

Research Status of Connection Joints of Laminated Bamboo Beams and Calculation Theory of Perpendicular-to-Grain Loading

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Abstract

Laminated bamboo is an engineered bamboo material with broad application prospects in building structures; however, the connection joints of laminated bamboo beams are prone to brittle splitting failure under loads perpendicular to grain, which threatens structural safety. This paper systematically reviews the research status of laminated bamboo beam connection joints and the calculation theories for perpendicular-to-grain loading. The research status is summarized from two aspects: beam-column connection joints and beam-beam connection joints, covering the failure modes, influencing factors of the load-carrying capacity, and strengthening methods (self-tapping screws, carbon fiber sheets, steel hoops, prestressed steel straps, etc.) of steel side-plate and slotted-in steel plate bolted connections. The calculation theories are also reviewed in two categories: the yield capacity theory based on Johansen's yield theory, including the capacity formulas of slotted-in steel plate and steel side-plate connections under the European yield modes, and the splitting capacity theory perpendicular to grain based on fracture mechanics, including the linear elastic fracture mechanics model of Van der Put, the non-linear fracture mechanics model of Jensen, and its modified model. The results show that current research mostly focuses on the mid-span joint load form, while the beam-end support joints (steel side-plate-dowel supports) that bear shear-dominated loads have been studied less; moreover, the existing models are mainly established for timber with the joint located at the beam mid-span, so their applicability to the support joints of laminated bamboo has not been systematically verified. Therefore, research on the applicability evaluation and modification of the splitting capacity calculation models perpendicular to grain is needed, so as to provide reliable calculation methods and a theoretical basis for the safe design of bamboo structure joints.

Keywords

Laminated Bamboo; Connection Joints; Perpendicular-To-Grain Loading; Splitting Capacity; Fracture Mechanics

1. Introduce

Laminated bamboo is an engineered bamboo material with broad application prospects in building structures [1]. For bamboo- and timber-based structures, connections must transfer forces between members while accommodating the anisotropic behavior of the material. However, when laminated bamboo specimens are subjected to bending or shear, splitting failure perpendicular to grain often occurs prematurely in regions such as bolt holes [2], instead of the ideal overall material bending or shear failure. This failure mode usually has no obvious precursor, and the load-carrying capacity of the joint is far lower than the bending strength of the material itself, which not only wastes the material strength but also poses a great safety hazard. Consequently, the mechanical behavior of a laminated bamboo beam cannot be assessed from the material strength alone; the connection may control cracking, deformation, and ultimate resistance.

This review examines the connection joints of laminated bamboo beams and the calculation theories for perpendicular-to-grain loading. The research status of the joints is summarized from two aspects: beam-column connection joints and beam-beam connection joints, covering the failure modes, influencing factors of the load-carrying capacity, and strengthening methods (self-tapping screws, carbon fiber sheets, steel hoops, prestressed steel straps, etc.) of steel side-plate and slotted-in steel plate bolted connections. The calculation theories are reviewed in two categories: the yield capacity theory based on Johansen's yield theory, and the splitting capacity theory perpendicular to grain based on fracture mechanics, including the linear elastic fracture mechanics model of Van der Put, the non-linear fracture mechanics model of Jensen, and its modified model. These models are not treated as directly transferable between connection configurations or materials. The objective is to identify recurring failure mechanisms, explain the limits of available comparisons, and define priorities for research on the beam-end support joints (steel side-plate-dowel supports) of laminated bamboo beams and on the applicability evaluation and modification of the existing splitting capacity models.

The paper presents a narrative synthesis of selected experimental, theoretical, and numerical studies, rather than a systematic review or quantitative meta-analysis. The discussion does not claim exhaustive coverage, pooled performance improvements, or a universal ranking of connection types and calculation models. Findings are interpreted in relation to the connection configurations, loading conditions, and material properties examined in the cited studies.

2. Research Status of Beam Connection Joints of Laminated Bamboo

Scholars at home and abroad have carried out extensive work on laminated bamboo, confirming its potential as a primary structural material[1]. However, some scholars found in their studies that, when laminated bamboo specimens are subjected to bending or shear, splitting failure perpendicular to grain often occurs prematurely

in regions such as bolt holes[2], instead of the ideal overall material bending or shear failure. This failure mode usually has no obvious precursor, and the load-carrying capacity is far lower than the bending strength of the material itself, which not only wastes the material strength but also poses a great safety hazard.

2.1. Beam-Column Connection Joints

In beam-column connection joints, the steel side-plate bolted connection and the slotted-in steel plate bolted connection are the two most widely used forms of modern metal connections. These two connection forms have clear load-transfer mechanisms and are convenient to construct; however, under loads perpendicular to grain, brittle splitting failure is prone to occur around the bolt holes, which is one of the key issues restricting the load-carrying capacity of the joints. Therefore, scholars at home and abroad have carried out a series of studies on the failure modes, influencing factors, and strengthening methods of beam-column joints.

