Sustainable Structures
ISSN: 2789-3111 (Print); ISSN: 2789-312X (Online)
http://www.sustain-dpl.com/journal/sust
DOI: 10.54113/j.sust.2024.000037

***REVIEW ARTICLE***

# Progress on the connection performance of steel-engineered bamboo beam-column connections under cyclic loads: a review

**Yang Liu[a,b,c,*], Kun Liu[a], Wentao Wang[d,e], Linlin Fan[a], Binbin Li[b]**

[a] School of Urban Planning and Municipal Engineering, Xi'an Polytechnic University, Xi'an, 710048, China.
[b] State Key Laboratory of Green Building in Western China, Xian University of Architecture & Technology, Xi'an,710055, China.
[c] The key laboratory of well stability and fluid & rock mechanics in Oil and gas reservoir of Shaanxi Province, Xi'an Shiyou University, Xi'an, 710065, China.
[d] Department of Civil and Environmental Engineering, University of Michigan, MI, 48109, USA.
[e]School of Civil and Environmental Engineering, Harbin Institute of Technology, Shenzhen, Shenzhen 518055, PR China
[*]Corresponding Author: Yang Liu. Email: yangliu@xpu.edu.cn.

**Abstract:** Bamboo is a great building material due to its low carbon and environmental friendless. The connection performance of beam-column joints had an impact on the seismic performance of the whole structure. The beam-column connection performance is critical in earthquakes. Steel-engineered timber connections have good seismic properties, and the properties of bamboo and timber are very similar. Therefore, the form of wood structure connection can be used in bamboo structures. The type of member materials used and the connection forms applied determine the structure elastic behavior. Common engineered bamboo has been introduced, and the current connection form of engineered timber has been summarized in this paper. Secondly, research on the indicators of connection performance under cyclic loads has been introduced, including damage forms, strength, ductility, and energy dissipation capacity. Thirdly, the traits of various types of connections are presented, and this paper could be taken as a reference for future studies on connections in steel-engineered bamboo structures.

**Keywords:** Engineered bamboo; connection performance; experimental study; numerical simulation

## 1 Introduction

The increase in the number of buildings has exacerbated energy shortage and global warming [1, 2]. According to the China Building Energy Consumption Annual Report (2020), building materials have long accounted for a significant proportion of carbon emissions [3]. Therefore, green building materials are a current focus of development [4]. Wood is a common environmentally friendly material, but its slow growth and extensive logging can lead to ecological issues [5, 6]. However, bamboo is a fast-growing and degradable tree-like grass. Because of its wide growing and large variety, bamboo has already become a potential substitute for wood [7, 8].

In recent years, the frequent occurrence of earthquakes has put forward higher requirements for buildings to resist earthquakes, necessitating building materials with certain ductility. It is common for most rural houses to use brick-concrete structures. Unlike brick-concrete structures, bamboo has good elasticity and it is lightweight, which is more conducive to seismic fortification. Furthermore, bamboo (wood) structure is usually a frame structure, and the core of frame structure design and its seismic



Received: 24 November 2023; Received in revised form: 2 April 2024; Accepted: 8 May 2024

performance depend on joints. Bamboo has geometric single, uneven structure, and a large variability of mechanical properties [9]. Unfortunately, this is not sufficient to ensure a safe and stable connection. Therefore, it comes the rise of various engineered bamboo materials [10, 11], has effectively addressed the problem of joint connections in bamboo structures [12, 13].

At present, most research focuses on wood structure joints. Due to the similarity in material properties between bamboo and wood, the connection forms of bamboo structural joints are based on wood as a reference [14-16]. Common joint connection forms in bamboo (wood) structure buildings include glued connection, tooth plate connection, and bolted connection. Most of them have some limitations. The failure mode of glued connection is brittle fracture, with poor reliability. Tooth plate is easy to corrosion, and not suitable for wet environment. Bolted connection is easy to construct and widely used in engineering [13]. Due to the biological properties of bamboo materials, the joints usually failure due to bolt holes splitting failure. Scholars use steel to improve joint stiffness and design various engineered bamboo composite members [17] (combination floor slabs, combination beams, combination columns, and combination walls) and combination systems [18] (like bamboo structure movable panel house and steel-bamboo combination structural system), and the study found that the steel-bamboo combination play is role effectively, taking advantage of both materials. It has light self-weight, small deformation, novel and unique architectural appearance. Not to mentions it is, energy saving, and environment friendly [19].

The influence of component materials and connection forms on the seismic performance of structures is a critical area of study. In this paper, the feasibility of engineering bamboo as a substitute to wood is further verified by reviewing the current common engineered bamboo. In addition, bamboo (wood) structure connection types, construction modes, and summarized the influencing factors of connection performance. The research reviewed steel-engineered bamboo beam-column joints from both domestic and international perspectives, focusing on indicators of different indexes of seismic performance (damage forms, strength, ductility, and energy dissipation capacity). The aim of this article is to assess the connection performance of these joints, with the anticipation of further research on the connection performance of steel-engineered bamboo beam-column connections.

## 2 Connection Performance

The connection performance of beam-column joints related to the seismic performance. A structure with good elasticity tends to exhibit better seismic performance. The type of member materials used and the connection forms applied are determine structure elastic behavior [20].

### 2.1 Member Materials

The steel-engineered bamboo frame structure is mainly made of various kinds of engineered bamboo (or a combination of engineered bamboo and steel), the common engineered bamboo materials are laminated bamboo lumber (LBL), bamboo plywood, bamboo scrimber lumber (BSL), and bamboo composite materials, etc. [21-23]. As there is no full international standardization of engineered bamboo, the products differ in naming. LBL is another name for bamboo glulam; BSL is parallel strand woven bamboo, laminated bamboo bundle lumber; bamboo plywood is also called as bamboo mat board, ply bamboo. LBL is one or more layers of material that are cold-or hot-pressed along the grain; BSL is inspired by scrimber, the reorganization and strengthening of bamboo into bamboo scrimber [24]; bamboo plywood is a bamboo material glued by cross-lamination. GluBam, similar to glued bamboo, is a new material proposed by Xiao et al. [25]. Compared with glued wood, GluBam has the advantages of a wide source of original materials and low cost [26]. Furthermore, scholars have developed members and structural systems composed of bonding with cold-formed thin-walled sections [27].

