

# Review of Connections for Engineered Bamboo Structures

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**Abstract:** Bamboo is a green building material that is environmentally friendly and has great development value. However, the limited mechanical properties and heterogeneous dimensions of natural bamboo poles curb the application of bamboo in building structures. A transverse section of engineered bamboo is regular and compact, and its mechanical properties are stable, which can meet the requirements for physical and mechanical properties of materials in modern building structures. Though application of engineered bamboo has just started, it is of great significance to study the connection performance and corresponding influence factors for popularization and application of modern bamboo structures. This paper is focused on a review of research progress for connections in engineered bamboo structures. Firstly, a study on embedding strength and the performance of bolted joints is presented, including calculation methods described with a proposal for future development of standards suitable for the characteristics of engineered bamboo materials. Secondly, research on carpentry joints is introduced, namely tenon-mortise joints, nail joints and truss plate joints. Finally, some engineering examples are briefly introduced. This work can provide a reference for further research on connections in engineered bamboo structures.

**Keywords:** Engineered bamboo; connection; connection calculation; embedding strength

## 1 Introduction

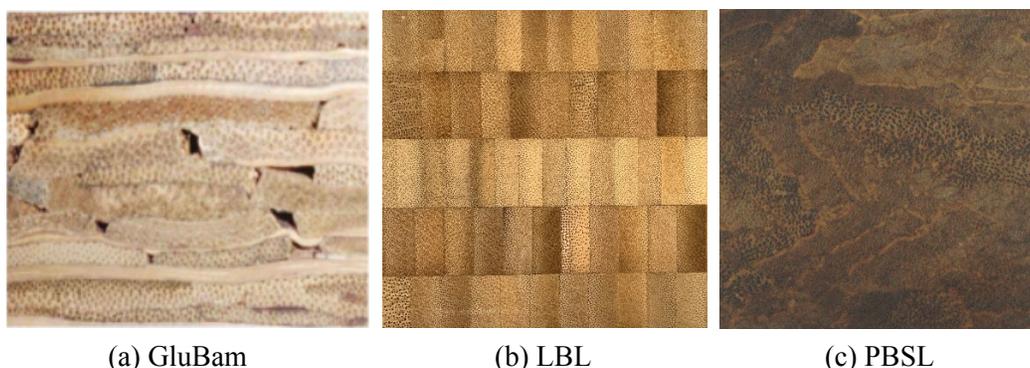
Bamboo is one of the few renewable resources in the world and an important non-wood product which can be used in many fields of application especially in residential buildings [1]. Bamboo has been used as building materials since ancient times and has a history of thousands of years. In ancient times, bamboo was used to build houses because of its relatively high strength and excellent flexibility. In modern times, people choose bamboo as building materials for the pursuit of natural texture as well as low-carbon environmental protection characteristics. In recent years, with the global development of economy and society, the progress of science and technology, and the promotion of national policies, bamboo structures have the potential to coexist with the ecological environment during their whole life cycle as a future development direction.

The connection of natural bamboo poles in buildings has always been a major difficulty in the application of bamboo [2]. Because of the complex form of natural bamboo joints, the construction process of natural bamboo joints is always confronted with problems such as inconvenience and poor reliability of connection, which severely hinders the development of natural bamboo buildings. In addition to the performance of the joints, the hollow and thin-walled characteristics of the raw bamboo curb the application as well [3]. Although some research has been carried out on the improvement of basic materials, it still cannot solve the problem perfectly [4], [5], [6]. However, the appearance of engineered bamboo can effectively solve these problems.

Typical forms of engineered bamboo used in building structures are laminated bamboo lumber (LBL),

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59 parallel bamboo strand lumber (PBSL) and GluBam (Fig. 1). Laminated bamboo lumber [7], [8], [9], [10],  
60 [11], [12], [13], [14], is made by gluing the thin flat laminates with a certain width and thickness together.  
61 The bamboo culm is disassembled into thin flat laminates firstly. After being dried to a moisture content of  
62 8%~12% and removed the inner skin and outer skin, the flat laminates can be glued together to form  
63 laminated bamboo lumber under hot pressing (or cold pressing). The cross-section size and length of LBL  
64 can be flexibly controlled by the current manufacturing technology, which can solve the limitation of  
65 member size and enhance dimensional consistency, strength and uniformity. When a larger cross-section is  
66 required, only the cold pressing process can be used. Because the hot pressing process cannot ensure that  
67 bamboo laminates are heated uniformly. If the temperature or the hot pressing time is increased, the degree  
68 of carbonization of bamboo laminates is uneven, and the outer laminates are easy to crack. However, the  
69 cold pressing process also has the problem of time-consuming. GluBam [15], [16], [17], is a composite  
70 material with a special arrangement of fibers and processed by special technology. The greatest advantage  
71 of GluBam is that it can determine the direction of layers and the ratio of longitudinal and transverse fibers  
72 in the interior according to the structural requirements. When making beam and column components,  
73 increasing the ratio of longitudinal and transverse fibers as much as possible is beneficial to improving the  
74 strength of GluBam and the utilization ratio of materials. However, an unreasonable ratio may lead to a  
75 larger deformation of GluBam panel and weaker transverse properties, which will cause adverse effects on  
76 processing and construction. Therefore, under the existing technical conditions, the most applied fiber ratio  
77 is 4:1, and the thickness of GluBam panel is 30mm [16]. This type of panel has good longitudinal  
78 mechanical properties, and a certain amount of fibers in the transverse direction can ensure the integrity of  
79 materials and components in the secondary direction. Parallel bamboo strand lumber [18], [19], [20], [21],  
80 [22], [23], [24], [25], [26], [27], [28], [29], is made by gluing the bamboo filament bundles together. The  
81 bamboo culm is disassembled into long bamboo strands firstly. After being dried and charred, the strands  
82 can be put into the molds and pressed into parallel bamboo strand lumber under hot pressing (or cold  
83 pressing). PBSL material and its texture are similar to hardwood, so it is welcomed by consumers. However,  
84 the disadvantage of this material is that the amount of adhesive is large, and the adhesive cannot be  
85 characterized by low cost and high bonding strength at the same time [19].

