Research Progress and Future Prospects of Bamboo-Steel Composite Beams

Jie Zheng*

Central South University of Forestry and Technology, Changsha 410004, Hunan, China

*2210410057@qq.com

Abstract

Amid the "dual carbon" strategy and green building trends, traditional steel and concrete structures have drawbacks like high carbon emissions. Bamboo-steel composite beams, merging bamboo and steel advantages, are a viable option, and this paper reviews their research progress. It classifies the beams by bamboo form, cross-sectional structure and connection method, summarizes domestic and foreign studies on composite beam structures and shear connectors, and elaborates on their theoretical analysis (flexural stiffness, serviceability limit state deflection, ultimate limit state moment). Finally, it notes current limitations and prospects for future development, to support engineering application and further research.

Keywords

Bamboo-steel Composite Beam; Structural Classification; Shear Connector; Theoretical Analysis; Green Building; Dual Carbon Strategy.

1. Introduction

Under the in-depth integration of the "dual carbon" strategy and the concept of green buildings, the field of structural engineering is undergoing a paradigm shift from "high-carbon dependence" to "low-carbon innovation" [1]. Although traditional steel structures have reliable mechanical properties, carbon emissions during steel production account for more than 7% of the global total, resulting in significant resource consumption and environmental costs. Concrete structures, on the other hand, face inherent drawbacks such as excessive self-weight and long construction cycles, making them difficult to meet the needs of low-carbon development.

Bamboo-glued laminated lumber has excellent mechanical properties, with an elastic modulus close to that of wood and a certain degree of toughness, which can meet the load-bearing requirements of structural components [2]. Moreover, it is highly environmentally friendly and sustainable, aligning with the "dual carbon" strategy and the concept of green buildings. In addition, bamboo has the advantages of convenient processing and construction, as well as high resource utilization rate. However, bamboo-glued laminated lumber has limitations such as anisotropic performance, weak environmental adaptability, insufficient long-term performance data, and lack of standardization and large-scale production, which restrict its application in engineering practice.

As one of the most widely used structural materials in the modern engineering field, steel has supported the development of multiple industries such as architecture, bridges, and machinery with its comprehensive and stable mechanical properties, strong processing and forming capabilities, durability, and convenient maintenance [3]. Meanwhile, it also has obvious shortcomings restricted by its own characteristics and production conditions, such as high carbon emissions and energy consumption during production, large self-weight, easy corrosion, poor high-temperature

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performance, and high cost affected by resources and the market. It can be seen that the mechanical properties and high consumption of components or structures affect the application of steel.

Bamboo and steel each have inherent performance advantages in the field of building structures. In modern building structure design, combining the two to form a new type of composite structure can maximize the excellent properties of each material, make up for their respective shortcomings, and thus achieve the optimization of structural performance. Regarding the research on steel-bamboo composite beams [4], domestic studies have been carried out on the shear performance and mechanical behavior under long-term loads. The results show that steel-bamboo composite beams have good bearing capacity and stiffness, can effectively exert the performance advantages of the two materials, and exhibit excellent overall working performance. This paper will detail the research progress of bamboo-steel composite beams.

2. Composite Beam Structure

2.1 Classifications of Composite Beam Structures

With the development and application of bamboo-steel composite beams, their types have become increasingly diverse. Classified by bamboo form, they can be divided into bamboo-glued laminated lumber-steel composite beams and raw bamboo-steel composite beams. Among them, raw bamboo-steel composite beams directly use natural raw bamboo (such as moso bamboo and Neosinocalamus affinis) combined with steel. Usually, multiple pieces of raw bamboo are bound or glued together, and then connected to steel materials such as I-beams and channel steels through bolts or welding.

Fig. 1 Raw Bamboo-Steel Composite Beam

Classified by cross-sectional configuration, they can be divided into composite laminated beams [5] (steel and bamboo are laminated in layers to form the beam cross-section; common forms include a "sandwich structure" of "bamboo layer-steel layer-bamboo layer", or a composite cross-section of "steel tension flange + bamboo compression flange + web"); box-section composite beams (a box-shaped frame made of steel, with bamboo-glued laminated lumber or raw bamboo filled inside to form a closed cross-section); and I-shaped composite beams (imitating the cross-sectional form of I-beams, with the upper flange and web made of bamboo (or bamboo-glued laminated lumber) and the lower flange made of steel, which are combined into an integral whole through connectors).