Hui Botao[3] carried out an experimental study on the splitting capacity perpendicular to grain of bolted glulam beam joints and conducted self-tapping screw strengthening tests on slotted-in steel plate bolted joints. The results revealed the load-transfer mechanism and failure mechanism of the joints and quantified the influence of the number and spacing of bolt rows on the bearing performance of the joints. Chen Li et al.[4] analyzed, through finite element simulation, the mechanical behavior and cracking displacement of glulam beam-column slotted-in steel plate bolted joints under applied loads.

Wang Chenxi[5] carried out an experimental study on the mechanical performance of glulam single-bolt and multi-bolt connections with slotted-in steel plates. The results showed that the thickness-to-diameter ratio is the key factor determining the yield mode of bolts in single-bolt connections. The influence of the number of bolt rows and columns and their arrangement on the bearing performance of multi-bolt connection joints was quantified, and a theoretical calculation formula for the load-carrying capacity of multi-bolt connections was proposed.

Wang Tongtong[6] carried out an experimental study on the load-bearing performance perpendicular to grain of compressed wood dowel connections. The influence of geometric parameters such as specimen thickness, height, and effective height on the splitting resistance was examined, and the results were compared with the splitting resistance of steel dowel connections loaded perpendicular to grain.

Wang[7] investigated the stiffness calculation method of bolted connections in timber structures through bending tests on bolted beam-column joints. The test results showed that the three yield modes of bolted beam-column joints in timber structures are similar to the European yield modes. By fitting the test results, an empirical formula for the stiffness calculation was obtained; on this basis, the stiffness calculation formula of bolted connections was derived according to the

theory of beams on elastic foundation.

To evaluate the mechanical performance of glulam beam-column slotted-in steel plate bolted joints under eccentric loads, Lu et al.[8] studied the influence of parameters such as bolt arrangement, diameter, and eccentricity through experiments. Wang S. et al.[50] studied the mechanical performance of steel side-plate bolted connections of laminated bamboo beams and explored the influence of different bamboo thicknesses and edge distances on the failure characteristics under loading parallel to grain. The test results showed that the specimens mainly suffered mixed mode I and mode II splitting failure perpendicular to grain.

Cao Jixing et al.carried out horizontal loading tests on beam-column type glulam structures to understand their mechanical response under earthquakes and established a damage assessment model. The study showed that the damage of the structure was mainly concentrated at the joints, accompanied by large horizontal deformation. The addition of chevron bracing at the joints could significantly reduce such horizontal deformation and improve the stiffness and load-carrying capacity of the structure.

Zhang Xiaocong.studied the carbon fiber sheet strengthening method to address the problem that glulam slotted-in steel plate bolted joints are prone to brittle failure. The test results showed that, after bonding carbon fiber sheets, the embedment strength of the glulam dowel grooves increased significantly, the failure mode of the joints changed from brittle to ductile, the ultimate load increased by up to 181%, and the ductility coefficient increased by up to 625%. On this basis, a calculation formula for the tensile capacity perpendicular to grain was proposed, providing a basis for the crack-resistant design of joints.

Ye Lingpeng et al.proposed three strengthening methods for cracked glulam beam-column slotted-in steel plate joints and analyzed the strengthening effects of steel hoops, carbon fiber sheets, and self-tapping screws through finite element simulation. Leng Yubing et al.studied the restraining effect of strengthening methods using internally bonded bamboo sheets and externally wrapped steel plates on the timber splitting that tends to occur when glulam beam-column joints rotate. Wang et al.strengthened bolted glulam beam-column joints with cross-laminated timber panels and analyzed the influence of the strengthening on the rotational capacity of the joints. Vrcce applied cyclic loads to glulam beam-column joints to study their lateral load-carrying capacity, considering two joint strengthening forms: wrapping fiber-reinforced composites and installing self-tapping screws.

To improve the bending performance of glulam beam joints, Shu et al.Proposed a new type of slotted-in plate bolted connection reinforced with long threaded steel rods with nuts to restrain the rotation behavior of the joints. Ma et al.proposed a new type of bolted connection reinforced with steel shapes. Wu et al.Proposed a

self-centering friction-type glulam beam-column joint with shape memory alloy (SMA) bars. Okunrounmu conducted standard fire tests on four types of slotted-in steel plate bolted joints strengthened with self-tapping screws to study the influence of the bolt number and arrangement on the fire resistance of the joints.

2.2. Beam-Beam Connection Joints

In beam-beam connections, there are two forms: the connection of cantilever continuous beams and the connection between main beams and secondary beams. The connection configuration of cantilever continuous beams is a combination of simply supported beams and cantilever beams, usually connected by metal cantilever bracket plates. The main beam and the secondary beam can be connected by side-fixed connectors, as shown in the figure. Under loads perpendicular to grain, both forms of joints may develop cracks and suffer brittle failure.

He Chaohong experimentally studied the influence of the thickness-to-diameter ratio, bolt spacing, and arrangement on the mechanical performance of glulam-steel side-plate bolted joints. The results showed that the thickness-to-diameter ratio changes the bolt failure mode, and the optimum ratio is 7.5–10; once the bolt spacing exceeds a certain range, it no longer enhances the mechanical performance of the joints. Finally, a theoretical calculation formula for steel side-plate bolted joints was derived, which can predict the load-carrying capacity with relatively good accuracy.