86 In contrast to timber, usable bamboo can be harvested in 3-4 years, and the mechanical properties of  
87 engineered bamboo compare favorably with those of timber [30]. Compared with natural bamboo, the  
88 mechanical properties of engineered bamboo are uniform and stable, but its physical properties change  
89 greatly. The transverse section is regular and compact, and the dimension is easy to be unified, so the rapid  
90 and mass production of steel member joints can be realized. At present, there are many studies on  
91 connections of timber structures, but relatively few on modern engineered bamboo structures. By studying  
92 the existing literature, it is found that the research of engineered bamboo connection can be roughly divided  
93 into bolted joints, tenon-mortise joints, nail/screw joints, truss plate joints. This paper summarizes the  
94 research progress of engineered bamboo joints, in order to provide a reference for the research and  
95 application of connection in engineered bamboo structures.



106 **Figure 1:** Common cross section forms of engineered bamboo (a, [17]; b, c reproduced with permission  
107 of Dong Yang)  
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## 2 Bolted Joint

Bolted joints are widely used in timber structures [31], [32] and have the advantages of simplicity, reliability and convenience, which can fully exploit the mechanical properties of the connected materials. There are many kinds of bolted joints, which can be classified into three types according to the stress conditions (Fig. 2): single shear connection, double shear connection, and multi shear connection. According to the position of steel plate, they can be classified into two types: bolted joint with steel splints and bolted joint with embedded steel plates. They can also be classified according to whether the metal plate is used or not [33].

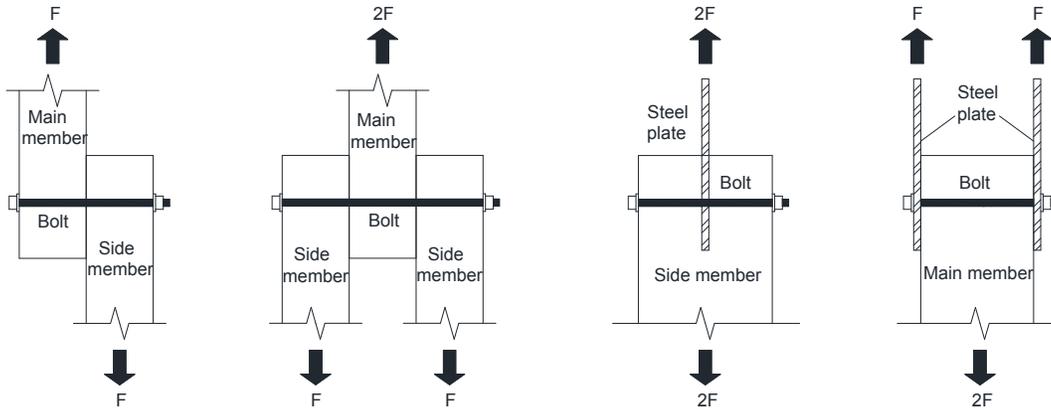
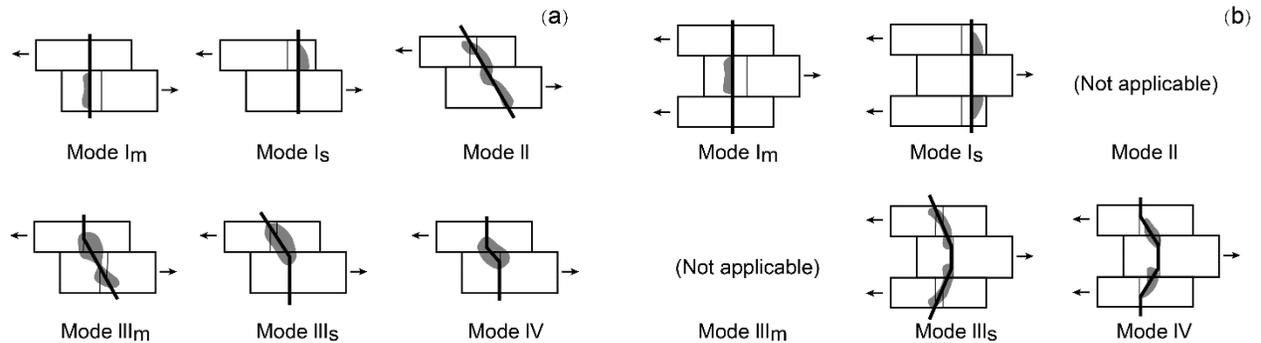


Figure 2: Schematic of single shear and double shear connection

### 2.1 Failure Mode of Bolted Connections

If there is no restriction on the construction of bolted joints, the joints may be damaged in many ways. In the study of bolted joints in timber structures, there are four main failure modes of connections (Fig. 3):



(a) Four failure modes of single shear connections (b) Four failure modes of double shear connections

Figure 3: Failure modes of bolted connections [34]