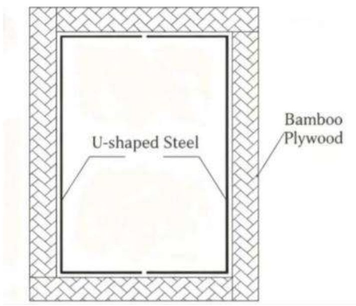

Fig. 2 Box Composite Beam

Fig. 3 I-shaped Composite Beam

According to the classification by connection method, it can be divided into bonded composite beams [6], mechanical connection composite beams, hybrid connection composite beams, etc. Among them, bonded composite beams directly bond the steel-bamboo interface with structural adhesives, and transfer the interface shear force relying on the shear strength of the adhesive layer. This connection method has a simple structure and can realize continuous force transfer at the interface. However, the durability of the adhesive (especially in humid and high-temperature environments) and its long-term performance need to be focused on, and it is suitable for indoor structures with high requirements for fire resistance and corrosion resistance.

Mechanical connection composite beams use mechanical fasteners such as self-tapping screws, bolts, and rivets to connect steel and bamboo, and transfer the interface force through the shearing and extrusion effects of the fasteners. Mechanical connection has high reliability, convenient construction, and is easy for disassembly and maintenance. It is suitable for outdoor, long-span or heavy-load structures, but attention should be paid to the local damage of bamboo caused by the fasteners.Hybrid connection composite beams combine the advantages of bonded connection and mechanical connection. They first achieve initial bonding of the interface with adhesives, and then strengthen it with mechanical fasteners, forming a synergistic effect of "adhesive shear resistance + mechanical pull-out resistance". This connection method has both the continuity of bonded connection and the reliability of mechanical connection. It is a relatively recommended form in current research and engineering applications, and can effectively improve the interface force transfer performance and structural durability.

In conclusion, steel-bamboo composite beams have various classification dimensions. Different types have their own characteristics in terms of material utilization, mechanical performance, and construction difficulty. They need to be reasonably selected according to engineering requirements (span, load, environment, etc.) to achieve the optimal balance between structural performance and economy.

2.2 Research Status of Composite Beam Structures at Home and Abroad

Team Yang Xiaoting [7] proposed an I-shaped steel-bamboo composite beam with self-tapping screws reinforcing the bonded interface. They took parameters such as steel thickness and screw diameter as test variables and conducted four-point bending tests. The results show that this beam can give full play to the advantages of steel and bamboo, with its flexural capacity and ductility higher than those of purely bonded beams. Additionally, they put forward calculation formulas for the deflection at the serviceability limit state and the flexural capacity of the beam.

Team Wang Huifang [8] carried out a three-dimensional nonlinear finite element analysis on the flexural performance of prestressed I-shaped steel-bamboo composite beams. They compared the simulation results with the test results and explored the influence of prestress magnitude. The results indicate that the arrangement of prestressed tendons can improve the beam stiffness; however, when the prestress value increases further, the stiffness shows no obvious change. Meanwhile, the ultimate bearing capacity and deformation capacity are enhanced, and the damage to the adhesive layer is delayed. They suggest that the applied prestress value should be equal to the allowable bearing capacity of ordinary beams.

Team Zhang Ye [9] performed four-point bending tests on composite beams to study the effects of interface connection methods and reconstituted bamboo positions on the beams' flexural performance. The conclusions are as follows: the shear stiffness of steel-wood screw connections is low; the beam first undergoes steel yielding, and then its bearing capacity fluctuates due to interface damage but still maintains load-bearing capacity. Moreover, the thickness of steel and the upper flange has a very significant impact on the peak load.

However, Team Dan Cheng [10] used finite element software to study the ultimate bearing capacity and deformation of cold-formed thin-walled steel-reconstituted bamboo box beams under different end connections. They established models of 6 beams with different cross-sections and obtained the load corresponding to the allowable mid-span deflection and the ultimate flexural bearing capacity of the beams through theoretical calculations.

Haoxuan Wu [11] proposed a new type of steel-bamboo composite beam with web openings. After conducting tests, he analyzed the main factors affecting the beam's mechanical performance and derived a calculation method for the ultimate shear capacity. The results show that web openings lead to a significant reduction in the beam's shear capacity and stiffness, and damage occurs in the opening area. Ding Jingshu [12] conducted shear tests on a new type of single-box double-cell steel-bamboo composite beam, evaluated its shear performance, revealed the influence of parameters on deformation and failure modes, and established calculation models for the shear stress at the limit state and the shear bearing capacity.

