, a bolt, and a nut, which are used to apply a high compressive deformation in the radial direction.

The mechanical properties of different bamboo node connections were examined; however, the connections were made of nonrenewable resources. Very few studies have investigated the coordination between deformation and corrosion in different materials; therefore, the standardization of joints is difficult to achieve. There is no universal standard design method for joints; hence, it is difficult to popularize and apply them on a large scale.

7 Bamboo Artificial Boards

According to Sharma et al. [115], the performance of artificial bamboo products can reach or exceed that of wood products, and the beam section can be optimized, taking into advantage the high bending strength to density ratio. According to Wu et al. [116], bamboo artificial boards mainly include woven bamboo plywood, composite plywood with bamboo mats and bamboo curtains, bamboo laminates, bamboo plywood, and high-strength coated bamboo plywood. According to Wei et al. [117], bamboo curtain plywood can be used as walls and floor slabs; bamboo laminates can be used as frame columns, frame beams, and wall panels; and bamboo scrimber can be used as frame columns and frame beams.

Huang et al. [118] studied the moist heat performance of bamboo building envelopes in high-temperature and humid areas, and found that using bamboo scrimber as the inner layer of the second layer structure, the bamboo laminate as the third layer structure, and the bamboo particle board as the sandwich panel manifested the best performance. However, a moisture-proof layer needed to be provided on the outside. The multilayered, independent, enclosed air layer was better than the single air layer with the same total thickness, and the thermal insulation effect of the thermal insulation layer provided inside the thermal insulation cavity was found to be excellent.

Lv et al. [119] conducted a full-scale experimental study on bamboo scrimber columns and laminated bamboo beams, and calculated the ultimate elastic strength and ultimate strength of bamboo scrimber pillars to be 34.3 and 53.0 MPa, respectively, and the bending strength and elastic modulus of the laminated bamboo beam to be 36.8 and 10000 MPa, respectively.

7.1 Bamboo Plywood

Bamboo plywood refers to plates made by processing raw bamboo into bamboo pieces (not fibers), and then pressing them with adhesives or various other techniques.

According to Fang et al. [120], the biomass utilization rate of common engineered bamboo products is low, and their binder content is relatively high. The bamboo flattening technology is used to flatten bamboo rods through indentation, grooving, and cutting under saturated, high-pressure steam. Zhang et al. [121] studied the softening and flattening of bamboo materials, and analyzed the influence of wall thickness, slub, bamboo green, the ratio of wall thickness to cavity, and bamboo pole parts on the flattening of bamboo materials.

Guan et al. [122] processed bamboo materials by cold plasma in a vacuum reaction chamber and then prepared over-laid laminated bamboo lumber (OLBL) by hot pressing. It was found that by properly arranging the radial bamboo curtains the density of the OLBL could be reduced by about 20% (about 850 kg/m^3). Moreover, the impact fracture section was mainly formed in the slub, which was relatively smooth. Due to its low density and irregular VB arrangement, the slub had a lower strength. Chow et al. [123] optimized the laminate orientation of the laminated bamboo structure and cut a 5-mm-thick laminated bamboo sheet at different inclination angles (0°, 5°, 10°, 15°, 30°, 45°, 60°, 75°, and 90°) to make rectangular bamboo pieces of 220 mm × 25 mm size. The polyurethane adhesive was used to glue these bamboo pieces together with a coating (300 g/m^2), and the two-layer laminated bamboo was manufactured by clamping at a pressure of 0.6 MPa for at least 8 h. It was observed that unidirectional lamination yielded the maximum strength, and cross-lamination caused thickness accumulation and quasi-two-dimensional isotropy. Brito et al. [124] studied the effects of heat treatment on the physical and mechanical properties of GluBam and asserted that the treatment resulted in loss of quality of the bamboo. At 160°C, there was an increase in the dimensional stability of the heat-treated bamboo glulam with resorcinol-formaldehyde; however, there was a decrease in the material mechanical strength values. Xu et al. [125] used the steady-state test method to determine the stress-strain relationship, and the reduction factors of strength and elastic modulus of laminated bamboo in different directions in the temperature range of 20°C–280°C; they found that, in the proposed temperature range, the compressive stress-strain curve of the laminated bamboo was nonlinear (plastic) and that the tensile constitutive relationship was approximately linear (fragile). Moreover, the compressive strength and modulus of the laminated bamboo gradually decreased with increasing temperature. The strength of parallel specimens was much higher than that of the vertical specimens. Ramage et al. [126] studied the thermal relaxation of bamboo laminates and pointed out that thermal relaxation caused viscoelastic changes under controlled and local heating. Therefore, it is appropriate to use the temperature at which the stiffness starts to decrease (150°C) as the lower limit temperature for bamboo sheet bending. When the temperature reaches 250°C, the material will undergo some thermal degradation. Yang et al. [127] studied the effects of density and heat treatment on the physical and mechanical properties of unidirectional, circular bamboo stick plates and found the optimal density of unidirectional, circular bamboo stick plates to be 1000 kg/m^3 and the optimal heat treatment temperature to be 155°C.