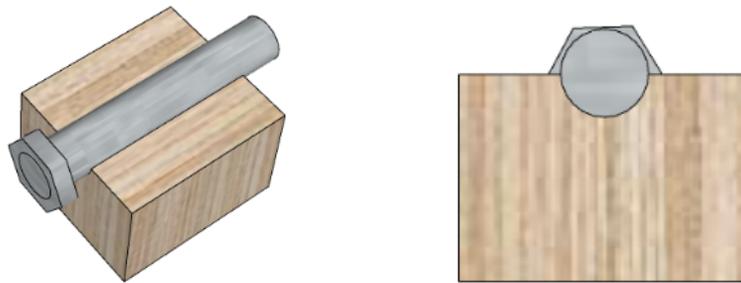
The failure mode I is determined by the strength of either the main ( $I_m$ ) or side ( $I_s$ ) member, which belongs to wood bearing failure. When the connector is damaged, the main or side member reaches the ultimate strength and bolts remain intact. The failure mode II is a rotation of the bolt in the connector without bending. The failure mode III and IV are mixed failure modes, which are a combination of wood bearing failure and one or several plastic hinge formations in the bolt. When the connector is damaged, the bolt reaches the ultimate bearing capacity and forms plastic hinges, while the member reaches the ultimate strength as

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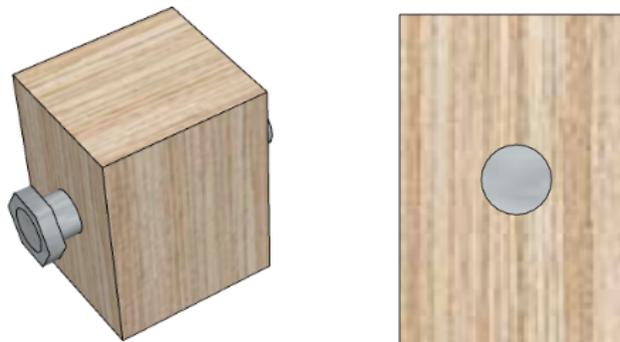
## 173 **2.2 Study on Embedding Strength**

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175 As early as 1932, Trayer [35] conducted axial compression tests on bolted joints. It was found that the  
176 performance of bolted joints was affected by the interaction between bolt bending and wood crushing. In  
177 1949, Johansen [36] put forward the European Yield Model (EYM) to predict the strength of bolted joints,  
178 which considered that the strength of bolted joints was mainly affected by two factors: the flexural strength  
179 of bolts and the embedding strength of wood. McLain et al. [37] and Soltis et al. [38] validated the  
180 applicability of EYM and perfected it to determine the yield strength of the connector within a specific  
181 precision range. In 1991, yield theory was introduced into the design code of timber structures in the United  
182 States to substitute the previous empirical design method. The theoretical calculation formula in the design  
183 code is closely related to the embedding strength of wood. Therefore, accurate determination of the  
184 embedding strength is the key to obtain the bearing capacity of bolted connections. Scholars have  
185 researched the embedding strength of engineered bamboo (Fig. 4-5).



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196 **Figure 4:** Schematic of half-hole test specimens



209 **Figure 5:** Schematic of full-hole test specimens

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211 Eratodi et al. [39] took the specific gravity  $G$  of material as the influencing factor and carried out  
212 experimental research and finite element analysis on the embedding strength of LBL. The results showed  
213 that the embedding strength parallel to the grain direction (parallel loading to grain radial, parallel loading  
214 to grain tangential) of the specimen was significantly higher than that perpendicular to the grain direction,  
215 which was found to be 54.13 MPa, 48.14 MPa and 30.27 MPa, respectively. Ramirez et al. [40] studied the  
216 dowel-bearing strength of LBL with the diameter of bolts and the direction of loading as the influencing  
217 factors. It was found that similar to wood, the dowel-bearing strength decreased as the fastener diameter  
218 increased because of the volume effect under the fastener hole, and the simulations indicated that this  
219 property depended on the specimen's width-to-fastener diameter ratio as well. Gonzalez [41] found that the  
220 direction of grain and the diameter of prefabricated holes did not have an effect on the embedding strength  
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227 of bamboo mat board and bamboo strip board, and the density of material was an essential factor to  
228 determine the strength. Based on the European Standard 383 test method, the embedding strength of  
229 bamboo mat board and bamboo strip board were 92.5 MPa and 86.2 MPa on average respectively.

230  
231 Li [42] comprehensively considered the influence of sample size, bolt diameter, moisture content,  
232 grain direction and loading direction, and carried out experimental research on the embedding strength of  
233 PBSL. The results showed that the sample size had no significant influence on the bearing strength under  
234 the premise of meeting the minimum requirements of size; with the increase of bolt diameter, the bearing  
235 strength decreased; with the increase of grain angle from 0° to 90°, the strength decreased firstly and then  
236 increased. The failure mode changed from a mixed failure of splitting in the parallel to the grain direction  
237 and crushing on the ends of sample, to a mixed failure of groove crushing and whole sample crushing, with  
238 45° sample as a turning point. Li et al. [43] analyzed the influence of bamboo lamination thickness, end  
239 distance and bolt diameter on the dowel-bearing strength. The results showed that the thickness of  
240 lamination had little effect on strength; when the end distance was not less than 64 mm, the influence of  
241 end distance was not significant; with the increase of bolt diameter, the dowel bearing strength  
242 approximately linear decreased.

