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Research Progress and Application Prospects of Bamboo-Wood Composite Structural Materials

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Abstract

Aiming at the dual challenges of high carbon emissions in the global construction industry and the shortage of high-quality structural wood resources in China, this paper systematically reviews the research progress of Cross-Laminated Timber (CLT), Hybrid Cross-Laminated Timber (HCLT), Laminated Veneer Lumber (LVL) and glued bamboo (Glubam), with a focus on analyzing the mechanical performance optimization and engineering application status of bamboo-wood composite structures. Studies have shown that although fast-growing poplar LVL can effectively improve the utilization rate of fast-growing wood, its mechanical properties are still difficult to meet the requirements of high-end structures; while Glubam glued bamboo has become an ideal structural reinforcement material due to its excellent strength-to-weight ratio and environmental protection characteristics. Based on this, this paper innovatively proposes a new bamboo-wood composite structure scheme using fast-growing poplar LVL as the core layer and high-performance Glubam as the reinforced outer layers. This scheme can give full play to the performance complementary advantages of the two materials and significantly improve the overall mechanical properties of the composite material. The research results provide a new idea for the high-value utilization of bamboo and wood resources in China, and have important theoretical significance and engineering value for promoting the sustainable development of the green building industry.

Keywords

Bamboo-wood Composite Structure; Cross-Laminated Bamboo Timber (CLBT); Laminated Veneer Lumber (LVL); Glubam; Mechanical Properties; Green Building Materials

1. Introduction

Bamboo and wood, as the earliest natural and sustainable building materials developed and utilized by human beings, occupy a pivotal position in the history of architecture owing to their excellent mechanical properties, wide distribution range and outstanding durability. However, following the Industrial Revolution, concrete structures gradually replaced traditional bamboo-wood structures with their superior durability, economic efficiency and industrialized construction advantages, particularly in meeting the demands of modern urban high-rise buildings and long-span structures.

At present, under the dual challenges of global climate change and environmental pollution, the construction industry is facing an urgent need for transformation towards an eco-friendly development model. According to the latest data from the International Energy Agency (IEA), the construction sector consumes 36% of the world's total energy and contributes 39% of global carbon emissions. Traditional building materials such as steel and concrete not only exhibit significant energy consumption throughout their entire life cycle but also impose a heavy environmental burden due to their substantial carbon footprints. This situation has made the exploration of sustainable and low-energy alternative materials a critical breakthrough for the development of the construction industry.

Against this backdrop, bamboo and wood materials have regained extensive attention from both academia and industry due to their unique environmental advantages. As renewable carbon sink materials, they can not only effectively reduce the carbon emissions of buildings throughout their life cycle but also align with the development concept of circular economy. Through the innovative application of modern engineering technologies and the optimization of structural design, bamboo and wood are demonstrating their potential as mainstream building materials, providing new solutions to promote the green transformation of the construction industry.

In recent years, the research and application of Cross-Laminated Timber (CLT) have revolutionized the construction industry in countries with abundant wood resources and become a research hotspot in the field of new building materials and civil engineering. As a large-scale engineered wood product, CLT is fabricated by gluing multiple layers of solid wood sawn timber in an orthogonally staggered manner. This unique structural design not only significantly improves the dimensional stability and load-bearing performance of the material but also makes it an ideal solution for multi-story buildings and long-span structures. Compared with traditional sawn timber, CLT effectively overcomes the inherent defects of wood such as knots and cracks through the orthogonal lamination process. Meanwhile, its prefabricated characteristics greatly shorten the construction period and enhance the level of engineering quality control, perfectly matching the development requirements of modern modular construction. CLT also possesses outstanding advantages including light weight, ease of processing, and excellent thermal and acoustic insulation properties.

Nevertheless, high-quality wood resources in China are mainly distributed in the northeast and southwest regions, and restricted by strict forest protection policies, their supply capacity is insufficient to meet the demand for large-scale CLT production. This status quo has prompted researchers to shift their focus to the development and utilization of indigenous wood species. How to develop high-performance CLT products based on domestic existing resources has become an important research direction at present. In this context, exploring an innovative development path of CLT materials adapted to China's national conditions is of great practical significance for promoting the development of green buildings.