3. Shear Connector

3.1 Classification of Shear Connectors

Shear connectors are widely used in composite beam structures. Their core function is to transfer shear force and tensile force between steel members and bamboo scrimber members in composite structures, prevent relative slip or separation of the two during loading, ensure the coordinated work of steel and bamboo scrimber to jointly bear loads, thereby improving the overall bearing capacity, stiffness and stability of the structure. Shear connectors are mainly divided into three categories: rigid shear connectors, flexible shear connectors and composite shear connectors [13].

Rigid shear connectors transfer shear force relying on their own stiffness and concrete bonding force. They have strong shear resistance and high stiffness, and are suitable for structures bearing large loads. They mainly include studs, section steel connectors, bolt connectors, etc. Flexible shear connectors transfer shear force through their own deformation or friction with concrete. They have low stiffness and good ductility, and are suitable for structures with high deformation requirements. Flexible shear connectors mainly include steel bar connectors (such as bent-up steel bars, polygonal steel bars), steel plate connectors (such as perforated steel plates, corrugated steel plates), fiber-reinforced polymer (FRP) connectors (such as FRP studs, FRP bars), etc. Composite shear connectors combine the characteristics of rigid and flexible connectors, taking into account both shear resistance and ductility, and are suitable for complex stress scenarios. Common combination methods include stud + steel bar combination (studs as the main part, steel bars assisting in shear resistance) and section steel + perforated steel plate combination (section steel providing stiffness, perforated steel plates improving ductility

3.2 Research on Shear Connectors at Home and Abroad

Lin Jinbiao [14] conducted in-depth research on the shear performance of embedded corrugated steel plate perforated connectors. He carried out push-out tests on two types of these connectors, incorporating the effects of the arrangement of binding reinforcement and penetrating reinforcement, analyzed and summarized the failure mechanism of the specimens, clarified the failure mode of the connectors, and simultaneously identified the unfavorable positions for concrete pin arrangement and the differences between the two embedding methods.

Zhao Yuchen [15] carried out static and fatigue tests on 13 groups of specimens to explore the evolution law of friction performance of steel-concrete composite interfaces with bolted connections under fatigue loads. He obtained the static friction bearing capacity of the interface and relevant parameters under cyclic loads, and revealed the fatigue evolution mechanism of the friction performance of the concrete interface from the micro-level. The results provide a reference for the design of frictional bolt shear connectors.

Fangwen Wu [16] fabricated 7 specimens for push-out tests to investigate the effect of steel pin parameters on shear performance. The results show that an increase in steel pin thickness improves the shear bearing capacity but reduces the stiffness; the height of the steel tenon has little influence; pre-tightening force can enhance the shear bearing capacity, but excessive pre-tightening force reduces ductility.

Sumei Liu [17] conducted a parametric study on nonlinear finite element analysis of corrugated steel-UHPC composite bridge decks with stud shear connectors. She found that the shear bearing capacity increases with the increase in the number and diameter of studs, and is less affected by the height; replacing ordinary materials with corrugated steel plates and UHPC can enhance the shear bearing capacity. Subsequently, she used the elastic foundation beam method to derive the calculation formula for the stud load-displacement curve, and the theoretical results are basically consistent with the finite element results. Finally, by comparing the current formulas with the finite element calculation results, she proposed that the theoretical calculation should consider the contribution of the weld hoop, as well as the influence of the stud aspect ratio and deformation degree.

4. Theoretical Analysis of Bamboo-Steel Composite Beams

At present, the theoretical analysis of bamboo-steel composite beams is relatively mature. Many scholars have conducted research on them, with the focus concentrated on their flexural stiffness, deflection under the serviceability limit state, and bending moment under the ultimate limit state.

4.1 Flexural Stiffness

The core method for calculating the flexural stiffness of bamboo-steel composite beams is the transformed section method [18] (also known as the "section conversion method"). The essence of this method is to convert the cross-sections of two materials with different elastic moduli (bamboo modulus Eb, steel modulus Es) into an equivalent cross-section of a single material (usually based on steel) according to the elastic modulus ratio (n = Eb/Es or n = Es/Eb). Then, the equivalent moment of inertia Ieq is calculated using the moment of inertia calculation method for a single-material cross-section. Finally, the flexural stiffness EIeq is obtained by combining the equivalent moment of inertia with the elastic modulus of the reference material[19].

