ISSN: 2414-1895 DOI: 10.6919/ICJE.202511_11(11).0011

# Advances and Future Directions in Laminated Bamboo Lumber-Steel Splice Connections

Yilei Qian[a]

School of Civil Engineering, Central South University of Forestry and Technology, Changsha 410004, China

[a]1356555458@qq.com

## Abstract

**With the growing emphasis on green building and sustainable development, laminated bamboo lumber (LBL) has gained increasing attention as a green construction material known for its excellent mechanical properties and short renewal cycle. Connections are crucial for the safe transfer of forces within bamboo structures, and among them, LBL-steel plate connections have become a key focus of research and application due to their ease of construction, reliable force transfer, and good deformation performance. This paper reviews the research progress on LBL-steel plate connections, systematically analyzing the mechanical properties, failure modes, and key influencing factors (such as bolt diameter-to-thickness ratio, end distance, and anchorage depth) of different connection forms, including bolted, screwed, and hybrid connections. Research indicates that the failure modes (e.g., bamboo bearing, bolt bending, screw pull-out, or shear failure) and mechanical properties (e.g., load-bearing capacity, stiffness, ductility) of the connections are highly dependent on their geometrical parameters and connection methods. Existing timber design codes show poor adaptability for bamboo connections, highlighting the urgent need to develop design methods and theoretical models (such as the tri-linear stiffness model and elastic foundation beam theory) tailored to the characteristics of bamboo. Numerical simulation technology, particularly finite element analysis based on cohesive zone models, has become an effective supplementary means for studying the force-transfer mechanisms within connections. Finally, this paper outlines future research directions, including the long-term performance and durability of connections, dynamic response and seismic design, standardization and code development, and the exploration of new connection technologies, aiming to provide references for the refinement of bamboo structure theory and the promotion of its engineering practice.**

## Keywords

**Laminated Bamboo Lumber-Steel Plate Connections; Mechanical Properties; Connection Design; Connection Performance; Numerical Simulation.**

## 1. Introduction

With the growing emphasis on green building concepts and sustainable development, laminated bamboo lumber (LBL)-a green building material known for its excellent mechanical properties, short regeneration cycle, and low carbon footprint-has garnered significant attention. In bamboo structures, joints serve as critical components for ensuring safe and reliable load transfer. Among these, steel gusset plate joints, which fasten laminated bamboo lumber and steel plates using bolts, screws, or other connectors, form nodes capable of effectively transmitting bending moments, shear forces, and

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axial forces. Such joints offer advantages such as rapid construction, high efficiency, and favorable deformation performance, making them a major trend in the application of bamboo structures.

Research on LBL-steel gusset plate joints involves various aspects, including connection methods, failure mechanisms, and joint design. Numerous scholars worldwide have conducted in-depth studies on the mechanical properties of different types of LBL-steel gusset plate joints through experimental research, theoretical analysis, and numerical simulations. These studies cover connections using bolts, screws, and adhesives, and investigate performance under monotonic, cyclic, and long-term loading conditions, thereby enhancing the understanding of joint design and application.

Currently, the application of bamboo structures in construction is transitioning from traditional to modern forms, with joint performance playing a key role in this evolution. Practical engineering projects, such as the Sichuan International Bamboo Products Trading Center, have demonstrated the feasibility of LBL-steel gusset plate joints. In this project, innovative joint designs were employed, connecting 75–110 mm diameter raw bamboo to steel components using internal sleeve dislocation methods, successfully ensuring the safety and reliability of large-scale bamboo structures.

This paper provides a comprehensive review of research related to LBL-steel gusset plate joints, analyzes factors influencing joint performance and design methods, and offers insights into future research directions. Through a literature review approach, it summarizes and evaluates the characteristics and trends in studies on LBL-steel gusset plate joints, aiming to promote the development and technical application of bamboo structures.