To break through the limitations of traditional CLT in raw material acquisition and meet diverse engineering requirements, researchers have innovatively developed a new type of composite material, namely Hybrid Cross-Laminated Timber (HCLT)[5-12]. This material achieves synergistic optimization of material properties by orthogonally combining and gluing various wood species and engineered wood products. Commonly used wood species include Spruce-Pine-Fir (SPF), while engineered wood products cover Laminated Veneer Lumber (LVL), Laminated Strand Lumber (LSL), Oriented Strand Lumber (OSL) and Construction Oriented Strand Board (COSB), etc. The uniqueness of HCLT lies in its high flexibility: the wood species and structural configuration can be adjusted according to specific engineering requirements to realize performance complementarity between different materials. More importantly, HCLT allows the incorporation of low-grade or fast-growing wood, thereby reducing the dependence on high-quality wood, improving resource utilization efficiency and lowering production costs. This not only helps alleviate the shortage of high-quality wood resources but also significantly enhances the overall economic benefits and environmental friendliness of the material. In this way, HCLT not only inherits the advantages of traditional CLT such as excellent dimensional stability and load-bearing capacity but also further expands its application scope and applicability. This innovative material provides a more sustainable and cost-effective solution for the construction industry, especially for projects with strict material and cost control requirements.

China has effectively alleviated the shortage of wood resources by developing artificial fast-growing forests. Fast-growing forests are characterized by a short growth cycle (rotation period of 4-10 years) and high afforestation survival rate, which can rapidly provide a large amount of wood resources. In terms of ecological benefits, fast-growing forests have not only improved the ecological environment in arid and semi-arid areas and significantly reduced soil erosion but also enhanced carbon sink capacity, playing an important role particularly in key ecological governance regions such as the Yellow River Basin. According to the national forestry census data, China's artificial forest area has reached 79.54 million hectares, accounting for 28% of the global total artificial forest area, among which fast-growing tree species (such as eucalyptus, poplar, masson pine and Chinese fir) account for more than 76%. However, fast-growing forest wood has obvious performance defects: due to the incomplete development of cell wall structure, its basic density is 18-25% lower than that of natural forest wood, resulting in reduced wood fiber content, loose material texture, abundant knots and significantly degraded mechanical properties. These defects severely restrict the application of fast-growing wood in load-bearing structures. To improve the performance of fast-growing wood, Laminated Veneer Lumber (LVL) technology effectively disperses internal material defects and breaks through size limitations through processes such as veneer rotary cutting, drying, gluing and hot pressing, thus obtaining more stable mechanical properties[14-16]. Nevertheless, tests have shown that the mechanical properties of fast-growing wood LVL are still inferior to those of high-quality log products, and further reinforcement treatment is required to meet the application requirements in fields such as construction.

Bamboo, as a fast-growing natural material with an excellent strength-to-weight ratio, is widely applied in Asian regions[17-21]. Its unique material properties are mainly manifested in three aspects: first, superior mechanical properties attributed to its densely arranged fiber structure; second, high flexibility; third, lightweight characteristics. These features make it an ideal material for structural applications such as scaffolding, bridges and residential buildings. From the perspective of resource characteristics, bamboo has remarkable regeneration advantages, reaching usable maturity in only 3-5 years, which is much faster than the growth cycle of traditional wood. As the country with the richest bamboo resources in the world, China has a total bamboo forest area of 7.01 million hectares (105 million mu), and its bamboo production and industrial scale rank first globally. At the national policy level, the Development Plan for Forestry and Grassland Industry (2021-2025) clearly sets a development goal of achieving a bamboo industry output value of 700 billion yuan by 2025. In engineering applications, modern processing technologies have converted bamboo into high value-added products such as glued bamboo and glued laminated bamboo. Among them, the Glubam glued bamboo developed by Professor Xiao Yan's research team is of breakthrough significance[23-25]. This material can be fabricated into various building components by processing moso bamboo into bamboo fibers and adopting a cold-pressing lamination process. Glubam not only retains the natural texture and aesthetic value of bamboo but also possesses mechanical properties comparable to those of steel and concrete. The development of this innovative material has not only improved the structural performance and utilization efficiency of bamboo but also promoted the technological upgrading and sustainable development of the entire bamboo industry.