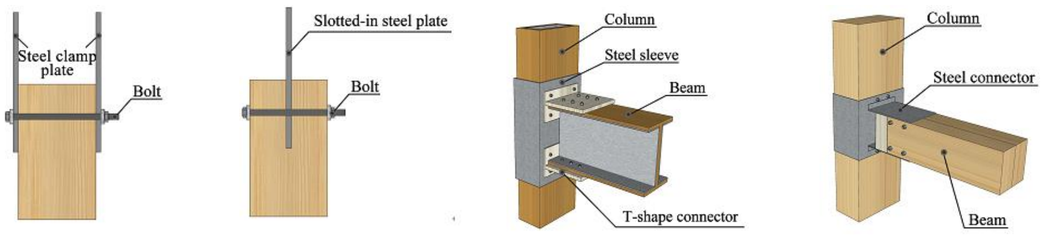
Scholars have conducted numerous mechanical property studies to verify the feasibility of engineered bamboo as a building material [28, 29]. **Table 1** presents the mechanical properties of several common engineered bamboo and engineered wood, and engineering bamboo has better performance. Research has found that the mechanical properties of engineering bamboo are influenced by the species and number of layers of bamboo [30, 31]. When *Dendrocalamus strictus* [32, 33] and *Guadua Angustifolia Kunth* [34] instead of Moso bamboo as the original material, the strength of engineered wood material was lower than that of engineered bamboo. Through testing the modulus of elasticity, compressive strength, flexural strength, and shear strength of GluBam, it was found that its mechanical properties were superior to those of wood [35, 36].

**Table 1.** Mechanical properties of engineered bamboo and engineered wood [28, 36]

| Material | Compression strength/MPa | Tension strength/MPa | Bending strength/MPa | Shear strength/MPa |
|---|---|---|---|---|
| LBL | 50~60 | 140~150 | 120~130 | 17~18 |
| LVL | 50~60 | 40~50 | 60~70 | 11~12 |
| BSL | 120~130 | 240~250 | 120~130 | 52~53 |
| Scrimber | 100~110 | 100~110 | 140~150 | 17~18 |
| GluBam | 50~60 | 80~90 | 90~100 | 16~17 |
| Glulam | 60~70 | 80~90 | 40~50 | 11~12 |

## 2.2 Connection Forms

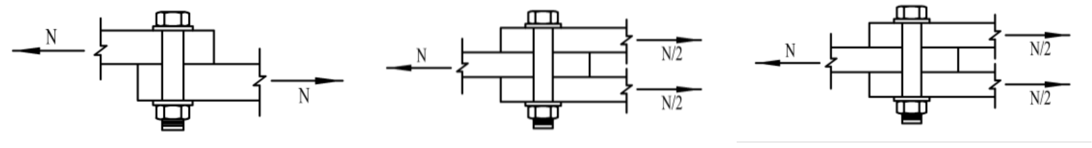
The joints are constructed in such a way that the beams and columns are connected by various forms of steel connectors. The majority of traditional wood structure connections are mortise and tenon joint structures [21], while modern wood structures mainly use truss plate connections and pin connections [22], with common bolted connections belong to pin connections. At present, there is a lack of standards and standard specifications for bamboo materials in the construction industry. Bamboo has similar properties to timber, therefore, drawing on the form connection of steel-timber combination structure [23]. **Fig. 1** shows the current common connection forms of steel-engineered bamboo structures [24-26]: bolt connections (bamboo-steel clamp bolted connection, slotted-in bamboo-steel plates bolted connection, steel connector and bolt combination connections) as well as steel sleeve connections.




(a) Steel clamp plate bolted connection (b) Slotted-in steel plates bolted connection (c) Steel sleeve connections (d) Steel connector and bolt combination connections

**Fig. 1.** Steel-engineered bamboo connection.

There are numerous forms of bolted connections, categorized into three types based on the force involved: single-shear connection, double-shear connection, and multi-shear connection in **Fig. 2**. Among these, multi-shear connections according to the relative positions of bamboo and steel plate are divided into bamboo-steel clamp bolted and slotted-in bamboo-steel plates bolted connection. The bamboo-steel clamp bolted connection is a precast (opened hole) steel plate, bamboo beam, and bamboo column, which are connected by bolts. When the connection is under stress, each bolt distributed the load.




(a) Single-shear (b) Double-shear (c) Multi-shear

**Fig. 2.** Forms of bolted connections.

The connectors in steel clamp bolted connections, slotted-in bamboo-steel plates bolted connections, and steel sleeve connections all serve to fasten the members. Given the similarities between bamboo and wood, research on the performance of steel-engineered bamboo beam-column connections can draw from the factors affecting the performance of wood bolted connections study on bamboo beam-column joints of steel structure by referring to the influencing factors of wood bolt connection performance.

## 3 Assessment of Connection

**Table 2** shows a variety of factors influencing the performance of bamboo (wood) bolted connections. It can be seen that the *L*/*D* ratio, the bolt position, and the number influence connection performance. Based on past studies, the main parameters that impact the connection performance of steel-engineered bamboo beam-column connections are as follows: (1) *L*/*D* ratio; (2) bolt diameter; (3) bolt position; (4) engineered bamboo thickness; (5) steel plate thickness; (6) reinforcement measures, such as stiffeners at the connection and bolt strength.

