A Review of Research on Laminated Bamboo Wood Structures

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Abstract

Bamboo and wood are among the earliest natural sustainable materials used by humans and have a long history of application in construction. After the Industrial Revolution, due to the superior durability, low cost, and ease of large-scale, high-efficiency production and construction of concrete structures, bamboo and timber structures gradually failed to meet the modern city's demands for high-rise buildings and large-span structures. As a result, bamboo and timber structures were largely replaced by concrete structures in modern construction.In the context of global climate change and the significant pollution caused by rapid development, sustainable development has become a critical issue in contemporary society. The construction industry is now facing an urgent need to transition towards green, low-carbon, and sustainable practices. This shift highlights the potential for bamboo and wood, as renewable and eco-friendly materials, to regain prominence in modern construction while addressing environmental challenges.Bamboo-wood composite structures have a promising future.

Keywords

Glued Laminated Bamboo; Laminated Veneer Lumber; Bamboo Wood Structures; Glubam.

1. Introduction

In the history of world architecture, ancient Chinese architecture, particularly timber-framed structures, holds a significant position due to its unique material selection, ingenious structural design, and distinctive stylistic artistry. These buildings have been praised as "frozen poetry and three-dimensional paintings." From the Dule Temple of the Tang Dynasty and the Nanchan Temple on Mount Wutai, to the Wooden Pagoda of Ying County from the Liao Dynasty, and the Forbidden City in Beijing during the Ming Dynasty, all are exemplary timber-framed structures. Compared to materials such as steel, concrete, and stone, wood is a naturally renewable resource with advantages such as being lightweight yet strong, easy to source, and environmentally friendly.In the 1980s [1], as China's infrastructure construction rapidly expanded, timber resources became severely depleted, leading to a dramatic increase in cement and steel production. Bamboo and timber structures were quickly replaced by reinforced concrete, and for the following two decades, modern timber structures remained largely stagnant. During this period, China experienced rapid economic development and achieved remarkable success in infrastructure construction. However, this progress came at a great cost-massive consumption of resources and energy, as well as severe environmental pollution. Statistics show that China emits approximately 1 billion tons of CO_2 per year and generates several hundred million tons of construction waste annually. Such extensive construction activities directly endanger public health and hinder national sustainable development. Therefore, entering the 21st century, it has become imperative to adopt green, low-carbon building structures that align with the principles of sustainable development.

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Figure 1. Yingxian Wood Tower

Figure 2. Nanchan Temple

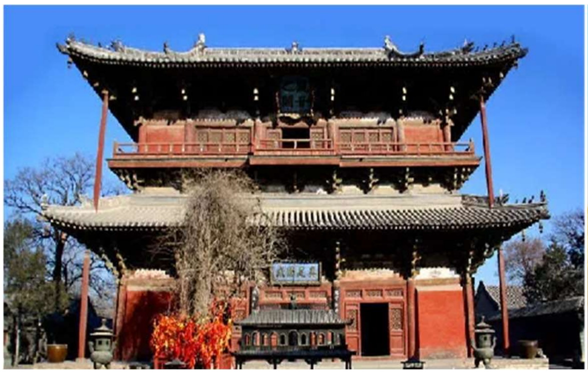

Figure 3. Dule Temple

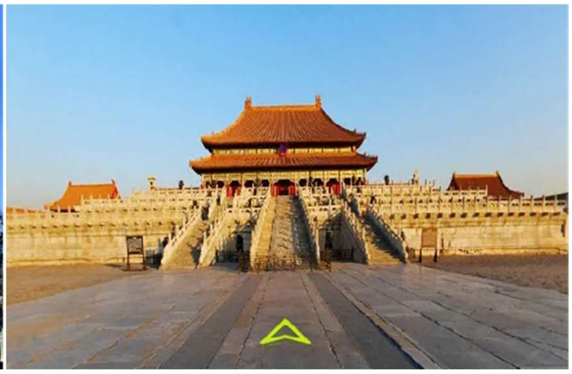

Figure 4. the Imperial Palace

The development of green and low-carbon buildings is not a temporary measure but an inevitable path toward sustainable development. According to data from the United Nations Environment Programme (UNEP), the construction industry consumes over 30% of global energy and accounts for nearly 40% of total global carbon emissions. As the country with both the largest existing building stock and the highest annual new construction volume globally, China faces an urgent need to improve energy efficiency and reduce emissions in its building sector. Green and low-carbon practices represent the main theme of our era, and green buildings are a global trend in architectural development.