**Table 1.** Major Research Progress on Laminated Bamboo Lumber - Steel Gusset Plate Joints

| Research Aspects | Main Research Methods | Key Findings |
|---|---|---|
| Performance of Bolt Connections | Monotonic Loading Tests, Finite Element Simulation | The influence of the thickness-to-diameter ratio on the bolt yield mode was established; recommended values for minimum end distance and main member thickness were proposed. |
| Performance of Screw Connections | Monotonic Loading Tests, Parametric Analysis | The governing mechanism of embedment depth on failure modes was revealed; a calculation method for the shear capacity of screw connections was proposed. |
| Performance of Adhesive-Bonded Joints | Long-Term Load Testing, Finite Element Analysis | The effectiveness of the bilinear cohesive zone model was validated; the degradation pattern of bond performance after long-term loading was analyzed. |
| Design Methods | Theoretical Analysis, Code Comparison | A tri-linear stiffness analysis model was developed; the inapplicability of timber design codes to bamboo joints was revealed. |

## 2. Joint Connection Types and Mechanical Performance

### 2.1 Performance of Bolted Connections

Bolted connections are one of the most commonly used methods in laminated bamboo lumber–steel gusset plate joints. Their mechanical performance is primarily characterized by bearing failure, bending yield, and combined failure modes. Li Xiazhen et al. [1] conducted axial compression tests on single-bolt connections in reconstituted bamboo–steel gusset plate joints to investigate the influence of parameters such as bolt diameter, bamboo member thickness, and end distance on joint performance. The results indicated that bolt diameter has a certain impact on the initial stiffness, post-yield stiffness, yield load, and ultimate load of the joint. When the bolt diameter was gradually increased from 8 mm to 12 mm, the ultimate load of the joint increased by approximately 35%, while the ductility ratio decreased by about 20%. Larger bolt diameters enhanced joint strength but reduced ductility.

The failure characteristics of the joints mainly include bearing failure in the bamboo at the bolt hole and bending failure of the bolt shaft. The study found that when the thickness-to-diameter ratio (L/D, i.e., the ratio of the main member thickness in the load direction to the bolt diameter) ranged from 3.75 to 6.00, the bolt yield mode exhibited "single-hinge" yielding. When the thickness-to-diameter ratio exceeded 6.00–13.50, the bolt yield mode transitioned to "double-hinge" yielding. This change in yield mode reflects a shift in the joint's internal force redistribution capacity, which is significant for ductility design. Particularly under optimal thickness-to-diameter ratio conditions, bearing failure of the main member at the bolt hole and bending of the bolt occur simultaneously at joint failure, allowing both materials to fully utilize their strength and achieve an ideal failure mode.

Additionally, the end distance (the distance from the bolt center to the end face of the bamboo) is a critical factor determining the joint's load-bearing capacity and failure mode. Studies have also shown that when the end distance is 4 times the bolt diameter (4d), the joint's ultimate load and ductility ratio stabilize. When the end distance is smaller than this value, the joint fails in a brittle manner due to bamboo splitting. When the end distance is larger, the joint transitions to a ductile failure mode involving bamboo bearing and bolt bending. This provides a basis for designing the minimum end distance in bolted bamboo connections.

Zhong Yong et al. [2] further investigated the influence of laminated bamboo thickness and bolt diameter on the performance of bolted laminated bamboo–steel gusset plate joints through bearing tests. The experimental results showed that as the bolt diameter gradually increased, the joint stiffness and yield force improved approximately linearly. However, increasing the laminated bamboo thickness significantly enhanced the joint's ultimate bearing capacity and ductility coefficient. When the joint failure mode was Type I, both the bolt and laminated bamboo materials fully utilized their strength, resulting in a higher ductility coefficient and optimal mechanical performance of the bolted connection.

## 2.2 Performance of Screw Connections

Screw connections are relatively widely used in laminated bamboo lumber-steel gusset plate joints due to their ease of installation and relatively minor material damage. Related research has conducted experimental studies on the shear strength of screw connections in laminated bamboo lumber-steel gusset plate joints [3], investigating the influence of different parameters such as screw diameter, embedment depth, end distance, spacing, and row spacing. The results indicate that the shear strength of screw connections largely depends on the embedment depth (the length of the screw embedded in the main material). When the embedment depth is small, the joint failure mode manifests as screw pull-out failure; when the embedment depth exceeds a certain critical value, the failure mode transitions to screw shear failure, significantly enhancing the joint's load-bearing capacity.