**Table 2.** Influencing factors in the load-bearing performance of bolted connections

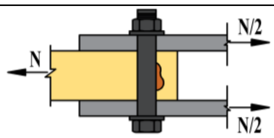
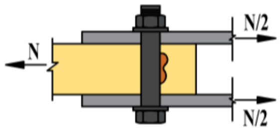
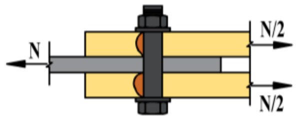
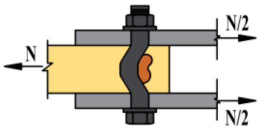
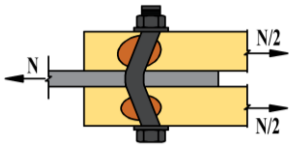
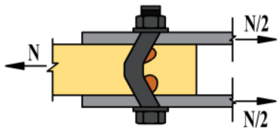
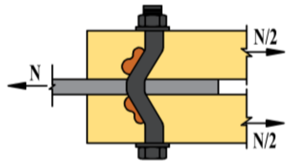
| Influencing Factors | Literature | Note |
|---|---|---|
| The *L*/*D* ratio | Soltis et al. [27] | Propose the concept of the ratio of main member thickness to bolt diameter (*L*/*D*) (the ratio of dimension (*L*) divided by the diameter of the bolt (*D*)). |
| | Li et al. [28] | The thickness to diameter ratio is the main factor that determines the load-bearing performance of the bolt. |
| | Yasamura [29] | When *L*/*D* is certain, the load capacity decreases with the increase of the number of bolts. |
| Position of the bolt | Trayer [30] | Propose the concept of center distance, edge distance, and end distance of bolted. |
| | Doyle et al. [31], Chen et al. [32] and Echavarrá [33] | The influence of end distance and center distance on the mechanical properties of bolted connections. When the end distance is small, the bolt diameter is the main influencing factor; when it changes from 4*D* to 6.7*D*, the load-bearing capacity increases. |
| | Sun et al. [34] and Gehloff [35] | The decrease in edge distance increases the ultimate bending moment. |
| Water content | Green [36] | The load-bearing capacity decreases with increasing water content and gradually stabilizes. |
| | Cousin et al. [37] | When the wood is dry, the joints break rings in the form of brittle damage in general. |
| Load action | Rosowsky et al. [38] | Short-term loads have less effect on bolted connections. |
| | Trayer [30] | The direction of load has a significant impact on the bearing capacity. |
| Group role | Wilkinson [39]and Gattesco et al. [40] | The same number of multiple bolts is less than the sum of the bearing capacity of single-bolt joints. |
| | Mohammad et al. [41] and Luo et al[42]. | The damage modes of multi-bolt connections are mainly shear damage and tear damage. The use of multiple bolts makes it more likely that splitting and ring breaking will occur. |
| Fiber orientation | Kei et al. [43] and Baba [44] | The orientation of the fibers around the bolted connection hole affects the form of damage. |
| | Yang [45] | Good bearing capacity and ductility of smooth specimens. |
| Other factors | Wang [46] | The connections with larger bolt diameters have higher stiffness. |
| | He et al. [47] | Compared with common engineered wood, glued bamboo and reconstituted wood have improved the energy dissipation capacity of the joints. |

### 3.1 Damage Modes

The damage modes serve as a way to visualize the effect of each factor on the performance of the connection. According to European Yield Model (EYM) of Johanson [48], **Table 3** shows three types of steel clamp plate-engineered timber bolted connection damage modes(European Committee for

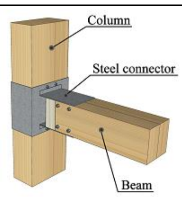
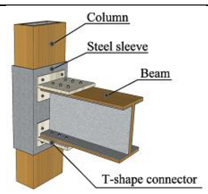
Standardization 2016) [49]. I: When the bamboo thickness is thin, the damage form is only dowel-bearing damage. As the bamboo thickness increases, dowel bearing damage and bolt bending occur simultaneously. II: Dowel bearing damage and bolt single hinge damage occur simultaneously. III: Dowel bearing damage and bolt double hinge damage occur simultaneously. Similarly, the damage modes of slotted-in steel plate bolted connections also depend on the engineered bamboo thickness and bolt diameter ($L/D$). The damage mode is determined by the size of $L/D$, with values less than 11.3 indicating I, 11.3<$L/D$<14.4 indicating II, and values greater than 14.4 indicating III [50].

**Table 3.** Damage modes of bolted connection in EC5

| Forms of connection | Steel clamp plate bolted connection | | Slotted-in steel plate bolted connection |
|---|---|---|---|
| | Thick steel plate | Thin steel plate | |
| I |   |   |   |
| II |   | |   |
| III | |   |   |

As the application of bamboo and wood structures continues to grow, the form of connection has diversified beyond steel clamp plate bolted connections and slotted-in steel plate bolted connections. T-shape connectors have good plastic deformation and obvious failure precursors, which are usually combined with steel sleeves as steel sleeve connections [52, 53]. At present, bamboo structure beam-column steel sleeve connections have two types in **Table 4**: one is the combination of bamboo members and steel connectors of different bamboo materials; the other is the combination of thin-walled steel and bamboo plywood through the adhesive into various structural members and through the combination of steel connectors.

**Table 4.** Types of steel sleeve connection

| Performance indicators | Steel-bamboo members composite [51] | Thin-walled steel-bamboo plywood composite [24] |
|---|---|---|
| Test specimen |   |   |
| Damage process | The damage mainly comes from the buckling of the beam flange steel plate under compression, but the steel plate does not show a yielding phenomenon. | The damage mainly from bamboo plywood and thin walled steel plates debonding. There is steel plate flange buckling and steel cylinder weld cracking. |
| Phenomenon analysis | When reversing the load, the steel plate and the bolt revert to contact, and there is a slippage phenomenon in this process. As a result, the hysteresis loops have a slight "pinching". | The "pinching" of hysteresis loops, is mainly caused by the slippage between the channel steel flange plate and the bamboo plywood, or the high-strength bolt and the section steel flange. |

Due to the characteristics of bamboo fiber distribution, its resistance to shear and splitting is relatively low, leading to eventual failure in bolted connections through bamboo splitting or shearing along the grain [54]. The sleeve connection form improves the weakening problem of the member and gives the member better integrity. They recorded the moments ($M$) and angles ($\theta$) of connection under cyclic loads tests, and found that the length-to-thickness ratio of the steel sleeve steel plate is crucial. **Fig. 3** shows that the connector with a large length-to-thickness ratio is ductile. Conversely, connectors with a smaller ratio are more susceptible to weld failure, and their envelope profile shows little post-peak strength degradation.[55].