When it comes to green and low-carbon structures, bamboo and timber structures are often the first to come to mind. Compared to concrete construction, timber construction is undoubtedly more environmentally friendly. Timber is renewable, recyclable, and can be dismantled and reused. Sourced directly from nature, wood possesses characteristics such as being eco-friendly, fresh, aesthetically pleasing, natural, and healthy, without the hazards associated with chemical substances or radioactive materials, thus promoting physical and mental well-being. In developed Western countries, modern timber structures have been widely adopted in various construction projects. Laminated veneer lumber (LVL) represents a major direction in modern timber construction, reducing defects such as knots, cracking, and warping while improving the utilization rate of wood. Cross-laminated timber (CLT), which originated in the 1990s, is a type of engineered wood that is low-carbon and environmentally friendly, offering excellent mechanical properties in both longitudinal and transverse applications [2]. CLT has been extensively used in building structures in Western countries and is gradually replacing traditional concrete construction. However, China remains a country with relatively scarce forest resources. For a long time, importing timber and planting fast-growing artificial forests have been the two primary approaches to addressing timber shortages [3]. Importing timber increases costs and exposes domestic markets to foreign monopolies. Currently, China’s widely planted fast-growing artificial forests have short growth cycles but contain lower

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amounts of wood fiber, resulting in loose textures, numerous knots, and poor mechanical properties. Their elastic modulus and strength often fail to meet engineering requirements. Structural timbers such as pine and fir require decades to mature, making it difficult to meet the massive demand [4]. Therefore, there is an urgent need to find a low-carbon, eco-friendly material to replace timber.

China leads the world in bamboo production, and bamboo is currently the only green material capable of substituting for timber. With a total bamboo forest area of 4.2 million hectares, China boasts the widest variety of bamboo species, the largest bamboo forest area, and the richest bamboo resource reserves in the world [5]. Bamboo resources are primarily distributed in subtropical regions south of the Yangtze River. Bamboo matures in just 3–5 years and stores carbon dioxide during its growth, making its short growth cycle and environmental improvement capabilities distinct advantages over other materials. Numerous studies have shown that engineered bamboo materials exhibit high strength, good flexibility, and excellent physical and mechanical properties, meeting various requirements for building structures in terms of material mechanics and dimensions. Both bamboo and timber are natural biomass materials with similar properties in many aspects, including bonding performance and deformation capacity. They maintain consistent deformation under load and can share forces effectively [6]. Based on research into modern bamboo structures, various forms of structures have been designed and constructed, including drivable modern bamboo bridges, bamboo villas, automobile impact laboratories, and heavy-duty frame buildings, as shown in the figure.

In this context, Xiao Yan et al. [7] combined the orthotropic layering concept of Cross-Laminated Timber (CLT) and further proposed Cross-Laminated Bamboo Timber (CLBT), also known as orthotropic or cross-laminated bamboo timber. They conducted research and experimental validation on the mechanical performance of CLBT components, including beams, plates, and columns [8-11]. CLBT not only addresses the issues of scarce wood resources and severe environmental pollution caused by traditional building materials but also improves material deficiencies such as poor shear resistance and low tensile strength in wood, as well as weak plastic deformation and low compressive strength in bamboo. By fully utilizing the excellent properties of both materials, CLBT achieves complementary performance. Compared to using wood or bamboo alone as structural components, laminated composite components offer significant advantages and have broad application prospects in modern architectural structures.

2. Current Status of LVL Research

Laminated Veneer Lumber (LVL), also known as single-board laminated material [12], originated in North America in the 1970s and has since been widely adopted in both North America and Europe. LVL is a structural material produced by rotary-cutting thick veneers, applying adhesive, layering them along the grain direction, and hot-pressing them into a cohesive unit. As an important engineered wood material, LVL is characterized by its high strength, excellent dimensional stability, good machinability, and superior bending performance [13]. It is extensively used in residential and commercial wooden structures. The production of high-strength structural LVL requires high-quality, strong wood. However, China faces significant shortages of timber resources, with a prominent supply-demand imbalance and a severe lack of large-diameter, high-quality wood. Developing fast-growing plantation forests can help alleviate this shortage to some extent. LVL not only retains the ideal natural properties of wood but also disperses defects, resulting in uniform material strength that surpasses solid wood itself. This enables the efficient utilization of low-quality plantation wood. Depending on their application, LVL can be classified into two categories: 1) non-structural LVL; and 2) structural LVL. The former exhibits high strength and dimensional stability and is commonly used for non-load-bearing components such as furniture. The latter demonstrates excellent structural stability and corrosion resistance and is often employed in applications like beams and trusses.