Its calculation logic is based on the assumption of "full shear connection" (i.e., no relative slip at the bamboo-steel interface). If the interfacial shear performance is insufficient, an additional shear connection coefficient needs to be introduced for correction.

Its formula is expressed as follows:

$$n = E_b/E_s \text{ or } n = E_s/E_b \tag{1}$$

$$I=\sum(I_i+A_iD_i) \tag{2}$$

$$EI_{eq}=E_bI_{eq} \tag{3}$$

Among them, E_b, E_s are the elastic moduli of bamboo scrimber and steel, respectively; I_i is the moment of inertia of each part of the cross-section; $A_i$is the cross-sectional area of each part; D_i is

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the distance from the centroid of each cross-section to the centroid of the composite cross-section; and I_{eq} is the calculated equivalent cross-sectional moment of inertia.

4.2 Deflection at the Serviceability Limit State

The calculation of deflection for bamboo-steel composite beams at the serviceability limit state needs to be based on cross-sectional stiffness analysis and the superposition method. The core is to consider the coordinated work of bamboo and steel as well as the slip effect. For deflection calculation, both the short-term load action and the influence of bamboo creep under long-term load action should be taken into account. The calculation follows the sequence from cross-sectional stiffness to short-term deflection, then to long-term deflection, and the key lies in determining the transformed section moment of inertia of the composite cross-section. The specific calculation formulas are as follows:

$$f_s=\frac{P_k}{48E_bI_{cr}}L^3 \tag{4}$$

$$f_s=\frac{5Q_k}{385E_bI_{cr}}L^4 \tag{5}$$

If creep under long-term loads needs to be further considered, an amplification factor θ should be multiplied. This factor is generally taken as 1.5-2, and its specific value should be determined based on the type of bamboo, with reference to relevant test data or code recommendations.Among the parameters, L is the calculated span of the beam; P_k is the concentrated load; Q_k is the uniformly distributed load.

If there is significant slip between bamboo and steel (no reliable connectors are used), a slip coefficient needs to be introduced to correct the stiffness Icr. For specific calculation methods, reference can be made to the slip effect calculation approach specified in Technical Code for Steel Structures[20].

4.3 Ultimate Bearing Capacity

For most steel-bamboo composite beams, the superposition principle can be used to calculate the bending moment at the ultimate limit state of bearing capacity, i.e., the flexural bearing capacityM_e [21]. The calculation formula is as follows:

$$M_e = M_b + M_s \tag{6}$$

$$M_b = \gamma_b \sigma_b W_b \tag{7}$$

$$M_s = \gamma_s f_s W_s \tag{8}$$

$$M_u=\frac{P_u a}{2} \tag{9}$$

Among them: M_b and M_s are the normal section bending moments of reconstituted bamboo and cold-formed thin-walled steel, respectively; $\gamma_b$is the strength adjustment coefficient of reconstituted bamboo; γ_s is the strength adjustment coefficient of cold-formed thin-walled steel;$\sigma_b$is the peak stress of reconstituted bamboo;$M_b$and $M_s$are the section modulus of reconstituted bamboo and cold-formed thin-walled steel, respectively; f_s is the tensile strength of cold-formed thin-walled steel; $P_u$is the bearing capacity of the self-tapping screw-reinforced bonded steel-bamboo composite I-shaped beam; P_u is the distance from the support to the adjacent load.

5. Conclusion and Prosperts

By complementing the properties of bamboo and steel, bamboo-steel composite beams achieve the coordinated optimization of low carbon performance and mechanical properties. Their different classifications (based on bamboo form, cross-sectional structure, and connection method) can meet diverse engineering needs. Existing studies have clarified the calculation methods for the flexural stiffness, deflection, and ultimate bearing capacity of composite beams, verified that composite connections and other forms can improve the interface force transfer performance, and confirmed the consistency between finite element analysis and test results. These provide support for theoretical application and highlight the application potential of bamboo-steel composite beams in the field of green buildings.

In the future, focus should be placed on the following aspects: first, improving the long-term performance database of bamboo materials and deepening the research on durability under harsh environments such as humidity and high temperature; second, promoting the standardized design of bamboo-steel composite beams to reduce the threshold for engineering application; third, exploring new types of shear connectors and intelligent monitoring technologies to further improve structural safety and applicability, and promote their large-scale application in long-span and heavy-load projects.

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