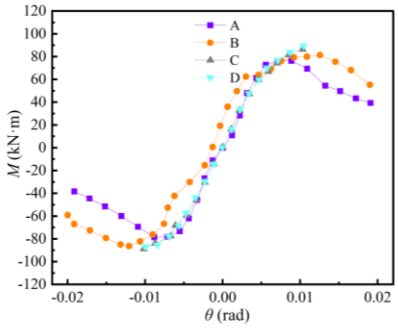
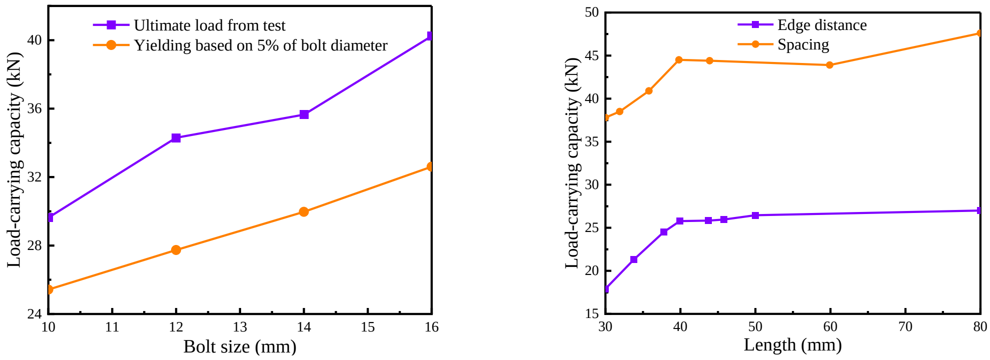



**Fig. 3.** Envelope curve of different length-to-thickness ratios (Length-to-thickness ratio: A=13.33, B=10, C=8, D=6.67).

## 3.2 Strength

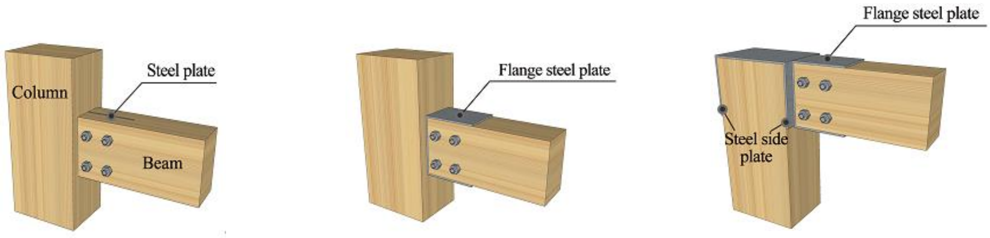
Current codes and standards for the design of engineered bamboo structures are not fully established, hence it is common to refer to various standards (such as GB, NDS, and Eurocode 5) to derive the calculation formula for the design value of connection strength [56]. In the formula, controlling the effects of material texture, processing technology, and other factors is challenging, so a reduction coefficient is often employed. Therefore, the number, diameter and arrangement of bolts are the main variables. **Fig. 4**(a) show that increased bolt diameter, the connection capacity of single bolt increases approximately linearly. **Fig. 4**(b). shows that the edge distance is greater than 5$d$ or the spacing between multi-bolt ($d$ is the bolt diameter=8 mm), the load capacity of the connection can be easily stabilized [57]. Due to the structural composition of bamboo and wood material, it is easy to break along the fiber direction when subjected to shearing force, resulting in poor connection performance of the bolted beam-column connections.




(a) (b)

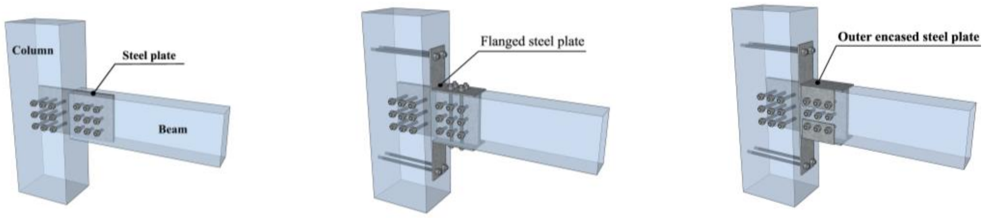
**Fig. 4.** Effect of bolts on load-carrying capacity.

Compared to traditional slotted-in steel plate bolted connection (**Fig. 5**(a)), adding flanges on both sides of the steel plate can effectively prevent damage along the fiber direction. The moment capacity of the middle of column connection (**Fig. 5**(b)) and the top of column connection (**Fig. 5**(c)) were increased by 78.7% and 123.0%, respectively [58]. Monotonic and cyclic loading tests were performed on two other reinforcement types as shown in **Fig. 6**(b) and **Fig. 6**(c). Comparison of their mechanical properties, such as the initial stiffness ($K_e$), plastic stiffness ($K_p$), Ductility ratio ($\mu$), maximum moment resistance ($M_{max}$) and relative rotational angle ($\theta_{max}$). It was found that the outer encased steel plates acted as a restraint to the fibers and retards the development of cracks. Not only the moment is improved, but also the stiffness and ductility are improved to a certain extent (in **Fig. 7**). Apart from steel plate reinforcement, increasing the friction surface slip resistance factor improve the flexural strength. Replacing bolts on coach screws could secure it tighter and increase overall integrity [59]. Using of reinforcing screws can increase the moment by approximately 36% [60].




(a) Slotted-in steel plate bolted connection (b) Flanged slotted-in steel plate bolted connection (middle of column) (c) Flanged slotted-in steel plate bolted connection (top of column)

**Fig. 5.** Schematic diagram of flanged slotted-in steel plate bolted beam-column connection.




(a) Slotted-in steel plate (b) Flanged steel plate (c) Outer encased steel plate

**Fig. 6.** Schematic diagram of the reinforcement structure of the slotted-in steel plate bolted connection.

Self-tapping screws enhance shear resistance, are easy to install, and do not affect aesthetics [61]. The strength of the bamboo material itself is significantly reduced after damage, and the combination of steel clamp bolted connection and slotted-in bamboo-steel plates bolted connection can make the bamboo material recover most of the deformation after unloading and maintain a certain bearing capacity [62].