Currently, there is limited research on the shear performance of LVL. Most studies focus on LVL's behavior under bending and compression loads, as well as finite element numerical simulations of LVL components.

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Wang[14] conducted unidirectional and low-cycle repeated tests on poplar LVL frames to investigate the lateral resistance performance of different frame configurations under two types of loading conditions. By establishing a finite element model and considering material and geometric nonlinearities, the study simulated the effects of parameters such as axial compression ratio and base shear force on the load-bearing capacity and deformation capability of reinforced steel frames connected with embedded bars. According to the results, frames connected with bolted steel plates exhibited higher load-bearing capacity compared to those connected with embedded bars. Additionally, poplar LVL frames combined with steel infill plates demonstrated superior lateral resistance performance compared to pure frames.

Zhao [15] enhanced poplar LVL with glass fiber reinforcement and found that placing glass fiber fabric on the outer layers significantly increased the modulus of elasticity (MOE). This study placed bamboo bundle veneers and bamboo mat veneers on the outer layers and combined them with poplar veneers to create structural bamboo-wood composite laminated materials, thereby improving the mechanical properties of poplar LVL.

Xu[16] conducted experiments and comparative analyses on the bending and creep performance of poplar LVL with varying compression ratios and cross-sectional structural designs. The findings indicated that increasing the density of the wood in LVL and optimizing the stacking density coefficient could relatively improve and enhance its mechanical and anti-creep bending properties.

Feng[17] conducted experimental research on various factors such as pressure, pressing temperature, pressing time, and adhesive application to explore their direct impacts on the dynamic modulus of elasticity (MOE) of poplar LVL. The study found that these factors all influence the performance of poplar LVL and its dynamic MOE. Among them, pressing temperature had the most significant impact, followed by adhesive application and pressure, while changes in pressing temperature had the least effect.

Tian[18] et al. demonstrated that bamboo-wood composite LVL exhibits superior performance in terms of MOR (Modulus of Rupture), MOE (Modulus of Elasticity), HSS (Horizontal Shear Strength), and TSR (Tensile Strength Ratio) compared to poplar LVL. Wang[19] enhanced poplar LVL beams with carbon fiber fabric and discovered that vertical carbon fiber reinforcement significantly increased the stiffness and failure load of vertical LVL wood beams, thereby improving their load-bearing performance to a large extent. Wang et al. [20] studied the parallel/vertical grain bending strength, bending modulus of elasticity, parallel grain tensile strength, parallel grain shear strength, parallel grain compressive strength, and perpendicular grain compressive strength of domestically produced poplar LVL. Liu [21] et al. conducted experiments and analyses on the physical and mechanical properties of Italian poplar LVL materials. The results showed that Italian poplar LVL materials possess excellent physical and mechanical properties, with uniform material strength and a small coefficient of variation, making them suitable for use as load-bearing materials in building structures.

Zhong[22] performed high-temperature hot-pressing static analysis of LVL materials within the temperature range of 20°C to 225°C, investigating the effects of various temperature parameters and their distribution on the mechanical properties of LVL under static compression. The study found that the compressive elastic modulus and compressive strength of LVL materials significantly decreased as the temperature increased. Further research established a comprehensive linear relationship model between the compressive strength coefficient along the grain of LVL materials and temperature changes.

3. Current Status of Glued Bamboo Research

Since the 1980s, inspired by modern wood manufacturing technologies in developed countries such as Europe and America, China has gradually developed modern glued bamboo technology. Thick-slat Glubam and thin-slat Glubam, as two types of engineered bamboo materials under the Glubam system, differ in their manufacturing processes. Thick-slat Glubam is produced by pressing bamboo strips that are 5–8 mm thick either flat or side-by-side, while thin-slat Glubam is made by hot-pressing thinner bamboo strips of approximately 2 mm. Glued bamboo used as a construction material exhibits advantages such as minimal deformation, high hardness, excellent strength, and superior wear resistance. However, the application of glued bamboo as an engineering component remains largely in the research stage.