Extensive studies have demonstrated that bamboo, as a reinforcing material, can significantly improve the mechanical properties of CLT, and has the advantages of abundant resources, low cost and environmental sustainability. In view of the current situation of wood resource shortage in China, this study innovatively proposes a new type of bamboo-wood composite structural material: using fast-growing poplar Laminated Veneer Lumber (LVL) as the core layer material and high-performance Glubam glued bamboo as the reinforced outer layers. Through the bamboo-wood composite approach, this material effectively improves the utilization value of fast-growing forest resources and alleviates the shortage of high-quality structural timber supply; meanwhile, it leverages the excellent high-strength characteristics of bamboo to compensate for the insufficient mechanical properties of fast-growing wood, resulting in a significant improvement in the overall performance of the composite material. This innovative material combination scheme not only opens up a new avenue for the comprehensive utilization of bamboo and wood resources but also provides a feasible technical solution to address the problem of structural timber shortage in China.

2. Research Status of Laminated Veneer Lumber Structures

Given The development of Laminated Veneer Lumber (LVL) can be traced back to the 1960s. At that time, the U.S. economy developed rapidly, and the construction industry entered a boom period, leading to a substantial increase in demand for wood, especially a sharp rise in the price of high-quality large-diameter timber. To improve the utilization rate of high-quality wood, researchers began to explore how to produce high-performance engineered wood using small-diameter timber. Meanwhile, technological progress in the petroleum industry significantly reduced the cost of adhesives such as phenolic resin. Against this background, LVL technology achieved a breakthrough. Researchers developed a method to manufacture structural materials with high mechanical properties from small-diameter or fast-growing forest wood through gluing technology. LVL gradually became a reliable alternative to traditional solid wood.

After entering the 20th century, with the increasing maturity of automated production technology, the production efficiency and quality of LVL have been significantly improved. More importantly, with the deepening of the global concept of sustainable development, LVL, as a green and low-carbon material, has been more widely applied in the construction field. The Black & White Building in East London is an office building mainly constructed with wood, with a height of 17.8 meters, and is one of the tallest large-scale timber office buildings in central London. The foundation and basement of the building are constructed with concrete, while the rest of the structure is entirely made of wood. Its curtain wall is made of Glued Laminated Timber (Glulam), and the columns and beams adopt LVL materials. Except for the underground part, this 4,480-square-meter building is entirely composed of prefabricated components, as shown in Figure 1.1. The Swedish National Museum of Technology is one of the most representative science and technology museums in Northern Europe. Its roof adopts a wooden grid shell structure composed of LVL plates, which is reinforced with LVL pins and bolts. Inside the museum, there is a "visual dome" composed of 277 triangular CLT plates, which is a major architectural feature of the Swedish National Museum of Technology, as shown in Figure 1.2, reflecting the dual pursuit of aesthetics and function in modern architecture. Figure 1.1 Black & White Building in London Figure 1.2 National Swedish Museum of Technology

LVL exhibits high flexural strength and elastic modulus, which can effectively resist deformation in long-span structures. In addition, the internal fiber direction of LVL is consistent, and its mechanical properties along the grain are far superior to those of ordinary solid wood beams. Therefore, LVL beams are one of its most widely used application forms. To investigate the shear performance of perforated Populus euramericana LVL beams, Wang Anlian et al. designed 6 specimens and conducted four-point bending tests. The results showed that the failure mode of unperforated beams was bending failure due to tensile cracking at the mid-span bottom, while the failure mode of circular-hole beams was grain shear failure caused by stress concentration around the holes. Ye Yujing et al. studied the effect of veneer thickness on the mechanical properties of laminated veneer lumber. The results indicated that veneer thickness had a significant influence on the static bending strength and elastic modulus of laminated veneer lumber, and both decreased with the increase of veneer thickness. In addition, Benoit et al. developed a mechanical model to accurately predict the strength of LVL beams, and found that the model could accurately reproduce the test results of flat bending and edge bending, and reasonably predict the nonlinear behavior of beams before failure. Wang et al. measured the planar shear properties of SPF (Spruce-Pine-Fir) dimension lumber and LVL using an improved method, and fabricated hybrid CLT (HCLT) with lumber and LVL to evaluate its bending performance in the main strength direction. It was found that using LVL as parallel layers improved the bending performance of CLT, while using LVL as orthogonal layers reduced the bending performance.