Penellum et al. [128] studied the relationship between the laminated bamboo fiber volume fraction and flexural stiffness; they found that the higher the fiber concentration, the higher was the bending stiffness of the pressed component. Li et al. [129–134] studied the axial and eccentric compression mechanical properties of laminated bamboo columns and the bending performance of laminated bamboo beams. Zhang et al. [135] observed that the bending performance, stiffness, and ductility of laminated bamboo beams were significantly increased when pressed with aramid fiber-reinforced polymer (AFRP) on their upper and lower sides. When the fabric ratio reached 0.72%, the stiffness increased by 15%. Li et al. [136] studied the compression behavior of parallel bamboo strand lumber under quasi-static and falling weight impact loads and observed that the maximum deformation and kinetic energy absorption were strongly dependent on the impact velocity. Li et al. [137] studied the compression characteristics of parallel bamboo wires under static loading and observed that the compressive strength parallel to grains was 2.1 times that perpendicular to grains, the compressive elastic modulus parallel to grains was 3.64 times that perpendicular to grains, and the compression ratios in these two compression directions were equal. The compression parallel to grains had better ductility than that perpendicular to grains.

Ge et al. [138] used the antibacterial properties of industrial bamboo vinegar (IBV) and the photocatalytic degradability of TiO_2 to pretreat bamboo materials and processed them into nonvolatile, antibacterial biological boards (NVABBs) consisting of 2% TiO_2 and 1% bamboo charcoal. The average density was 0.96 g/cm^3. Hot pressing at 170°C for 15 min increased the thermal stability of the NVABBs and IBV pretreatment for 10 min enhanced their antibacterial properties.

Guan et al. [139] found that carbonized plywood had a higher oxygen index than untreated plywood. Carbonized plywood fulfilled the standard of Class B1 flame retardant materials and had good flame retardant properties.

Reynolds et al. [140] studied the properties of an embedded tenon-and-mortise structure connection between the bamboo laminates and wood and asserted that the failure modes of bamboo laminates and wood were shear plug failure and splitting, respectively.

The processing and mechanical properties of bamboo plywood have been investigated extensively; however, different processing technologies result in a large difference in the performance. No uniform standard for promotion and application has yet been described, and only very few studies on the durability of bamboo-based artificial boards under the action of different adhesives are available.

7.2 Bamboo Scrimber

Bamboo scrimber is a kind of biomass composite material that is used to cut, soften, and unravel the bamboo into fiber bundles, and then perform drying, sizing, arranging preforms parallel to the fibers, and hot pressing.