Some scholars have investigated the performance of glued bamboo combined with steel reinforcement and concrete. In studies focusing on glued bamboo beams and columns, more attention has been paid to the mechanical properties of glued bamboo beams than to those of glued bamboo columns. Only a few researchers have explored the behavior of glued bamboo columns under axial and eccentric compression. Among these, Xiao et al. [23] conducted axial compression tests on Glubam glued bamboo columns with varying slenderness ratios. Liu et al. [24] performed eccentric compression tests on glued bamboo columns with different eccentricities. The results showed that all specimens ultimately failed due to the initial rupture of tensile fibers near the mid-span. As the initial eccentricity increased, the ultimate load capacity of the specimens decreased, and the lateral deformation under the same load increased. During bending deformation, the lateral deflection curve of the specimens generally followed a half-sine wave, and the average strain distribution at the mid-span section was approximately linear, conforming to the plane-section assumption. Additionally, they proposed a calculation formula for the ultimate load-carrying capacity of glued bamboo columns under eccentric compression, which yielded results that matched well with experimental data. Naresworo et al. [25] conducted axial compression tests on three groups of Gigantochloa apus specimens with varying slenderness ratios.

Researchers from the Research Institute of Wood Industry of the Chinese Academy of Forestry, such as Liu , compared the standards GB/T 15780-1995 "Test Methods for Physical and Mechanical Properties of Bamboo" and JG/T 199-2007 "Test Methods for Physical and Mechanical Properties of Building Bamboo Materials" [26]. JG/T 199-2007 focuses on the physical and mechanical properties of defect-free small bamboo sheet samples and involves aspects such as sample preparation, testing equipment, and methods. However, there are significant differences between bamboo sheet tests and Glubam material tests in terms of sampling, specimen size, testing methods, and equipment. Therefore, this test method cannot fully apply to Glubam research.

In the field of glued bamboo materials abroad, Correal, J. from Colombia began his research earlier and conducted systematic studies. He investigated the mechanical properties of Colombian glued bamboo materials using the ASTM-recommended defect-free small wood sample testing method [27]. His results demonstrated that the mechanical properties of Colombian glued bamboo materials could rival those of the best local woods. While his research approach is worth referencing, the materials he studied differ significantly from Glubam in terms of raw materials, internal structure, processing methods, and finished product forms. Notably, the bamboo strips used in his glued bamboo materials were thicker (generally 7–10 mm), and the finished product dimensions were larger than those of Glubam boards.

Li et al. [28] studied the compressive properties of 24 laminated bamboo specimens from three different growth positions, each with a cross-sectional size of 100 mm × 100 mm. Through compression tests, they obtained load-strain and load-displacement relationships and reported detailed failure modes, compressive strength, and elastic modulus for all specimens. The results indicated that the average compressive strength increased with the height of the growth section, while the variation in compressive strength also increased with height. Li et al. [29] tested two types of glued bamboo beams made from differently pre-treated bamboo strips: one using 2 mm thick strips and the other using 5–6 mm thick strips. Full-scale beam tests revealed that the glued beams exhibited elastic brittleness similar to typical wood-based beams.

Xiao et al. [30] reviewed domestic and international research achievements on the mechanical properties, connection methods, and seismic performance of cross-laminated timber structures. They introduced the results of experiments on the mechanical and physical properties of cross-laminated bamboo timber (CLBT), including bending tests on CLBT panels and beams, axial compression tests on CLBT columns, and thermal and acoustic performance tests on CLBT walls. Based on higher-order shear deformation theory, they proposed an analytical model to estimate the deformation of CLBT beams and columns under corresponding loads, which was validated through experiments. Preliminary results indicated that CLBT possesses good mechanical properties and thermal insulation and soundproofing capabilities comparable to cross-laminated timber. Using domestically grown fast-growing poplar wood and Glubam glued bamboo to fabricate CLBT beams and panels yielded mechanical properties no less favorable than those of similar products made from imported wood. Thus, the development and application of CLBT can help better utilize China's fast-growing forest resources and abundant bamboo resources, promoting the use of biomass materials in construction toward achieving carbon neutrality.

Fan et al. [31] experimentally studied CLBT columns made from Glubam glued bamboo and SPF (spruce-pine-fir) wood, as well as CLT columns made solely from SPF wood. They analyzed changes in vertical strain, lateral strain, lateral deflection, and ultimate load capacity with varying slenderness ratios. By comparing CLBT and CLT, they examined differences in ultimate load capacity, failure modes, and failure mechanisms. Finally, they calculated the load-bearing capacity of the specimens using improved formulas referenced from domestic and international timber structure design standards and compared these results with experimental values.

4. Conclusion

(1) By combining bamboo with fast-growing economic tree species, bamboo-wood composite materials can not only achieve better mechanical properties but also effectively enhance structural quality, enabling the efficient utilization of green building materials.

(2) A series of studies have demonstrated that bamboo-wood composite structures possess excellent performance, offering broad application prospects in regions where bamboo resources are abundant but timber resources are limited.

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