A large number of the above studies have shown that bending performance is the core mechanical performance index of LVL beams, and its reinforcement technology has also become a key research direction for scholars at home and abroad. Xu Yuwei et al. conducted an experimental study on polyacrylonitrile-based carbon fiber reinforced eucalyptus LVL. The results showed that when the fiber laying rate increased from 30% to 50%, all mechanical indexes of the material presented a significant enhancement trend; however, when it continued to increase to 70%, the performance increase slowed down significantly, indicating that an appropriate laying rate should be selected to fully utilize materials and save costs. Xu Jiale et al. systematically investigated the mechanical behavior of 9 groups of steel-LVL composite I-beams through four-point bending tests. The results demonstrated that adjusting section parameters such as increasing the height-width ratio, web height-thickness ratio and reducing the flange width-thickness ratio could effectively improve the flexural bearing performance of composite beams. Francisco et al. reinforced the bending performance of LVL beams with unidirectional carbon and bidirectional carbon Fiber Reinforced Polymer (FRP) respectively, and found that unidirectional carbon FRP had a more obvious reinforcement effect than bidirectional carbon FRP. Deam et al. found that applying prestressed tendons to LVL beams had little effect on stiffness and strength, but could reduce the deflection caused by permanent loads.

In the field of structural engineering, significant progress has also been made in the research on the performance of slab-column systems composed of LVL members. Li Shihong et al. studied the reinforcement effect of carbon fiber cloth hoop reinforcement on fast-growing poplar LVL columns through axial compression tests. It was found that there existed an optimal threshold of carbon fiber cloth volume stirrup ratio, which could not only ensure the structure presents an ideal failure mode but also maximize the bearing capacity. Zhang et al. proposed a new type of LVL floor, and evaluated the vibration comfort of the floor using root mean square acceleration, peak acceleration and acceleration vibration level. Shan Liang and Zhou Chao conducted axial compression and eccentric compression tests on LVL columns respectively, and found that compared with traditional log sawn timber, LVL axial compression members significantly improved the stiffness and strength of poplar materials, and analyzed the performance differences between axial compression columns and eccentric compression columns under the ultimate bearing state through comparative tests.

2. Research Status of Glued Bamboo Structures

Because joint tests are costly and the parameter coverage is limited, finite element analysis has gradually become an important approach in the study of the static behavior of tubular intersecting joints. Existing studies generally show that, when material constitutive laws, boundary conditions, weld modeling, and mesh discretization are properly defined, finite element models can reasonably predict the load-displacement relationship, local stress distribution, plastic development process, and ultimate bearing capacity of joints. With the aid of finite element analysis, researchers are able to systematically investigate the effects of diameter ratio, diameter-to-thickness ratio, wall-thickness ratio, branch inclination angle, gap parameter, and loading regime on the static performance of joints over a relatively wide parameter range.

Furthermore, finite element studies are no longer limited to the prediction of bearing capacity for conventional joints, but have gradually extended to spatial effects, combined loading effects, hot-spot stresses, and failure mechanisms. For example, some studies have shown that the bearing capacity of spatial KK or XK joints is usually lower than that of the corresponding planar joints, indicating that spatial effects cannot be neglected[12,13]. Other studies, through comparison between finite element results and experimental data, have found that the actual failure modes of some complex spatial joints are inconsistent with the assumptions adopted in current design codes, and the direct use of traditional formulas may therefore be unsafe or overly conservative. Accordingly, finite element analysis not only improves research efficiency, but also provides important support for revising design formulas, revealing mechanical mechanisms, and carrying out parametric studies.