Jin [141] regarded bamboo as a composite material consisting of fibers and a matrix and studied the stress-strain behavior of the bamboo fiber bundles and the thin-walled tissue matrix during the bamboo fiber rolling process. Lin [142] noticed that the amount of glue used in the cold pressing process had a significant effect on the bonding strength and expansion rate of bamboo scrimbers. The best result was obtained when the amount of glue was 10%, and the best mechanical properties were achieved when the moisture content of the bamboo bundle was 12%. Moreover, the higher the density of the bamboo scrimber, the better the performance index. Yu et al. [143] used the phenol formaldehyde (PF) resin to impregnate bamboo fiber bundles to prepare bamboo scrimbers, and studied the effects of the resin content and density on their physical and mechanical properties. It was observed that under the optimal parameters of 16% PF and 1.30 g/cm^3 density, the water absorption rate of bamboo scrimbers was 2.35%, and the thickness and width of swelling were 2.09% and 0.78%, respectively. The bending strength, modulus, and the shear strength were 310.0 MPa, 29.7 GPa, and 28.2 MPa, respectively. With the increase in the resin content and density, most properties except for bending modulus were improved. Furthermore, the thickness and the width were greatly affected by the resin content, and the water absorption capacity and the mechanical strength were greatly affected by density. According to Sánchez et al. [144], bamboo fibers have a low moisture content and an average density (0.75 g/cm^3) when compared with other plant fibers; these properties are conducive to the bonding of fibers and the matrix, improving the dimensional stability of the composite materials. Alkali treatments can change the crystallinity and morphology of fibers, increase the surface roughness, improve the adhesion to resins, and reduce the risk of delamination.

Kumar et al. [145] studied three different types of bamboo scrimbers with densities in the range of 800–1200 kg/m^3. The tensile strength, compressive strength, shear strength, flexural strength, elastic modulus, and water absorption capacity of the scrimbers changed significantly with density and fiber orientations. According to Shu et al. [146], the strength-to-weight ratio of bamboo scrimbers is 2.74–2.94, which is slightly higher than that of ordinary steel and much higher than that of wood and concrete. Takeuchi et al. [147] investigated the shear strength and crack mode of bamboo scrimbers through experiments and numerical simulations and posited that the shear strength of the bamboo scrimber was 6.0 MPa and the standard deviation was 0.6 MPa when fibers were parallel to the loading direction. When fibers were parallel to the loading direction, the crack was parallel to the loading direction, and when they were perpendicular to the loading direction and did not intersect with the reduction plane, the crack was inclined at 45° to the loading direction. Furthermore, when fibers were perpendicular to the loading direction and intersected with the reduction plane, the crack was perpendicular to the loading direction and formed multiple strips. Zhao et al. [148] studied the bending resistances of bamboo scrimbers with four different diameters and five holes and observed that the drilling holes reduced the bending resistance. The larger the hole diameter, the higher was the decrease in the bending resistance. When the hole was positioned away from the center in the longitudinal direction, the bending characteristics of the scrimbers first decreased and then increased, and when the hole was positioned away from the center in the vertical direction, the bending characteristics decreased gradually. The coefficient of variation of MOE was between 0.66% and 7.17%, and the coefficient of variation of MOR was between 2.86% and 14.99%.

Liang et al. [149] found that carbonized bamboo scrimbers degraded cellulose and hemicellulose due to the high-temperature treatment of bamboo bundles. After 2 h of boiling, the elastic modulus, static bending strength, and 24 h of water absorption thickness expansion rate of the scrimbers decreased and the internal bonding strength increased. Bamboo scrimbers have good corrosion resistance. Xu et al. [150] studied the compression and tensile properties of bamboo scrimbers at high temperatures through experiments. The tensile stress-strain curve parallel to the fiber was found to be linear. When the temperature increased from 20°C to 270°C (except at 200°C), the tensile strength and modulus decreased gradually. The tensile stress-strain curve perpendicular to the fiber direction was nonlinear, and the ultimate strength was very small. Cui et al. [151] pointed out that the specific heat of bamboo scrimbers manifested two peaks between 20°C and 500°C and mutation between 100°C and 120°C. The relative density ratio decreased with increasing temperature. The thermal conductivity of the scrimbers was higher than that of glulam and wood, and increased in the temperature range of 20°C–100°C and decreased in the temperature range of 100°C–300°C. The electrical conductivity was found to be in the range of 1.26–1.63.