Unlike bolted connections, screw connections typically exhibit significant nonlinear characteristics in their load-displacement curves without a distinct yield point, making it necessary to define shear capacity based on the yield point. In their study on laminated bamboo lumber-bamboo veneer nail connections, Chen Guo et al. used an offset of 5% of the nail diameter to estimate the joint's yield load, which reasonably reflected the actual stress conditions of the joint. The study pointed out that the ductility of screw connections is largely related to the joint's geometric parameters. When the end distance, spacing, and row spacing are well configured, the joint exhibits better deformation capacity and is less prone to brittle failure.

The calculation of shear capacity for screw connections is relatively complex. The authors analyzed the design methods for dowel-type connections in Chinese, American, and European timber design codes. The predictions for screw connections in laminated bamboo lumber using different codes were unsatisfactory. Although the European code considers the "rope effect," the error still exceeded 50%. Therefore, through simple derivation, they proposed a method specifically for calculating the shear capacity of screw connections in laminated bamboo lumber-steel gusset plate joints, and the results obtained using this method showed good agreement with experimental values.

### 2.3 Performance of Hybrid Connections

Hybrid connections, as a method to enhance joint performance in the future, are also worth exploring. These connections often combine bolts and screws as force-transfer mechanisms, or integrate bolts, screws with steel gusset plates or other materials. For instance, the laminated bamboo lumber-bamboo veneer nail joint studied by Chen Guo et al. is essentially a hybrid connection, where bolted bamboo veneer plates work in conjunction with steel nails to form a truss-like force-transfer mechanism.

In the context of toughening glued laminated timber beam-column joints, studies have explored two approaches: externally attached steel plates and internally filled reconstituted bamboo plates. Low-cycle reversed loading tests demonstrated that both toughening methods improved the joint's load-bearing capacity, deformability, and energy dissipation capacity. This concept can be referenced to enhance the mechanical performance of laminated bamboo lumber-steel gusset plate joints, such as by adding bamboo or steel reinforcement strips in the joint region to reduce stress concentration and minimize cracking.

Li Yushun et al. conducted push-out tests under simulated long-term loading conditions on purely adhesive and hybrid adhesive steel-bamboo interfaces. The results revealed that the hybrid adhesive steel-bamboo interface specimens exhibited greater shear ductility. After long-term loading, the bearing capacity, bond stress, and relative slip of the hybrid adhesive interface showed minimal difference compared to short-term loaded specimens. Self-tapping screws were found to enhance the interfacial shear strength, with specimens having screws spaced at 80 mm intervals achieving a maximum interfacial shear stress of 1.7 MPa. This provides valuable insights for the design of hybrid laminated bamboo lumber-steel gusset plate connections.

**Table 2.** Performance Comparison of Different Connection Types in Laminated Bamboo Lumber - Steel Gusset Plate Joints

| Performance Indicators | Bolted Connections | Screwed Connections |
|---|---|---|
| Ultimate Load Capacity | High | Medium |
| Initial Stiffness | High | Medium to Low |
| Ductility Performance | Medium (depends on configuration) | Medium to Low |
| Installation Convenience | Medium (requires pre-drilling) | High (self-tapping) |
| Material Weakening | Significant | Minor |
| Failure Mode | Bearing failure of bamboo, bolt bending | Screw pull-out, shear failure |
| Long-term Performance | Stable | Requires further verification |

## 3. Influencing Factors and Design Optimization

### 3.1 Influence of Material Properties

The physical and mechanical properties of laminated bamboo lumber play a significant role in joint behavior. Previous studies have shown that the grade of raw bamboo has varying effects on different types of joints. For example, research on raw bamboo tenon-beam-column joints [4] indicated that the influence of raw bamboo grade is negligible for simple steel gusset joints (J1) and self-tapping screw joints (J3), whereas it significantly affects through-bolt joints (J2). The joint and connectors demonstrated optimal when the raw bamboo grade was T8. These findings suggest that the sensitivity of joints to material properties is also related to their structural configuration.