3. Research Status of Glued Bamboo Structures

Bamboo is renowned for its fast growth and high strength-to-weight ratio, and is particularly popular in Asian countries. Bamboo has a wide range of applications in the construction field due to its high tensile strength, excellent strength-to-weight ratio, uniform material texture, good stability and strong wear resistance. As a natural building material with important historical value, round bamboo has a lasting influence on the development of China's architectural civilization. The remains of bamboo structures unearthed from the Hemudu Site in Zhejiang (about 7000 years ago) and the Jinsha Site in Sichuan (Shang and Zhou Dynasties) confirm the early application practice of bamboo as a primitive building material. In terms of traditional construction systems, the overhead structure of stilt-style dwellings in western Hunan and the Dai dry-land bamboo stilt houses (Figures 1.3 and 1.4) centrally demonstrate the structural innovation of bamboo in residential buildings[40,41]. It is worth noting that in the rammed earth walls of Fujian Tulou, bamboo was innovatively used as transverse tie reinforcement, which significantly improved the integrity of the walls through its excellent tensile properties. In modern engineering practice, bamboo, with its characteristics of light weight and high strength, is still used as the core component of scaffolding for multi-story building construction, and its engineering application value continues to be verified.
Figure 1.3 Stilt-style dwellings of Xiangxi Figure 1.4 Dai "dry-land" bamboo stilt houses

In the late 20th century, with the increasing global demand for green and low-carbon materials, bamboo has attracted extensive attention as an important resource to replace wood. Meanwhile, the research and development of new adhesives and processing equipment have also promoted the progress of glued bamboo technology, and glued bamboo has been gradually applied to floors, automobile floors, packaging boxes, etc.. In the early 21st century, academia and industry at home and abroad began to focus on promoting the structural engineering application of glued bamboo. To this end, researchers have developed a series of structural glued bamboo, namely engineered bamboo, including Glubam glued bamboo, bamboo mat plywood, bamboo strip laminated lumber, bamboo scrimber, bamboo plywood, bamboo particleboard, bamboo mat-bamboo curtain composite plywood, etc.. Among them, Glubam glued bamboo is one of the most typical engineered bamboo products.

As an important breakthrough in modern engineered bamboo materials, Glubam glued bamboo was developed by Professor Xiao Yan's research team after more than ten years of research, and formed a structural engineered bamboo material with stable mechanical properties based on the innovation of secondary gluing lamination process. Xiao Yan's team systematically studied the basic mechanical properties of Glubam. Li et al. monitored the full-field strain fields of specimens under 15 stress states using Digital Image Correlation (DIC) technology, and revealed the failure evolution laws of materials under different loading conditions. Xiao et al. introduced the manufacturing process of Glubam, investigated and analyzed its energy consumption and carbon dioxide emissions, and obtained the main mechanical properties of Glubam through material property tests. Yang et al. conducted off-axis tensile tests on Glubam specimens with a longitudinal-transverse fiber ratio of 4:1, and proposed a failure analysis method for Glubam with bidirectional fibers using the Hankinson formula and Tsai-Wu failure criterion. On this basis, a series of studies have been carried out on beams, plates and column members made of Glubam. Lv Xiaohong et al. compared the test results with the calculated bearing capacity specified in Code for Design of Timber Structures (GB 50005-2003) and the American National Design Specification (NDS) for Wood Construction, and found that the actual test bearing capacity of Glubam columns exceeded the calculated values of existing wood structure codes. Huan Yapeng et al. conducted four-point bending tests on 14 Glubam glued bamboo I-beams. The results showed that the web performance was the key factor determining the strength of I-beams, and the flange strain did not reach the material limit state. Li et al. tested the mechanical properties of two types of Glubam beams made of bamboo plates with different pretreatments, and proposed a strength capacity equation to calculate the bending stiffness and strength capacity of Glubam beams. In addition, a large number of engineering projects have been constructed using Glubam materials. Shan Bo et al. built a modern bamboo structure pedestrian bridge through prefabricated assembly, and carried out overall waterproof treatment on the bridge during construction. One year of actual operation monitoring showed that the structural performance was stable. Xiao et al. designed and built the world's first Glubam single-lane vehicle bridge. With the in-depth research on the mechanical properties and processing technology of Glubam, its application has gradually expanded to the fields of multi-high-rise structures and long-span spatial structures. Based on the in-depth research on the mechanical properties and processing methods of Glubam, Xiao et al. successfully completed the design and construction of two multi-high-rise engineered bamboo structures by drawing on the design methods of existing wood structures. This progress not only demonstrates the application potential of Glubam in complex building structures but also provides important technical support and practical reference for the further promotion of engineered bamboo materials.