Taking glulam beam steel side-plate bolted connection joints as the research object, Niu Dong systematically investigated their bending performance through experiments, theory, and numerical simulation. The results showed that the bolt spacing parallel to grain is the key factor affecting the load-carrying capacity: the larger the spacing, the higher the capacity, and the initial stiffness of the connected beam is superior to that of pure glulam; the influence of the bolt arrangement is relatively small. A load-carrying capacity calculation formula was proposed, and the differences in the slip modulus calculation of Eurocode 5 (EC5) were verified.

In view of the susceptibility of glulam bolted joints to brittle fracture, Liu et al. proposed a prestressed steel strap strengthening technique. The test results showed that this technique can delay the initiation and propagation of cracks and significantly improve the load-carrying capacity of the joints, with a maximum increase of 53.33%, and provides higher deformation capacity. Finally, combined with finite element simulation analysis, the strengthening mechanism of the prestressed steel strap was revealed and design recommendations were proposed, providing a theoretical basis for engineering application.

Tang conducted a series of tests on single-bolt and multi-bolt connections of laminated bamboo and steel plates. The influence of the edge distance, bolt diameter, and laminated bamboo thickness on the load-carrying capacity of single-bolt connections was studied. The capacity increases with increasing bolt diameter and

bamboo thickness, but tends to stabilize beyond a certain level. The staggered arrangement of multi-bolt connections improved the load-carrying capacity of multi-bolt connections. The failure modes of the specimens were splitting perpendicular to grain, shear, and a combination of splitting perpendicular to grain and bamboo crushing.

In summary, the current research and applications of laminated bamboo beam connection joints are mostly focused on the mid-span joint load form shown in Fig. 1pz, and their mechanical performance has been studied relatively systematically. , especially the mechanical performance of steel side-plate-dowel supports, has been studied less. In actual engineering, however, the support joints at beam ends mostly bear loads dominated by shear and are prone to splitting failure perpendicular to grain, and their failure mechanism, influencing factors of the load-carrying capacity, and design methods lack systematic research. Therefore, it is necessary to carry out in-depth research on the load-bearing performance perpendicular to grain of steel side-plate-dowel supports of laminated bamboo beams, so as to provide a basis for improving the design theory of bamboo structure joints.

3. Calculation Theory of Laminated Bamboo Beams under Perpendicular-to-Grain Loading

3.1. Yield Capacity Calculation Theory

The calculation theory of the yield capacity is mainly based on Johansen's yield theory, which divides the yielding of dowel connections into two modes: embedment yielding of the dowel hole and yielding of the dowel. Slotted-in steel plate connections and steel side-plate connections are classified as double-shear connections in the European yield theory.

The theoretical calculation of the European yield modes is based on rigid-plastic analysis, which assumes that the stress-strain curve of timber is rigid-plastic. Under the compression of the dowel, the embedment stresses of the dowel holes all reach the embedment strength, and the dowel is entirely in the plastic stage.

3.2. Splitting Capacity Calculation Theory Perpendicular to Grain

In dowel connections, besides the ductile yield modes described in the previous section, there is also a typical brittle splitting failure. At present, the calculation formulas for the splitting capacity perpendicular to grain are generally established on the basis of fracture mechanics.

=Van der Put et al. were the first to use linear elastic fracture mechanics to calculate the splitting capacity perpendicular to grain. In this theoretical model, the joint is located at the mid-span of a simply supported beam with a span of $2l$, a height of h , and a thickness of b ; the initial crack has a length of $2a$ and is symmetrically distributed at the mid-span; at the location of the mid-span concentrated load, the distance from the fracture crack to the edge of the member in the load direction is

he.

Jensen, in contrast, derived the capacity calculation formula based on non-linear fracture mechanics. This theoretical model is likewise a simply supported beam with the joint located at mid-span. It is assumed that a fictitious fracture layer exists at the section where the initial crack is located: below the fracture layer is a Timoshenko beam of height h_e , and above it is a rigid foundation of height $h-h_e$; the two are connected through the fictitious fracture layer, whose stiffness is equivalent to the tensile strength of the material perpendicular to grain and the mode-I critical energy release rate, i.e., $K = ft_{902}/Gf$.

In summary, whether it is the Van der Put model based on linear elastic fracture mechanics or the Jensen model based on non-linear fracture mechanics, the derivation of both takes the joint located at the mid-span of the beam as the basic premise and is mainly established for timber materials. For laminated bamboo and the load form of steel side-plate-dowel joints at beam-end supports, the applicability of the existing calculation models has not yet been systematically verified. Moreover, most existing models do not consider the influence of the dowel end distance, effective height, and the cooperative work of the dowel group on the splitting capacity of the support. Therefore, it is necessary to carry out research on the applicability evaluation and modification of the splitting capacity calculation models perpendicular to grain based on the material characteristics of laminated bamboo and the actual load-transfer mechanism of the support joints, so as to provide reliable calculation methods and theoretical support for the design of bamboo structure joints.

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