The bearing strength of bamboo at the bolt hole is critical to joint strength. Previous experimental studies have measured the bearing strength of laminated bamboo lumber in different grain directions.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202511_11(11).0011

Results show that the bearing strength parallel to the grain is substantially higher than that perpendicular to the grain, highlighting the influence of material anisotropy that must be considered in joint design. Additionally, factors such as density, moisture content, and internode characteristics in different sections of laminated bamboo lumber also affect the mechanical strength of joints, though existing research lacks comprehensive analysis in this area.

The thickness and strength of the gusset plates similarly influence joint performance. Sufficient plate thickness can prevent failure in the bamboo member and ensure failure occurs in the steel gusset plate, thereby maximizing the compressive capacity of the bamboo. Li Xiazhen et al. demonstrated that when the main member thickness reaches 90 mm, the mechanical properties of reconstituted bamboo-steel gusset plate single-bolt connections generally stabilize, achieving the highest ductility.

### 3.2 Influence of Structural Parameters

The dimensional parameters of joint configurations also significantly influence their mechanical properties. Proper configuration design represents another crucial aspect for joint optimization. Among these parameters, end distance, spacing, and row spacing are three primary dimensional factors. As previously mentioned, insufficient end distance leads to premature cracking and splitting of bamboo, while inadequate spacing (the distance between two fasteners along the load direction) causes stress overlap, reducing joint capacity. Row spacing (the distance between two fasteners perpendicular to the load direction) also affects stress distribution and load-bearing capacity.

Another critical parameter affecting bolt yield behavior is the thickness-to-diameter ratio (the ratio of main member thickness to bolt diameter). Studies have demonstrated that when this ratio ranges from 3.75 to 6.00, bolts exhibit a single-hinge yield mechanism. When the ratio increases to 6.00-13.50, the bolt transitions to a double-hinge yield mechanism. This transition enhances joint deformation and ductility, serving as a beneficial factor for seismic resistance.

For screw connections, embedment depth is the key parameter determining the failure mode. Specific studies on laminated bamboo lumber with wood screws have identified critical embedment depths. Exceeding these depths enables full utilization of joint capacity while shifting the failure mode from screw pull-out to screw yielding and fracture. This provides valuable guidance for the design of screw-connected joints.

### 3.3 Influence of Loading Conditions

The loading environment significantly influences the mechanical performance of joints. Chen Guo et al. experimentally investigated the effects of different load angles (pure shear, shear-tension, and shear-compression) on laminated bamboo-bamboo veneer nail joints. The results demonstrated that failure in pure shear and shear-tension specimens was primarily caused by bamboo veneer fracture and nail "double-hinge failure," whereas shear-compression specimens mainly failed due to nail "double-hinge failure." Under the same angle conditions, the ultimate load of shear-tension specimens consistently exceeded that of shear-compression specimens, highlighting the impact of stress state on joint strength.

Loading rate and cyclic loading also markedly affect joint performance. While most tests in this study involved monotonic loading, joints in structural members may experience dynamic or cyclic loads. Low-cycle reversed loading tests on glulam beam-column joints reinforced with external steel plates or internal reconstituted bamboo plates showed that such reinforcements significantly improved deformation capacity and energy dissipation under cyclic loading, providing valuable insights for seismic design of laminated bamboo-steel gusset plate joints.

Li Yushun et al. [5] studied the bond behavior of steel-bamboo interfaces after long-term loading. Their findings revealed that pure adhesive-bonded interfaces experienced a degradation in load capacity after long-term loading, with reduction factors of 0.91 and 0.81. In contrast, hybrid bonded interfaces (with self-tapping screws) showed no significant changes in load capacity, bond stress, or bond deformation compared to short-term loaded specimens. This indicates that appropriate structural measures can effectively maintain joint performance stability under long-term loading conditions.