According to Zhang et al. [152], bamboo has poor mold resistance but good decay resistance. Heat treatment and bleaching can improve the decay resistance of bamboo but have a little effect on mold resistance. Zhong et al. [153] studied the flexural performance of a reinforced bamboo composite beam (Fig. 9) and observed that steel bars and bamboo were firmly formed a composite structure. The superposition principle was used to simplify the mechanical model and predict the deflection and load capacity of the structure. The coefficient of variation of the tension strength was between 9.71 and 12.34%, the coefficient of variation of the compression strength was between 9.35 and 11.08%, and the

Figure 9: Bamboo composite beam reinforced with steel bars [153]

coefficient of variation of the shear strength was between 13.10 and 15.69%. Wei et al. [154] embedded fiber-reinforced polymer (FRP) composite sheets in the internal tensile zone to improve the bearing capacity of bamboo beams (Fig. 10). The coefficient of variation of the tensile strength was between 9.3 and 16.7%, the coefficient of variation of the compression strength was between 5.6 and 19.6%, the coefficient of variation of MOE was 5.4%, and the coefficient of variation of MOR was 6.2%. Shu et al. [155] used bamboo scrimbers as the main structural member to build a two-story bamboo museum.

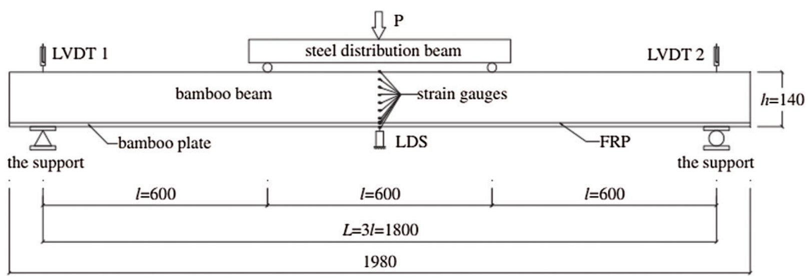

Figure 10: FRP-reinforced bamboo beam [154]

The processing and mechanical properties of bamboo scrimbers have been studied extensively. China generally adopts laterally restricted processing to suppress bamboo scrimbers, while other countries generally use the unconfined compression. The laterally restricted processing technology provides better performance. However, the durability and mechanical properties of bamboo scrimbers under the long-term effects of temperature and humidity have not yet been explored. How to reduce the coefficient of variation of bamboo scrimbers requires further research. Very few practical cases have used bamboo scrimbers as the main force component in buildings, and there is a lack of systematic design and construction standards for their promotion and application.

7.3 Bamboo Binderless Plywood

Binderless plywood is formed by self-gluing under certain conditions by the chemical composition of the material itself.

Wu [156] studied the characteristics of a binderless, wet, medium density fiberboard (MDF). Cao [157–160] used infrared spectroscopy to study the bonding mechanism of a dry binderless fiberboard and scanning electron microscopy to study the water resistance of the plate. Wang [161] treated the residue of bamboo processed with laccases to press a binderless bamboo particleboard and analyzed the bonding mechanism. Wang [162] prepared a binderless particleboard by the hemicellulose/laccase synergistic pretreatment of small-leaf dragon bamboo particles. Lv et al. [163] studied the effects of hot-pressing temperature, hot-pressing time, and slab moisture content on the mechanical properties of bamboo fiberboards glued with a modified soybean protein adhesive. The best properties were obtained under the following optimal conditions: hot-pressing temperature = 167°C, hot-pressing time = 7.8 min, and slab moisture content = 34.2%. Under these conditions, the static flexural strength, elastic modulus, tensile strength, and thickness expansion rate of the bamboo fiberboards were 16.5 MPa, 1032.6 MPa, 10.4 MPa, and 31.0%, respectively. Nguyen et al. [164] optimized the hot-pressing conditions for bio-insulated fiberboards made of bamboo fibers and protein-based bone glue. It was observed that under the hot-pressing time of 15 min, hot-pressing pressure of 150 kgf/cm^2, and hot-pressing temperature of 160°C, the 30% w/w bone glue parameter could be used as a good internal adhesive for bamboo fiberboards to achieve the best mechanical properties and water resistance.