243  
244 Zhou et al. [44] carried out monotonic loading tests on 15 PBSL specimens in parallel to the grain  
245 direction and 15 PBSL specimens in perpendicular to the grain direction. The results showed that the  
246 distribution of ultimate strength along grain direction was relatively stable, with an average value of 91.59  
247 MPa, and the failure of specimens showed obvious brittle characteristics; while the strength in  
248 perpendicular to the grain direction of the specimens varied greatly, of which the average value is 71.81  
249 MPa, while the failure showed good ductility. Zhou et al. [45] designed 5 groups of specimens with  
250 difference only in bolt diameter in order to study the influence of bolt diameter on the embedding strength  
251 of PBSL. It was found that the yield strength was stable, and the coefficient of variation was between 5.88%  
252 to 13.34%; with the increase of bolt diameter, the yielding strength decreased.

253  
254 Cui et al. [46] studied the influence of temperature on the embedding strength of PBSL. The results  
255 showed that the average ultimate strength was 75.2 MPa at 20 °C. The bearing strength gradually decreased  
256 with the increase of temperature between 20 °C to 110 °C. While in the temperature range from 110 °C to  
257 170 °C, the strength increased because of the water evaporation. When the temperature continued to rise  
258 between 170 °C and 270 °C, the strength decreased again due to the decomposition of bamboo fibers at high  
259 temperature. When the temperature arrived at 270 °C, the embedding strength was only 9.6 MPa. Tang [47]  
260 found that the embedding strength parallel to grain of PBSL was directly affected by the compressive  
261 strength parallel to grain, while the embedding strength perpendicular to grain was affected by shear  
262 strength perpendicular to grain and bonding strength between layers.

263  
264 Khoshbakht et al. [48] prepared specimens according to ASTM standard. The dowel-bearing strength  
265 of LBL was studied by experiment and finite element analysis. It was found that the failure area of the  
266 specimens occurred off-center of the contact region and was controlled by the shear stress-to-strength ratio.  
267 The tensile stress perpendicular to grain was often the primary cause of wood failure and was regarded as  
268 a secondary cause of failure. The friction coefficient was the critical factor to predict shear stress.  
269 Khoshbakht et al. [49] also evaluated the applicability of the testing method of dowel-bearing strength in  
270 ASTM D5764 standard for LBL. Three-dimensional bilinear finite element models for half-hole and full-  
271 hole were established. Based on Tsai-Wu failure criterion, the failure mechanism of half-hole and full-hole  
272 specimens was analyzed. The experimental and simulation results showed that the failure mechanism of  
273 half-hole and full-hole specimens was different and therefore care should be taken to select a reasonable  
274 test method suitable for engineered bamboo.

275  
276 In summary, scholars have considered the influence of different factors on the embedding strength of  
277 engineered bamboo. The main factors are material specific gravity, bolt diameter, end distance, loading  
278 direction, moisture content, grain direction, external temperature et al. However, most of the existing studies  
279 aimed at parallel bamboo strand lumber, and a few aimed at other types of engineered bamboo. The  
280 universality of the existing conclusions needs more analysis and verification by a large number of

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283 experimental studies.  
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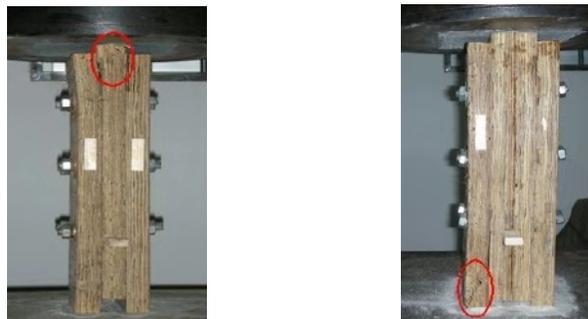
### 286 **2.3 Study on Performance of Bolted Joint**

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288 Scholars have carried out experimental research on the bolted connection of engineered bamboo. Li  
289 [42] selected end distance, the thickness of main member and bolt diameter as the influencing factors to  
290 study the bearing capacity of single-bolted joint. It was found that the initial stiffness, yield stiffness, yield  
291 load, ultimate load and ductility of the joint were affected to different degrees by the three factors. The  
292 ultimate load decreased with increasing end distance or bolt diameter but increased with the thickness of  
293 the main member increasing. There were two main effective failure modes for single-bolted joints, which  
294 were "one hinge" and "two hinges" failure mode. Both modes could fully exploit the mechanical properties  
295 of the material. Based on Foschi model, the experimental data were fitted, and the thickness of the main  
296 member was recommended to be set to 90 mm.

297  
298 Li [42] also carried out experimental studies on multi-bolted joints, and analyzed the effect of the  
299 number of bolt rows, row space, space between the adjacent bolts and the number of bolts per row on the  
300 bearing capacity of the joints. The results showed that with the increase of space between adjacent bolts,  
301 the failure mode of the specimens gradually changed from the mixture of row split and 'one hinge' yield to  
302 'one hinge' yield; with the number of bolt rows increased, the failure changed from single split to both sides  
303 split; with the increase of row space, the split failure of the specimen gradually disappeared, only the dowel-  
304 bearing failure and hinge yield failure occurred; the load distribution of multi-bolt joints was not uniform,  
305 resulting in uneven deformation of bolts.

306  
307 Zhang et al. [50] studied the bearing capacity and failure mode of the bolted joints. The experiment  
308 results showed that the main member and bolts were destroyed at the same time, which indicated that the  
309 joints had good overall mechanical properties and could ensure the effective transmission of shear force.  
310 Zhong et al. [51] conducted an experimental study on the compression performance of bolted joints with  
311 steel splint. The effects of board thickness and bolt diameter on stiffness, yield load and failure mode were  
312 analyzed. It was found that the failure modes of the joints were affected by both bolt diameter and thickness  
313 of bamboo board: with the increase of bolt diameter, the initial stiffness and yield load of the joints increased  
314 approximately linearly by 58.2% and 65.6% respectively (diameter of bolts were 12mm and 16mm,  
315 thickness of board was 60mm); with the increase of the thickness of the board, the ultimate load and  
316 ductility coefficient could be significantly increased by 19.7% and 36.3% (diameter of bolts were 12mm,  
317 thickness of boards were 60mm and 90mm).