# 4. Theoretical Models and Design Methods

## 4.1 Joint Stiffness Calculation Model

Accurate prediction of joint stiffness is a critical issue in the design of bamboo structural materials. Zhang Ming et al. proposed an elastic stiffness prediction method for reconstituted bamboo-steel gusset plate bolted connections, which adopts the assumption of an elastic foundation beam in an infinite body. This simplified approach reduces computational parameters, making calculations more convenient and practical, thereby enabling rapid prediction of connection elastic stiffness during design and ensuring connection safety.

For the nonlinear behavior of connections, the tri-linear stiffness model effectively captures the segmented stiffness characteristics of joints. This model simplifies the moment-rotation relationship into three linear segments representing the elastic, elastoplastic, and developed stages, with corresponding stiffness coefficients approximately determined from experimental data. Based on this model, researchers applied the joint classification algorithm from the European steel structure standard to evaluate the semi-rigid behavior of raw bamboo tenon-beam-column joints. The results identified through-bolt connections and simple steel gusset plate connections as semi-rigid, while self-tapping screw connections were classified as pinned.

Regarding screw connections, Chen Guo et al. found that the Hassanieh model effectively represents the load-displacement constitutive relationship across different loading stages of nailed joints. This model accounts for nonlinear characteristics and stiffness degradation of nailed connections, enabling precise prediction of force-displacement behavior in laminated bamboo lumber-bamboo veneer nailed joints.

## 4.2 Adaptability of Design Codes

Currently, China lacks specific design codes for bamboo structures, leading most bamboo structural engineering projects to adopt timber design methodologies for reference. Researchers have compared steel gusset plate dowel connection design methods from timber design codes of different countries (China, the United States, and Europe) and found significant discrepancies in their predictions for laminated bamboo lumber connections. While the European code incorporates the "rope effect" in its estimations, the errors remain substantial (still exceeding 50%), demonstrating its limited applicability to bamboo. This incompatibility arises from notable differences in mechanical properties between bamboo and timber, such as bamboo's more pronounced anisotropy, higher compressive strength parallel to the grain, and lower compressive strength perpendicular to the grain compared to wood.

In response to this situation, researchers have developed specialized calculation methods for the load-bearing capacity of bamboo-based connections. For instance, derived formulas have been established to calculate the shear capacity of wood screw connections in laminated bamboo lumber-steel gusset plate joints. Li Xiazhen et al. proposed appropriate minimum values for the main member thickness and end distance in single-bolt connections for reconstituted bamboo-steel gusset plate joints. These provide valuable references for developing bamboo structure design codes.

Furthermore, Li Yushun et al. considered steel-bamboo interfaces under long-term loading and proposed a calculation formula for the bond stress of bamboo-steel interfaces. The results from this formula show good agreement with experimental values, offering a theoretical basis for designing bamboo-steel interfaces accounting for long-term loading effects.

## 4.3 Numerical Simulation Techniques

With the advancement of computer technology, numerical simulation has become increasingly important in the study of laminated bamboo lumber–steel gusset plate joints. Researchers from Ningbo University developed a three-dimensional model of steel–laminated bamboo beam-column joints using the ABAQUS finite element program, incorporating a bilinear cohesive zone model to simulate the adhesive layer [6]. This approach enabled the calculation of the joint loading process and

ISSN: 2414-1895 DOI: 10.6919/ICJE.202511_11(11).0011

stress distribution within the adhesive layer. The results demonstrated that the established finite element model effectively represents the loading behavior of steel–bamboo beam-column joints, validating the feasibility of using the bilinear cohesive zone model to simulate the adhesive layer.

Zhong Yong et al. created a three-dimensional nonlinear finite element model of bolted laminated bamboo–steel gusset plate joints based on ABAQUS to investigate the influence of factors such as laminated bamboo thickness and bolt diameter on joint stiffness, yield capacity, and failure modes. The nonlinear finite element calculation results showed good agreement with experimental values, accurately predicting joint stiffness, yield load, and failure modes.