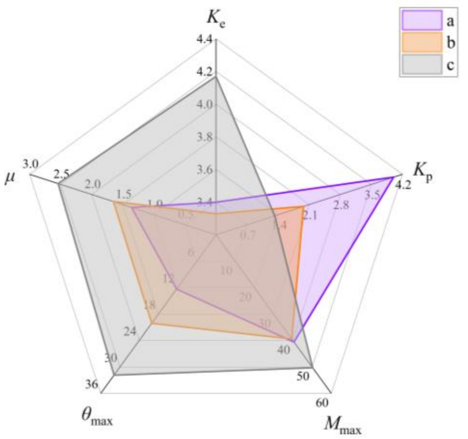



**Fig. 7.** Mechanical property parameters of the three forms of bolted connection in **Fig. 6**.

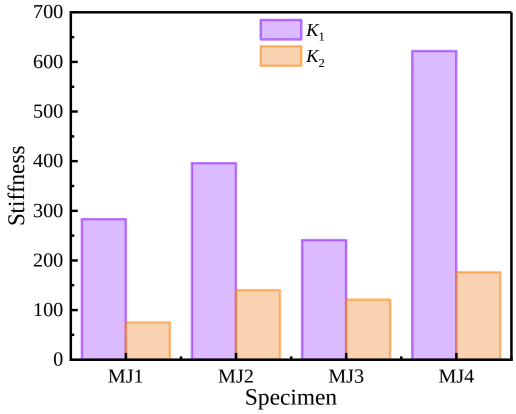


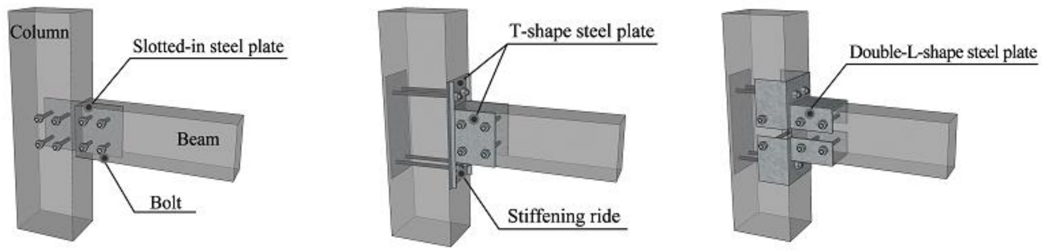

**Fig.8.** First stiffness of the connection.

The strength of the steel sleeve connection is related to the design of the steel sleeve shown in **Fig. 8**. When the thickness is 4 mm (MJ1), the steel plate bulge at the connection due to the low strength of the connection; When the thickness is 6 mm (MJ4), there is no deformation at the joints, but the energy dissipation capacity is poor; the connection performance is better when the thickness is 5 mm (MJ3). Without changing the thickness of the steel sleeve steel plate (5 mm), increasing the thickness of the beam flange steel plate is beneficial to improve the first stiffness of the connection [51] (The moment-rotation curve of each specimen has a turning point, and the stiffness before the turning point is called the first stiffness $K_1$, and the stiffness after the turning point is the second stiffness $K_2$).

### 3.3 Ductility

Ductility refers to the deformation capacity of a structure or member after it has entered the plastic state, and it is one of the indicators for assessing the seismic performance of a structure, calculated using the ductility coefficient (the ratio of ultimate displacement to yield displacement) [63].The deformation usually includes the elastic deflection of the beam, the integral deformation of column, the shear deformation and the overall deformation of the beam-column connection. The deformation is mainly reflected by the displacement and moment-rotation. From a practical point of view, both axial displacement and shear displacement are small. The magnitude of the relative angle of rotation can more intuitively represent the deformation capacity of the joint and reflect its rotational performance [64].

The rotation of the joints causes relative displacement of the bolts and the bamboo, which is one of the factors that affects the performance of the connection. Increasing the bolt edge distance reduced the reaction force, which weakening the bending strength. And the smaller edge distance reduced the bending capacity of the outer material of the bolt, thus increasing the parallelogram tensile stress and reducing the deformation capacity [65]. In addition, when the bolt diameter is smaller, the effective area of material bearing is also smaller, which increases deformation due to stress concentration around the bolt hole, thus reducing the stiffness of the joint. Adopting a staggered arrangement instead of a parallel one can result in less degradation of the overall joint stiffness and thus better seismic performance.




(a) I-connection (b) T-connection (c) Double-L-connection

**Fig. 9.** Three types of bolted beam-to-column connections.

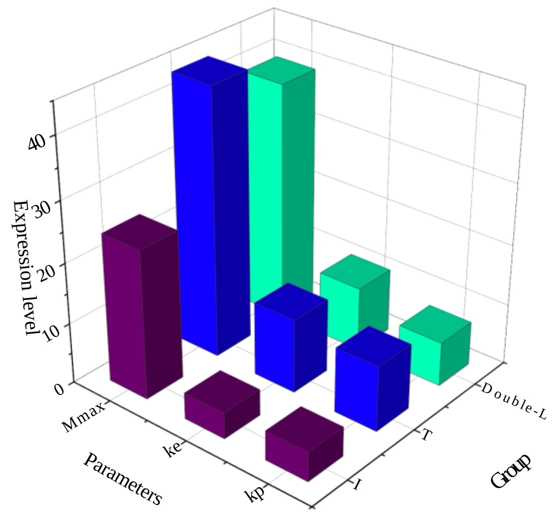
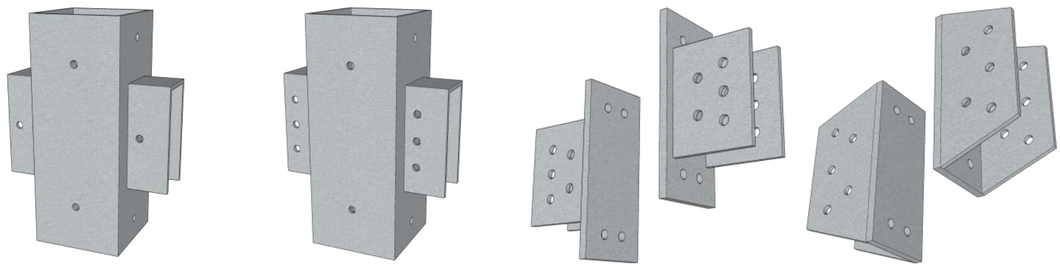