In the "glued bamboo +" structural system, glued bamboo materials exhibit excellent mechanical properties. Ye Xin et al. conducted bending tests on 5 groups of full-scale glued bamboo-concrete composite beams (BCC), and confirmed that increasing the number of shear connectors could effectively improve the overall flexural stiffness and ultimate bearing capacity of the composite system. At the same time, it was found that the mechanical properties of the finger joint nodes of glued bamboo beams had a significant impact on the failure mode of composite beams. To solve the structural defects existing in the traditional bamboo-concrete interface connection technology, Shan Bo et al. innovatively proposed using Reactive Powder Concrete (RPC)-steel composite connectors. This technology significantly improved the interface cooperative working performance of prefabricated glued bamboo-concrete composite beams through material compounding and structural optimization. Gao et al. conducted monotonic and cyclic lateral loading experiments on Cold-Formed Steel (CFS) shear walls sheathed with Glubam plates. The study found that this new type of shear wall had a similar failure mode to traditional wood-sheathed shear walls and could provide comparable nominal shear strength, showing good engineering application prospects. In the field of engineering applications, researchers have also achieved certain results in the "glued bamboo +" structure. Wu et al. proposed a new type of Glubam-steel hybrid truss system and designed and built a prototype structure for the canopy of an office building. Meanwhile, Li et al. developed an asymmetric steel-Glubam truss with the help of BIM technology, and confirmed the excellent performance of this hybrid truss system in meeting deflection limits and bearing capacity requirements. Due to its convenience in manufacturing, transportation, prefabrication and installation, this prefabricated hybrid truss achieves a good balance between structural performance and economic cost

4. Research Status of Bamboo-Wood Composite Structures

China began to apply bamboo-wood composite structures as early as ancient times. Ancient craftsmen skillfully combined bamboo and wood through traditional processes such as mortise and tenon connection and binding, forming a unique architectural style. Such structures not only possess excellent mechanical properties but also demonstrate a high level of craftsmanship. In many ancient buildings, bamboo was used as the main load-bearing material due to its light weight and high strength, while wood was mainly used for node connection and auxiliary support. However, in the early 20th century, with the promotion of the Industrial Revolution, steel and concrete gradually replaced traditional materials and became mainstream building materials, and the research on bamboo-wood composite structures also stagnated for a time. It was not until the late 20th century, with the rise of the concept of sustainable development, that people paid renewed attention to environmentally friendly building materials, and bamboo-wood composite structures once again became an important research direction in the construction field and gradually received extensive attention.