Numerical simulation allows for the observation of stress distribution, deformation localization, and damage evolution during the loading process, complementing experimental observations. Parametric analysis through numerical simulation can also examine the effects of various factors on joint performance, reducing experimental costs and improving research efficiency. However, it is important to note that reliable numerical simulation depends on experimental validation, and must account for challenges such as the anisotropic and nonlinear constitutive behavior of bamboo materials.

## 5. Conclusion and Prospects

### 5.1 Research Conclusion

Based on a systematic review of existing research on laminated bamboo lumber-steel gusset plate joints, the following key conclusions can be drawn:

The performance of laminated bamboo lumber-steel gusset plate joints is influenced by multiple factors including connection methods, structural parameters, and material types. Different connection methods each have their own advantages and limitations, making them suitable for different loading conditions and applications. Bolted connections offer high load-bearing capacity and stiffness, while screwed connections provide ease of installation and minimize damage to bamboo materials. Hybrid connections combine the advantages of multiple connection types.

Various potential failure modes exist in both bolted and screwed connections, including bamboo bearing failure, fastener bending yield, and bamboo splitting, all of which can lead to joint failure. By optimizing joint parameters such as end distance, thickness-to-diameter ratio, and embedment depth, joints can be designed to achieve ideal failure modes.

When the thickness-to-diameter ratio of laminated bamboo lumber-steel gusset plate joints falls within the range of 6.00-13.50, bolts exhibit a "double-hinge" yield mode, allowing full utilization of both the main members and bolts. Semi-rigid behavior is a fundamental characteristic of these joints, and the tri-linear model effectively simulates their moment-rotation relationship. The elastic foundation beam stiffness prediction method and specialized load-bearing capacity formulas for bamboo materials provide theoretical references for joint design.

Existing timber design codes show poor adaptability to laminated bamboo lumber joints and cannot meet the design requirements for bamboo structures, highlighting the need to develop specialized design methods for bamboo structures. Numerical simulation technology can serve as a valuable complement to experimental techniques, accurately predicting the complex stress states in bamboo structural joints.

### 5.2 Research Prospects

Although significant progress has been made in the study of laminated bamboo lumber-steel gusset plate joints, several aspects require further in-depth research:

(1) Long-term Performance: Current research primarily focuses on short-term mechanical behavior, while aspects such as creep, durability, and environmental degradation of joints need further investigation. Long-term performance monitoring should be conducted to understand the evolution of joint performance under sustained loading and harsh environmental conditions, enabling predictions of bamboo structures' service life. Further research is needed on joint responses under

random dynamic loads such as earthquakes and wind vibrations. Additional testing through low-cycle reversed loading and dynamic loading should be performed to establish restoring force models for joints, providing basis for seismic design of bamboo structures.

(2) Standardization and Codification: There is an urgent need to develop standards for testing, design, and construction of bamboo structural joints to promote standardized application of bamboo structures. This requires collaborative efforts across the industry, integrating existing research findings to establish consensus in design codes and construction practices.

(3) Innovative Joint Connections: Research should focus on developing new connection methods such as prestressed connections and energy-dissipating connections to enhance the overall performance and seismic capacity of bamboo structures. Leveraging the characteristics of both steel and bamboo materials to develop optimal new connection types represents an important direction for future work.

(4) Multi-scale Modeling: Developing multi-scale modeling approaches ranging from the nanoscale (bamboo fibers) to the meter scale (joints) will help reveal load-transfer mechanisms and guide joint design optimization.

(5) Fire Resistance and Durability: Bamboo's fire resistance and durability significantly influence its structural applications. Further research is needed on fire protection techniques and durability enhancement for laminated bamboo lumber-steel gusset plate joints. For instance, the Sichuan International Bamboo Products Trading Center employed water mist protection technology, which could provide technical references for broader applications of bamboo structures.

With the growing emphasis on green building and sustainability principles, research and application of "laminated bamboo lumber-steel gusset plate" joints will continue to advance both theoretically and technically, playing a crucial role in promoting wider adoption of bamboo structures. Through interdisciplinary collaboration and integrated approaches, new ideas will emerge to continuously improve joint performance, supporting the development and refinement of modern bamboo structure technologies.

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