**Fig. 10.** Mechanical property parameters of the three forms of connection in **Fig. 9**.

Bamboo is prone to splitting during joint rotation, it is common to use reinforcement techniques to improve such issues. **Fig. 9** illustrates the T-connection and double L-connection are both higher than I-connection in elastic stiffness, plastic stiffness, bearing capacity, and energy dissipation. The mechanical property parameters of the three connection forms are shown in **Fig. 10**. Compared with the I-connection, the outer wrapped steel plates play a restraining role on the cracks, thus enhancing the deformation capacity of the joint, and the double L-connection increases the angle of rotation by up to 348.1% compared with the I-connection [66, 67]. As shown in **Fig. 11**, four cruciform connections were tested under cyclic loading. Joint No.1 is made of two U-groove steel plates welded to the column sleeve on one side. The design of joint No.2 takes into account the damage form of joint No.1 and possible weak parts, so it is reinforced on the basis of joint No.1, and the U-shaped bracket is fixed on the steel sleeve by double-sided fillet weld. The design of joint No.3 avoids the gap between the steel sleeve and the column in joint No.1 and 2, and the beam end utilizes two staggered bolts to better limit the rotation of the beam end. Joint No.4 is connected by a whole steel plate rolled into a U-shape, avoiding welding and ensuring the integrity of the connection. The results show that when the assembled joints also use this form of outer wrapped steel plates, the integrity of the connections is more important for the seismic performance. Unlike the other three joints, Joint No.4 does not use welded connections but instead opts for roll forming. This not only saves steel but also improves the flexural strength of the joint [68]. Besides, the installation of stiffening ribs is also a reinforcement method. The corner of the beam end without stiffening ribs is larger than that with stiffening ribs, which means that the stiffness of the frame beam end with stiffening ribs increases, and the deformation decreases. To verify the reliability of the experimental data, and based on the fitted *M*-*θ* polynomials [24], numerical simulations of the steel-bamboo frame were conducted. The results show that the stiffening ribs increased bearing capacity, good ductility, and seismic performance, which accorded with experimental results.



(a) No.1 (b) No.2 (c) No.3 (d) No.4

**Fig. 11.** Stereoscopic view of the four connections.

The end distance and spacing of bolts have little effect on the ductility, which is instead enhanced by the staggered arrangement of the bolts. However, too many columns can lead to poor ductility [69]. The most common method to improve this problem is to use numerous small diameter bolts, so that the connection is easy to deform in order to achieve energy consumption, but its disadvantage is not easy to construct [70]. In addition to the form of construction, ductility also depends on the splitting or shear properties of the material [71]. Bamboo has low shear and splitting resistance, and replacing common bolts with shear connector type (i.e., screw, high strength bolt) can effectively retard the cracking of the material. This not only can improve the ductility and seismic performance of the joints, but also enhance the lateral force resistance of the structure [72]. Effect of size effect by numerical simulation is analyzed (**Table 5**). The connections of two different scales of scaling are all showing too low bearing capacity, and setting stiffening ribs and connecting with high strength bolts meet the requirements of semi-rigid joints [73].

**Table 5.** Scale model comparison table

| | | 1:2 scaling ratio | 1:3 scaling ratio |
|---|---|---|---|
| Model | Beam, column | Beam189 | Beam189 |
| | Beam-column connection | Combin39 | Combin39 |
| | Concentrated mass of the structure | Mass21 | Mass21 |
| stiffeners at the connection | | Yes | Yes |
| Bolt number | | 4 | 4 |
| Analysis results | | The hysteresis loops are fuller; the joint ductility coefficients are all greater than 2. | The ductility coefficients of each layer are greater than 2, and some even reach 5. |

Compared with bolted connection, steel sleeve connection can enhance the integrity of upper and lower frame columns, and its joint ductility factor can reach up to about 5 [74]. The setting of stiffening ribs plays a strong restraining effect on the joint domain and forms a whole with the steel casing, which can reduce the deformation of the beam body due to the force. This form of connection is similar to the effect of bolted connections and also fulfills the requirements of semi-rigid joints.

### 3.4 Energy Dissipation

The energy dissipation capacity can evaluate the seismic performance, and it uses the shape of the hysteresis curve to determine energy dissipation. The two ways of energy dissipation and damping are the member material itself and the connection form. The steel-bamboo connection not only improves the initial stiffness, but also has high ductility and energy dissipation, and can be used as a sustainable alternative to reinforced concrete [72]. Bamboo does not have a high energy dissipation capacity after deformation, but the accumulation of damage before joint damage is not severe due to the stiffness of scrimber. **Fig. 12** shows that when comparing the second and third cycles, the energy consumption of the steel-reconstituted bamboo is greater than that of the same type of laminated bamboo joint [67].

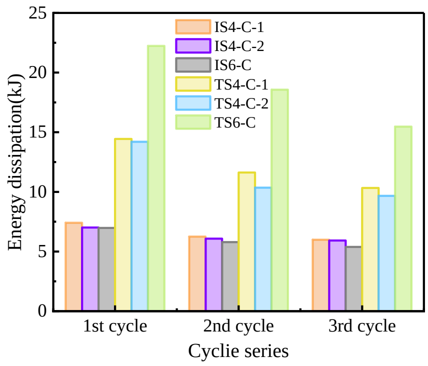
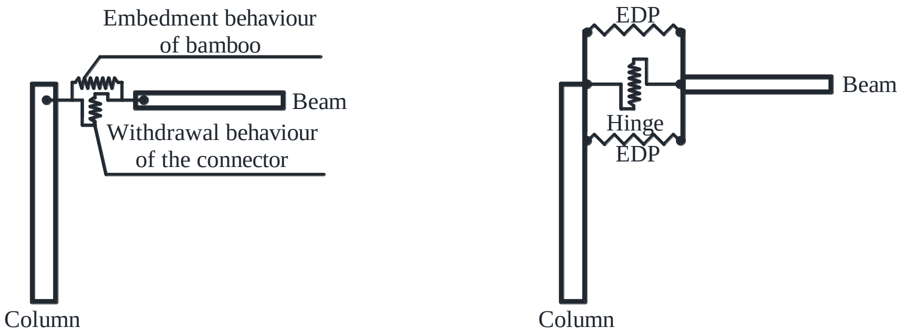