318  
319 Yang [52] analyzed the failure mode and bearing capacity of the GluBam bolted joints according to  
320 the tightening force of the bolt and the thickness of the main board. The results showed that the bolted joints  
321 had high strength and stiffness, and could ensure the reliable transmission of shear force; the joint with  
322 tightening force occurred buckling failure mode in the main member and the side member (Fig. 6); the  
323 thickness of the main member had little effect on the bearing capacity. Yang [53] also studied the tensile  
324 properties of GluBam bolt joints around factors such as edge distance and end distance. Two main failure  
325 modes, which were shear surface extraction and net section broken (Fig. 6), were obtained. It was found  
326 that GluBam single-bolted joints had high bearing capacity and good ductility along the main grain direction.  
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339 (a) Buckling of main member (b) Buckling of side member  
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349 (c) Shear surface extraction (d) Net section broken  
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351 **Figure 6:** Test specimen of Yang [52], [53]  
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353 Feng [54] studied the lateral load-carrying capacity of bolted joints of four GluBam beam-column  
354 frame by monotonic and cyclic test (Fig. 7). The results showed that the bolts were not uniformly loaded:  
355 under monotonic loading, the bolts in the middle part could hardly bear the load, while under cyclic loading,  
356 the middle bolt could also participate in the seismic energy dissipation. Through the analysis of joint  
357 rotation, it was found that the joint was semi-rigid; the tearing of GluBam material was the main reason of  
358 joint failure. Zhou et al. [55] studied the mechanical properties, failure modes and failure mechanisms of  
359 the bolted PBSL-steel-PBSL joints by tensile test, and considered the thickness of side member and the end  
360 distance of bolts as impact factors. It was found that with the increase of the thickness of side member, the  
361 failure modes of joints changed from pure groove crushing to a mixed mode of groove crushing and bolt  
362 bending, and the bearing capacity and ductility of joints increased as well; the bearing capacity increased  
363 with the increase of end distance, while the effect could be neglected when the end distance was greater  
364 than  $7d$  ( $d$  is the diameter of bolt).  
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375 (a) Loading of GluBam frame  
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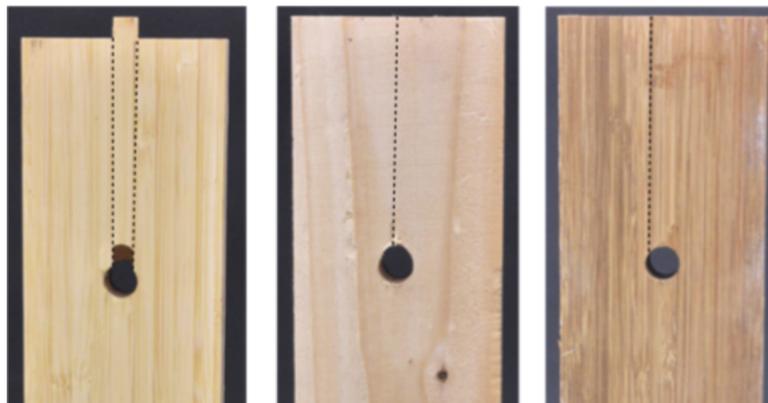
387 (b) Failure of test specimens  
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395 **Figure 7:** Test specimen of Feng [55]  
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397 Debije [56] studied the mechanical properties of LBL-steel-LBL bolted joints through a large number  
398 of experiments, and observed a variety of failure modes. Dai [57] studied the mechanical properties of  
399 single-bolted joints in parallel and perpendicular to the grain direction of PBSL with end distance and edge  
400 distance as the impact factors. The results showed that the failure modes of single-bolted joints could be  
401 divided into two types. The first was the failure controlled by end distance or edge distance. Within a certain  
402 range, the ultimate load of materials increased with the increase of end distance or edge distance. The  
403 second was the failure controlled by the strength of the material. The holes on the specimens were enlarged  
404 when damaged.

405 Wang [58] carried out 12 groups of single-bolted joints with steel splints under uniaxial tension at  
406 room temperature firstly. The effects of bamboo thickness, bolt diameter, end distance and the number of  
407 bolts on the bearing capacity of the joints were studied. The test results showed that each variable had  
408 different degrees of influence on the bearing capacity and failure mode of the joints. Based on the scenario  
409 of heating standard, the fire resistance of 24 groups at high temperature was tested. The results showed that  
410 the fire resistance limit time of the specimens increased by 54% on average when the load level decreased  
411 from 0.3 to 0.1 (0.3 to 0.1 times the ultimate bearing capacity), and the average fire resistance limit time  
412 increased significantly with the increase of the end distance and the edge distance.