China is a country rich in bamboo resources but relatively deficient in wood resources. Since the beginning of the 21st century, the concept of "replacing wood with bamboo" has gradually emerged, which has promoted the development of bamboo-wood composite materials. Xiao Yan et al. made new breakthroughs in the engineering of bamboo materials and systematically proposed a new structural system of Cross-Laminated Bamboo Timber (CLBT). Through systematic mechanical performance tests on CLBT beams and columns, it was confirmed that this material has excellent structural load-bearing characteristics. Comparative studies have shown that CLBT reaches the technical indicators of CLT of the same specification in terms of thermal insulation and sound insulation performance, and its full life cycle sustainability further demonstrates the ecological advantages of bamboo[61,62]. Li et al. prepared CLBT using bamboo curtain plates and hemlock, and studied its bending and shear properties in the main and secondary strength directions. The study found that if the Modulus of Elasticity (MOE) in one strength direction decreases, it will increase correspondingly in the other direction, depending on the material properties of each layer. Zhang et al. conducted four-point bending static load tests on bamboo-wood composite beams made of Laminated Bamboo (LB) and Laminated Veneer Lumber (LVL). The results showed that increasing the number of bamboo plate layers could improve the ultimate bearing capacity of composite beams. After replacing SPF (Spruce-Pine-Fir) as the transverse layers and the outermost longitudinal layers with glued laminated bamboo, the apparent bending modulus of the prepared CLTB beams increased by 23.69%, and the peak load increased by 60.50%, which performed better than the standard SPF CLT specimens. In addition, replacing the outermost layer of SPF with glued laminated bamboo could increase the compressive strength of CLBT short columns by 90%. With the increase of CLBT specimen height, the contribution of the outermost glued laminated bamboo to the compressive strength gradually decreases, but this reinforcement still effectively improves the safety and stability of CLBT long beams. Wei et al. pasted glued laminated bamboo and Carbon Fiber Reinforced Polymer (CFRP) to the tensile area at the bottom of wood beams, and found that the bending stiffness and bending strength of the beams increased with the increase of glued laminated bamboo thickness, but the increase of CFRP layers did not significantly affect the performance. Leng Yubing et al. compared the bending tests of full-scale Douglas-fir glued wood beams, glued bamboo beams, bamboo scrimber beams and glued bamboo-wood beams, and found that glued bamboo-wood beams performed better than single bamboo material beams in terms of ultimate load and corresponding mid-span displacement. This result indicates that combining engineered bamboo materials with fast-growing wood can significantly improve the bending performance of glued bamboo-wood beams, while giving full play to the high strength and good deformation capacity of glued bamboo. In further research, Leng Yubing et al. selected bamboo scrimber, glued bamboo and spruce glued laminated wood to fabricate 30 six-layer glued bamboo-wood composite beams, and conducted bending performance tests. The results showed that when the upper 1 layer and lower 2 layers of spruce glued wood beams were replaced with bamboo scrimber/glued bamboo, the bearing capacity of the specimens increased by 82.3% compared with pure wood beams, and the overall performance was close to that of full bamboo material beams, indicating that this layup scheme is an ideal laminate combination method.

A series of studies have shown that CLBT can effectively improve the mechanical properties of CLT and has broad application prospects in areas rich in bamboo resources but limited in wood resources.

5. Conclusions

This paper systematically reviews the domestic and international research progress of Cross-Laminated Timber (CLT), Hybrid Cross-Laminated Timber (HCLT), Laminated Veneer Lumber (LVL) and glued bamboo (Glubam), with a focus on analyzing the mechanical performance optimization paths and engineering application status of bamboo-wood composite structures. The research shows that:

1.Traditional CLT is restricted by the shortage of high-quality wood resources in China, making it difficult to achieve large-scale production. HCLT effectively alleviates the pressure of raw material supply by introducing low-grade wood and engineered wood products, but the problem of insufficient mechanical properties of fast-growing wood has not been fundamentally solved.

2.Fast-growing poplar LVL can significantly improve the utilization rate of fast-growing forest resources, but its flexural strength and elastic modulus are still lower than those of high-quality log products, requiring reinforcement treatment to meet the requirements of high-end structures. Glubam glued bamboo has become an ideal structural reinforcement material due to its excellent strength-to-weight ratio, rapid regeneration characteristics and stable mechanical properties.

3.Bamboo-wood composite structures can fully exert the performance complementary advantages of the two materials. Among them, Cross-Laminated Bamboo Timber (CLBT) exhibits outstanding performance in flexural and compressive properties. Replacing the outermost layer of CLT with glued laminated bamboo can increase the compressive strength of short columns by 90% and the peak load of beams by 60.50%, verifying the feasibility of the "replacing wood with bamboo" technical route.

4.The new bamboo-wood composite structure scheme proposed in this paper, which uses fast-growing poplar LVL as the core layer and high-performance Glubam as the reinforced outer layers, not only solves the problem of insufficient mechanical properties of fast-growing wood but also reduces the dependence on high-quality wood, providing a new technical approach for the high-value utilization of bamboo and wood resources in China.

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