Yue et al. [165–168] used steam blasting to process bamboo fibers to form binderless fiberboards. It was found that steam blasting had a good effect on bamboo fiber separation. The fiber diameter was reduced, and the longer the holding time, the better the fiber dispersion effect and the flexibility. The steam explosion treatment could effectively promote the degradation of hemicellulose and the separation of lignin in bamboo fibers, thus increasing the specific surface area and improving the morphological structure of the bamboo fibers. At a steam explosion pressure of 3.0 MPa and a holding time of 180 s, the maximum static bending strength of the bamboo binderless fiberboards was 15.9 MPa, maximum internal bonding strength was 0.48 MPa, thickness swelling was reduced by 73%, and the water absorption was reduced by 44%.

The production of binderless plywood from bamboo fibers has been studied widely. Chemical agents are costly, cause environmental pollution, and the water resistance of the as-prepared plates is very poor. The enzyme-activated method is used to produce binderless plates in order to reduce pollution; however, the method is relatively cumbersome. The water pressure resistance and strength of binderless plywood compressed by the common hot-pressing method and the steaming hot-pressing method are not good.

Bamboo fibers are prepared by steam blasting and then pressed into binderless plywood. Currently, a single blasting raw material is generally used. Although the physical and mechanical properties are good, the density of as-prepared boards is large, and the performance gets reduced with the decrease in the density.

8 Comparison of the Performance of Materials

Some distinctions exist inevitably between the statistical material properties (Tab. 1) and the true properties of the wood or bamboo products available in markets. For obtaining the mechanical properties of the products in markets, it is more reliable to obtain the data from the material tests or from the material manufacturers directly.

Tab. 1 shows a comparison of some of the performance characteristics of bamboo and engineered bamboo. The distinctions between statistical material properties and true properties do not affect the comparison between bamboo and wood, engineered bamboo and engineered wood.

It may be seen from Tab. 1 that the density of bamboo is comparable to that of conventional wood, but the mechanical properties are superior to those of conventional wood, indicating that bamboo is advantageous over wood. Therefore, it is worth investing in the further research on raw bamboo.

Comparing engineered bamboo with glued wood, it is found that the density of engineered bamboo is relatively high, indicating that they need to take measures to reduce the size (such as improving processing technology, using high-efficiency adhesives, etc.).

The mechanical properties of engineered bamboo and glued wood are equivalent, indicating that engineered bamboo can be used as a substitute for glued wood. However, because the tensile, compressive, and shear failures render the engineered bamboo brittle, it is important to consider the safety factors during use.

Table 1: Comparison of the mechanical properties of bamboo and engineered bamboo

Material type	Density (g/cm^3)	Compressive strength (MPa)	Tensile strength (MPa)	Shear strength (MPa)	Bending strength (MPa)	Flexural MOE (MPa)
Bamboo	0.68 [61]	64–80 [82]	300 [77]	10–17 [81]	62–151 [82]	7071–10487 [82]
Larix principis-rupprechtii	0.6–0.7 [169]	15 [170]	9.5 [170]	1.6 [170]	17 [170]	10000 [170]
Pinus sylvestris var. mongolica	0.4–0.5 [169]	10 [170]	8 [170]	1.4 [170]	13 [170]	9000 [170]
Chinese fir	0.355 [171]	28.8 [172]	7.5 [170]	1.4 [170]	49.3 [172]	9000 [170]
Oak	0.8–0.9 [169]	16 [170]	11 [170]	2.4 [170]	17 [170]	11000 [170]
Birch	0.6–0.7 [169]	14 [170]	10 [170]	2 [170]	15 [170]	10000 [170]
GluBam	0.89 [173]	51.0 [173]	82.0 [173]	4.6 [173]	99.0 [173]	10400 [173]
Glulam	0.484 [173]	26.1 [173]	53.0 [173]	6.2 [173]	46.5 [174]	11438 [174]
Bamboo scrimber	1.13	64.13 [175]	112.5	16.5	106.63 [175]	23300
Wood scrimber	0.885 [173]	101 [173]	108 [173]	17 [173]	140 [173]	22310 [173]
LWPC	0.6 [176]	–	31.47 [176]	–	40.36 [176]	11490 [176]
LVL	–	13.8 [175]	8.5 [177]	2.0 [177]	14.7 [175]	11000 [177]
CLT	0.492 [173]	18.3 [173]	–	–	22.42 [173]	11670 [173]