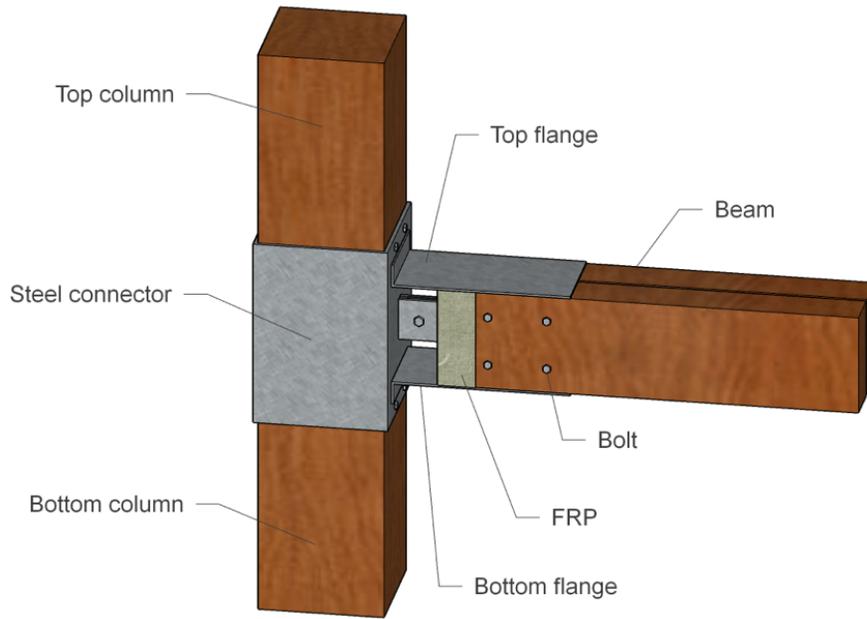
413 Reynolds et al. [59] compared the mechanical properties of the bolted joints of LBL and spruce, and  
414 found that the failure modes of the two joints were significantly different (Fig. 8). The LBL failed most  
415 often by the formation of a shear plug, and the failure occurred at the location of maximum shear stress.  
416 The spruce failed by a single split, which occurred at the location of maximum tensile stress perpendicular  
417 to the grain. Therefore, the design method for timber structure may not be directly applied to the design of  
418 LBL. Qin [60] studied the corner joint performance of LBL furniture. The results showed that the average  
419 tensile strength of bolt connection was 1354.3 N and the average compressive strength was 652.9 N, which  
420 indicated that the corner was more easily damaged under pressure than under tension.



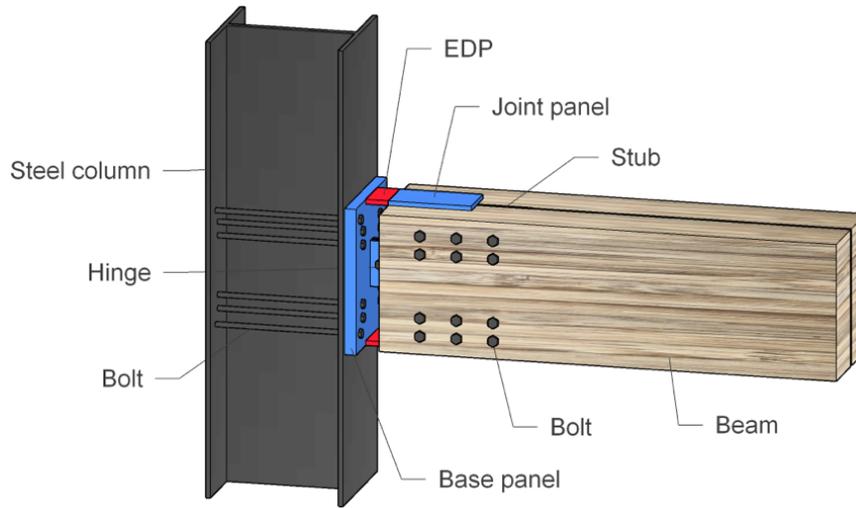
431  
432 (a) A shear plug in bleached bamboo (b) A crack in spruce (c) A crack in caramelized bamboo  
433

434 **Figure 8:** Test specimen of Reynolds [59]  
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436 Zhou et al. [61] proposed an energy dissipation joint of bamboo/timber structure (Fig. 9). The  
437 mechanical properties of the joint under cyclic loading were studied. The results showed that the thickness  
438 of the hollow steel column had a significant effect on the energy dissipation capacity and strength. The  
439 failure of the joint was caused by the buckling in the compression. Huang et al. [62] proposed a joint form  
440 for connecting engineered bamboo beams and steel columns (Fig. 10). The joint is composed of a steel  
441 hinge, steel brackets and energy dissipation panel (EDP). The seismic performance of the frame was studied  
442 by lateral cyclic loading test. The results showed that the hysteresis loops of the frame showed less pinching  
443 than that of frames with dowel- or bolt-type connections; after the yielding of EDP, the joint could provide  
444 more than 10% damping for the frame.  
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**Figure 9:** Zhou jointing method [61]



**Figure 10:** Huang jointing method [62]

Tang et al. [63] conducted a study on the LBL single-bolted joints and multiple-bolted joints. The influence of the thickness of laminated bamboo strips, end distance, bolt diameter and configuration of the bolts on the bearing capacity was considered. It was found that there were three typical failure modes, which were the longitudinal splitting, shear out, and combined longitudinal splitting and bamboo crushing. The results for multiple-bolted joint showed that stagger configuration of the bolts improved the capacity of the multiple-bolted joints. Zhang et al. [64] found that although the overall load carrying capacity of MPB (Mould-pressed Bamboo) glued bamboo (Fig. 11) was relatively low, the bolted joints had good performance and high strength. The failure yield load reached 7.624 kN on average.