**Fig. 12.** Summation of energy dissipation.

The common bolted connection has a certain energy dissipation, but the frequent occurrence of earthquakes has led to more demanding in terms of seismic performance[75]. A variety of energy dissipation members are used to improve the seismic performance of the joints, and members are generally non-bearing members or devices set in certain parts of the structure (such as connections or joints). The energy dissipation panel (EDP) is to balance the bending moment by using the deformation of tension and pressure, in order to achieve energy dissipation and vibration damping (**Fig.13**). The study found that the length-to-thickness ratios affect the performance of energy dissipation. When the length-thickness ratio of EDP is 8~12, the failure mode of EDP is ductile. The damaged part can be controlled on EDP, while other parts are not damaged [55]. The calculation of energy dissipation, based on the area of a standard hysteresis loop, necessitates ensuring the validity of the resilience model. The finite element software is used to optimize the model parameters, to avoid the failure of the model due to its inherent complexity. Structural dynamic non-linear time course analysis uses natural seismic waves, and its simulation analysis results are in good agreement with the test [76].




(a) Common beam-column connection (b) Energy-dissipation beam-column connection

**Fig. 13.** Close-up of the numerical model of the beam-column connection component.

The assembled structure is one of the main forms of bamboo buildings, but the integrity and stiffness of assembled buildings are weak, in need of force on improving seismic resistance and energy dissipation. In frame structure, the frame beam transfers the vertical shear force to the frame column, which tends to cause stress concentration at the end of the column, causing brittle damage to the wood material. Full section pressure bearing of the column through steel sleeve connection (material is Q235), the structure dissipates seismic forces through plastic deformation of joints. And its ductility coefficient reaches about 5, the effective damping ratio can reach 20% [77]. Due to the similar mechanical properties of wood and bamboo, designed a new beam-column assembled sleeve joint composed of Q235 connectors and bamboo scrimber, it also had remarkable energy dissipation capacity [78]. Steel plate thickness affects the energy dissipation, and the first secant stiffness is higher under cyclic loading [79]. On this basis, increasing the thickness of in thickness of beam flange steel plate -can not only improves the bearing capacity, but also promotes the rotation capacity and initial rotation stiffness [51].

## 4 Discussion

With the growing environmental problems, green materials are getting more and more attention. In recent decades, structural bamboo (wood) has become a new trend because of its low cost and good seismic resistance. In structural seismic design, the beam-column connection is the key point in structural design. Due to the similarity between bamboo and wood, the beam-column joints of the steel-engineered bamboo composite were studied by referring to the common beam-column joints of the wood structure. The following is the discussion of the current research results in this paper:

(1) Engineered bamboo materials

At present, performance of common engineered bamboo is slightly inferior to that of steel, which is decided by the materials and microstructure characteristics of each component of bamboo. Bamboo fiber are composed of vascular bundles and parenchyma cells, serving as a main component of bamboo mechanical properties [80]. The bamboo fiber is distributed unidirectionally along the longitudinal direction (along the height direction of bamboo), and the cross-section is distributed gradient, resulting in low shear and splitting resistance [54, 81]. Therefore, unlike steel, bamboo is a material with uneven material, discrete mechanical properties and anisotropy. Compared with wood, bamboo fiber is fine and dense, which is regarded as reinforcement, so its performance is superior to engineered wood.

LBL is formed by the parallel cementation of all the plates along the grain, so the longitudinal strength is high and the transverse strength is low. The glued bamboo is composed of bamboo strips perpendicular to each other according to adjacent layers, and its material properties are more similar to those of round bamboo, so the material properties are poor. Recombinant bamboo is made of a bamboo fiber bundle as the basic unit. It is a kind of engineered material with high strength, high density, and uniform material, so it has better performance than other engineered bamboo materials.

(2) Connection forms

The connection forms of modern bamboo buildings are mainly glued connections and metal connector connections. The metal connector connection is mainly in the form of bolted connection, steel sleeve connection, and all kinds of energy dissipation joint connection. When the component forms are different, the connection forms of joints are also different. There are two main forms of modern bamboo components: one is made of cold-formed thin-walled steel and bamboo plywood; the other is made of reconstituted bamboo or integrated bamboo.

The combination of cold-formed thin-walled steel and bamboo plywood often experiences debonding, but the cold-formed thin-walled steel hasn't yielded. The reason is that the large deformation difference between the two materials. In the test process, due to the uneven thickness of the sample material, resulting in large interface stress on the bonding surface. When the interface stress reaches the adhesive strength, there will be a bond failure. Then that the specimen will lose the overall mechanical properties before the thin-walled steel yield, namely, the degumming phenomenon. So, improving bonding strength to prevent delamination and fully utilizing mechanical advantages of components [82]. This kind of steel-bamboo composite beam and composite bamboo are usually connected by steel sleeves. The steel sleeve connection solves the connection problem between the column and the column to a certain extent, and strengthens the integrity of the component. However, the production, processing, and installation of components require high precision.

Components made of LBL or BSL are mostly bolted, and the ultimate failure of bolted connection are that the bolt section is striation splitting or bolt bending. This happens because when the joint rotates, the bolt hole wall bears lateral tensile stress. The transverse tensile strength of bamboo is low, so the bending capacity of the screw determines the load capacity of the joint [83]. Although outsourcing steel is helpful to delay the development of cracks, and connection properties of bamboo joints and bolts need further study. The improvement of bamboo performance is mentioned in (1). Regarding bolts, the primary topics of discussion include their type, layout, number, and size.