Note: All properties in the table refer to those in the parallel-to-grain direction, except for CLT, for which the in-plane compressive strength along the major strength direction is provided.
In GluBam, strips are arranged 80% in longitudinal direction and 20% in the transverse direction, with a thickness of 30 mm.
Glulam is made from Douglas fir and has a thickness of 300 mm.
Bamboo scrimbers impregnate bamboo fiber bundles with PF resin at normal pressure, with a dipping concentration of 16% and a dipping time of 20 min; the fiber bundles are then dried at 50°C to a moisture content of 12%, and pressed using a cold compression molding process with a pressure of 60 MPa.
Wood scrimbers are made from fast-growing poplar and have a thickness of 20 mm.
Laminated wood plastic composites (LWPC) are obtained by laminating wood veneer (2-mm-thick poplar veneers) and plastic sheets (0.3-mm-thick thermoplastic sheet with a PP and PE weight ratio of 1/1) together.
LVL is made from Douglas fir rotary cutting board.
CLT is made from Canadian hemlock and has a thickness of 175 mm.

9 Conclusions and Recommendations

This paper systematically summarizes the research status of bamboo as building materials from the aspects of bamboo composition, gradation, material properties, bamboo building components, connection nodes, and use of artificial boards. On this basis, some constructive suggestions are put forward for further study of bamboo in the field of architecture.

(1) As far as raw bamboo is concerned, the bamboo can be divided into multiple areas according to the distribution of bamboo materials, and the study can be carried out in units of plots, and the classification of bamboo materials can be further studied. To solve the sharp defects of bamboo, cutting the bamboo sections into sub-sections and then lengthening the bamboo sections of the same specifications to form standardized raw bamboo building components, is considered.

The connection and extension of bamboo segments should be connected with biomass materials as much as possible to maintain the biomass characteristics of bamboo. To study the coordination between the deformation of bamboo and wood, the welding technology of bamboo and wood needs to further study its welding mechanism, and put forward the moisture-proof treatment technology of bamboo and wood welding nodes from the mechanism. Based on the principles of simple manufacturing and convenient installation, the node connection needs to be standardized.

On the basis of the standardization research of structural members and connection nodes, the basic characteristics of bamboo materials can be combined with building structure design and construction specifications, so as to put forward the standardized design and construction methods of bamboo buildings, which is convenient for the large-scale promotion and application of bamboo-based materials in the construction field.

By analyzing the differences of the main component of the same bamboo material in different regions and bamboo pole positions, the differences in mechanical properties of the bamboo in the radial and tangential directions, and the differences of mechanical properties between the nodal and internodes, the cracking mechanism of the bamboo material can be studied, and the measures to prevent bamboo cracking can be put forward. The relationship between the degree of bamboo cracking and its mechanical properties can be analyzed to establish the relationship between bamboo cracking and mechanical properties under local damage.

The environmental protection treatment technology and methods of various kinds of biomass can be studied to improve the anti-corrosion and anti-mold effects of bamboo, and reduce the current environmental pollution caused by anti-corrosion and anti-mold agents.

Further research on 3D scanning and other nondestructive testing techniques and their use to accurately determine the mechanical properties of bamboo should be undertaken, so as to better realize the application of raw bamboo classification.

(2) As far as engineering bamboo is concerned, it is necessary to further study its processing technology to maintain or improve its existing performance while reducing the amount of sizing as much as possible. On this basis, the processing technology with smaller coefficient of variation is selected as the technical standard. At the same time, the long-term effects of different adhesives under different temperature, humidity and other environments on engineering bamboo durability and changes in stress and strain can be studied.

Binderless technology is the future research direction and must be strengthened. Mixed binderless technology and its processing technology optimization between different biomass materials can be studied so as to take advantage of the natural characteristics between different materials, realize the complementarity between composite materials, and improve the performance of binderless plywood.

Under certain processing technology standards, considering the time reduction of material performance, we can further study the method of using engineering bamboo as the main stress component of buildings, and gradually formulate corresponding design and construction technical standards.

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