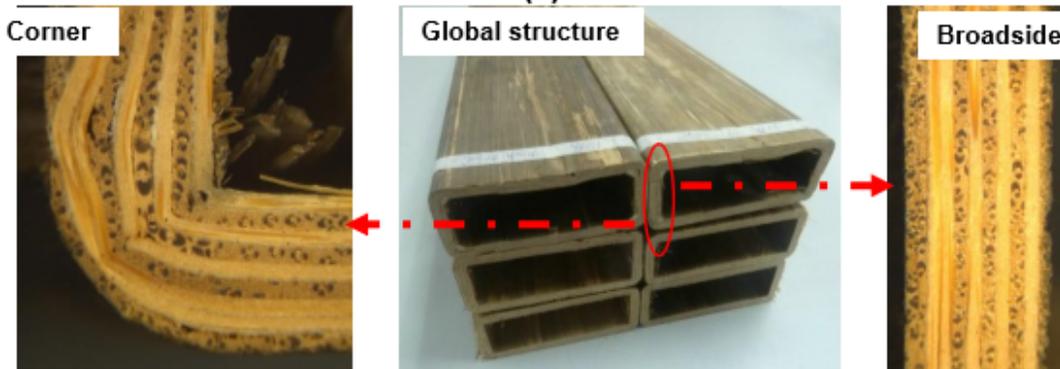


Figure 11: MPB glued bamboo [64]

It can be seen that the mechanical properties of bolted connections are very complex, which are affected by many factors such as the characteristics of the connecting material, bolt diameter, bolt end distance and edge distance. In the design of timber structure, the bearing strength of bolted joints is obtained through a large number of experiments and theoretical analysis. Although scholars have carried out some experimental studies on bolted joints of engineered bamboo structures, the number of tests is far from enough.

#### 2.4 Study on calculation method of engineered bamboo bolted joints

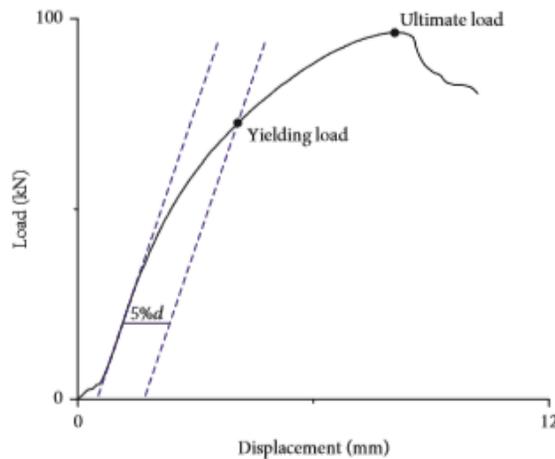
Gatóo et al. [65] described the existing design and testing standards for full culm bamboo from various countries, and analyzed the relations between production, application, economic benefits and standardization. It can be seen that codes and standards are important for specific implement. However, there is no unified design theory and calculation system for engineered bamboo structures yet, which becomes a major barrier to promote the utilization of new materials in construction area. The investigation on timber structures started much earlier, and the researchers have considered many impact factors. Until now, there are still many comprehensive experiments and theoretical basis appearing [66], [67], [68], [69], [70]. The structural form of engineered bamboo structures is analogous to that of timber structures. Thus, most of the existing literature evaluates the applicability of national codes and standards of timber structures in bamboo structures, and makes corresponding adjustments and improvements on this basis.

Based on the experimental data, Eratodi et al. [39] obtained the relations between the specific gravity  $G$  of glue-laminated bamboo and the embedding strength. The embedding strength could be well predicted using  $78.4G$  for parallel to grain radial,  $72.79G$  for parallel to grain tangential, and  $69.96G$  for perpendicular to grain radial. Ramirez et al. [40] found that the local behavior of the zone under the fastener was different from the bulk material, and proposed expressions to determine local properties as functions of the bulk properties. Equations for the bearing strength in terms of the specimen width-to-fastener diameter ratio were also proposed. Li [42] found through experiments that the predicted values of embedding strength of PBSL in Eurocode 5 and NDS-1997 were relatively small, and established the calculation formula for different texture direction, with bolt diameter, moisture content, and texture angle as independent variables. Li [42] compared the calculation results of NDS-1997, CSA, Eurocode 5, 'GB 50005-2003 Code for design of timber structures', and 'GB/T 50329-2002 Standard for test methods of timber structures', and proposed the calculation formula suitable for single-bolted and multi-bolted connections for PBSL.

Li [43] obtained influence coefficient of bolt diameter by regression analysis and established a simplified theoretical calculation formula of dowel bearing strength, of which the results had a good agreement with test results. Zhou et al. [45] proved that the theoretical equation on embedding yielding strength of wood in NDS-2015 and Eurocode 5 could be applied to PBSL. Cui et al. [46] suggested that Eurocode 5 could be used to calculate the embedding strength of PBSL in normal temperature by comparing

with Eurocode 5, CSA, ‘Manual for design of timber structures (Chinese)’, ‘GB/T 50708-2012 Technical code of glued laminated timber structures’, and NDS-1997, and put forward a fitting formula for the reduction coefficient of embedding strength in high temperature. Zhang et al. [50] found that the design bearing capacity of bolted connection could be relatively accurately obtained by 5% bolt diameter offset (Fig. 12), and proposed a reduction coefficient of 0.95 according to the ‘GB/T 50329-2002 Standard for test methods of timber structures’.

Yang [52] compared the calculation results of NDS-2005, ‘GB 50005-2003 Code for design of timber structures’, and ‘GB/T 50329-2002 Standard for test methods of timber structures’, and found that the calculation values from NDS-2005 were not desirable, while the calculation values of Chinese codes were too conservative, and the bearing capacity obtained by 5% bolt diameter offset could be used as the design standard. According to the two failure modes, Yang [53] obtained the nominal theoretical formula for calculating the tensile strength of GluBam single bolt, revised it by regression, and established the formula for calculating the maximum load, but the results were still very discrete.