(3) Seismic performance

Seismic performance depends on the relationship between structural stiffness, bearing capacity, and ductility. Increasing structural stiffness can reduce the loss of earthquake disasters at a cost of reducing ductility. Good seismic performance is due to each component fully exerting its bearing capacity, and the first thing is to strengthen the connection between components to meet the strength requirements when transmitting seismic force and the ductility requirements in order to adapt to large seismic deformation.

The splitting problem of bolted connections is almost inevitable. Although outsourcing steel plates or other reinforcement measures can effectively limit the extension of cracks, as the crack widens the load carrying capacity fails. Therefore, the joint performance can be improved by improving the deformation capacity (rotation angle) of the joint [84]. The steel sleeve is made of steel plate by welding. Increasing the weld size will slightly reduce the ductility of the joint, so the weld quality of the steel sleeve affects the mechanical properties of the joint. The strength and stiffness of assembled steel sleeve energy dissipating joints after deformation is low. The energy dissipation joint uses the deformation of steel to offset part of the seismic force. Since Q235 steel has good elastic-plastic deformation ability, it is usually chosen as the material of energy dissipation components. In the design, the plate thickness is mainly used as a variable to avoid buckling of the plate before yield. In contrast, energy dissipation joints yield through the steel plate, so that the components are in an elastic working state, with good ductility and a damping effect.

Most of the steel-bamboo beam-column joints developed by scholars have only been implemented in local seismic performance tests. Because the seismic test is large, the number of test joints is generally small (3~9). Compared with the overall frame structure, the data obtained by joints are local, so there is a certain controversy. To verify the reliability of experimental data, experimental research and numerical simulation are combined. The finite element software used are mainly ANSYS and ABAQUS, so the modeling method is different. For example, the steel at the steel-engineered bamboo joint is set as a shell element or solid element, and the problems such as bolt slip, pin groove pressure and steel plate warping in the test cannot be accurately considered by solid modeling. To ensure the operational efficiency of the finite element software, appropriate simplification is made in the analysis. For example, bamboo is an anisotropic material, but to simplify the calculation, bamboo is usually considered isotropic. The contact between bolt and bamboo usually uses binding, and only a few studies consider bolt coupling.

## 5 Conclusions

### 5.1 Conclusions

Beam-column connection forms are an important element affecting the seismic performance of structures, as they play a crucial role in ensuring strength and ductility under static and dynamic loads. In this paper, the connection performance of steel-engineered bamboo beam-column nodes is analyzed, the existing research results of domestic and foreign scholars are summarized, the types of steel-engineered bamboo beam-column joints are briefly introduced, and the research contributions made by relevant scholars on steel-engineered bamboo beam-column joints are presented. The seismic performance parameters of various types of joints are evaluated, and the conclusions are drawn as follows:

(1) At present, the performance of engineered bamboo is better than engineered wood, which is verified in the implementation of engineered bamboo in buildings replace engineered wood. However, due to the fiber distribution characteristics of bamboo, its resistance to bending and splitting is comparatively poor. Thus, it is necessary to improve bidirectional performance of bamboo and to develop new engineered bamboo.

(2) Bolted connection: steel plywood bolted connection and steel infill plate bolted connection, compared with the mortise and tenon connection of wood structure, effectively solve the problem of mortise and tenon detachment; the combination form of various steel connectors and bolts, whose joint bearing capacity is higher. However, most of the bolted connections are required to slot the members, so it forms a kind of weakening to the members, which is not conducive to the joint force. Bamboo joints are prone to tearing and damage, which can compromise their load-bearing capacity.

(3) Steel sleeve connection: To a certain extent, it solves the problem of connecting columns to each other. It strengthens the integrity of the member, thus improving the bearing capacity and ductility. Its disadvantage is its high accuracy requirement for fabrication, processing, and installation. The strength and stiffness of assembled steel sleeve energy dissipating joints after deformation is low.

### 5.2 Future Work

With the frequent occurrence of earthquakes, more and more scholars are doing research on this aspect of structural energy dissipation and damping technology. There are more and more types of energy dissipation and damping techniques being studied, ranging from types of dampers to energy dissipation elements. However, for steel-bamboo structures, there are still some issues that need further research.

(1) Compared with the original bamboo, the shear and splitting resistance of the combined bamboo materials were improved, but the theory about the biaxial anisotropy mechanics needs further verification;

(2) Existing research on energy-consuming joints has less practical application in engineering when compared with other connection methods joints, and studies on the feasibility of application in earthquake-prone areas is not sufficient. Therefore, subsequent research should focus on the developing high energy-consuming and low cost devices to expand application scope;

(3) Previous research on seismic performance mainly used quasi-static tests. Reciprocating load is usually used to simulate seismic load, but it is different from the effect of building structures under earthquakes. In terms of design, the seismic load is more suitable for practical engineering applications;

(4) A multitude of studies on the finite element analysis of joints are modeled by perspective methods. However, it is difficult to compare and summarize the differences in calculation results and not to mention to judge the reliability and accuracy of various finite element models. Therefore, starting from the principle of the finite element, the general method of joint finite element modeling is summarized, which will be beneficial to the development of finite element analysis;

(5) At present, there are more theoretical studies on steel-engineered bamboo beam-column joints, with relatively few practical applications in engineering. Only some certain projects have applied steel-engineered bamboo beam-column joints with only one or two floors, the number of floors is one or two, and the scope of architectural application is even more limited.

### Acknowledgement

This research was funded by the Key Research and Development Program of Shaanxi (Program No.2022SF-085), the Opening Fund of State Key Laboratory of Green Building in Western China (LSKF202116), Science and Technology Plan Project of Yulin (CXY-2020-053), and Key Laboratory of Well Stability and Fluid & Rock Mechanics in Oil and Gas Reservoir of Shaanxi Province (No. WSFRM 20200102001).

### CRediT authorship contribution statement

**Yang Liu**: Conceptualization, methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Kun Liu**: Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Wentao Wang**: investigation, formal analysis. **Linlin Fan**: Supervision. **Binbin Li**: data curation.All authors have read and agreed to the published version of the manuscript.

## Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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