**Figure 12:** 5% bolt diameter offset method to evaluate the yielding load [45]

Zhou et al. [55] compared the test results with the calculation results of the codes, and found that the formula recommended in the ‘Manual for design of timber structures (Chinese)’ was suitable, while the calculation results obtained by ‘GB 50005-2003 Code for design of timber structures’ and NDS-2012 were conservative and the calculation error could be more than 200%. On the basis of EYM and in combination with the failure form of specimens, Dai [57] established a mechanical model for predicting the bearing capacity of single-bolted joints along the grain direction of PBSL. Wang [58] found that Johansen’s formula was applicable to calculate the bearing capacity of PBSL-steel-PBSL bolted joints under room temperature, and established the formula suitable for joints under high temperature. The calculation results showed that the theoretical calculation values had high accuracy when the temperature was determined.

**Table 1** Calculation formula and methods

Literature	Formula/Standard/Method	Note
Eratodi et al. [39]	$F_e = 78.4G$ (parallel to grain radial) $F_e = 72.79G$ (parallel to grain tangential) $F_e = 69.96G$ (perpendicular to grain radial)	$F_e$ is the embedding strength; $G$ is the specific gravity of the glulam bamboo.

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Ramirez et al. [40]	$BSN_{\parallel} = -5.8D + 63.9$ $BSN_{\perp} = -4.1D + 55.9$ $BSB_{\parallel} = -0.44D + 67.5$ $BSB_{\perp} = -0.55D + 36.9$	$BSN_{\parallel} = 2.2R + 18$ $BSN_{\perp} = 2.1R + 3$ $BSB_{\parallel} = 0.9R + 50$ $BSB_{\perp} = 1.6R + 18$	$BS$ is the embedding strength; $N$ is nail; $B$ is the bar; $\parallel$ means parallel to the grain; $\perp$ means perpendicular to the grain; $D$ is the diameter; $R$ is the width-to-fastener diameter ratio.
Li [42]	$f_{e,\parallel} = \left[ -0.554 \left( \frac{D}{10} \right) + 1.853 \right] f_{c,0}$ $f_{e,\perp} = \left[ 3.673 \left( \frac{D}{10} \right)^2 - 10.59 \left( \frac{D}{10} \right) + 10.15 \right] f_{c,90}$ $\begin{cases} f_e = 91.144 - 1.217m & m \leq 22.2\% \\ f_e = 64.5 & m > 22.2\% \end{cases}$ $\begin{cases} f_e = \frac{f_{e,\parallel} f_{e45}}{f_{e,\parallel} \sin^2 \alpha + f_{e45} \cos^2 \alpha} & 0^\circ \leq \alpha \leq 45^\circ \\ f_e = \frac{f_{e45} f_{e\perp}}{f_{e45} \sin^2 \alpha + f_{e\perp} \cos^2 \alpha} & 45^\circ < \alpha \leq 90^\circ \end{cases}$		$f_{e,\parallel}$ is the embedding strength in parallel to the grain direction; $f_{c,0}$ is the compressive strength in parallel to the grain direction; $f_{e,\perp}$ is the embedding strength in perpendicular to the grain direction; $f_{c,90}$ is the compressive strength in perpendicular to the grain direction; $D$ is the diameter of bolt; $f_e$ is the embedding strength; $m$ is the moisture content; $f_{e45}$ is the embedding strength in the $45^\circ$ direction; $\alpha$ is the angle.
Li [42]	$N_v = (-0.0009c^2 + 0.0145cd - 0.017d^2) \sqrt{f_e}$ $P_v = \left( -0.0009 \left( \frac{c}{d} \right)^2 + 0.0145 \left( \frac{c}{d} \right) - 0.0173 \right) \eta_r n^{0.94} d^{\frac{3}{2}} \sqrt{\frac{a_1 f_e}{13}}$		$N_v$ is the bearing capacity in each shear plane of single-bolted joints; $C$ is the thickness of main member; $d$ is the diameter of bolt; $f_e$ is the embedding strength; $P_v$ is the bearing capacity in each shear plane of multi-bolted joints; $\eta_r$ is the number of bolt rows; $n$ is the number of bolts per row; $a_1$ is the space between the adjacent bolts along grain direction.
Li [43]	$f_e = 0.88K_D f_{c,0}$ $K_D = 1.797 - 0.792 \left( \frac{D}{12} \right)$		$f_e$ is the embedding strength; $f_{c,0}$ is the compressive strength in parallel to the grain direction; $K_D$ is the influence coefficient; $D$ is the diameter of bolt.
Zhou et al. [45]	NDS-2015 and Eurocode 5		
Cui et al. [46]	Eurocode 5 $\eta_T = \begin{cases} 1.12 - 0.0059T, & 20^\circ\text{C}, T < 110^\circ\text{C} \\ 0.0058T - 0.18, & 110^\circ\text{C}, T < 170^\circ\text{C} \\ 1.94 - 0.0066T, & 170^\circ\text{C}, T \leq 270^\circ\text{C} \end{cases}$		$\eta_T$ is reduction coefficient; $T$ is the temperature;

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Zhang et al. [50]	$\rho = n \times \rho_{single} \times C_g$	$\rho$ is strength of connection; $n$ is the number of bolt; $\rho_{single}$ is strength of single bolt connection; $C_g$ is the reduction factor.
Yang [52]	5% bolt diameter offset	
Yang [53]	$F = 2eSt$ $F = (b - d)Tt$ $F = \min(2eSt \alpha, (b - d)Tt \beta)$	$F$ is the bearing capacity; $e$ is the end distance; $S$ is the shear strength of GluBam; $t$ is the thickness of specimen; $b$ is the width of specimen; $d$ is the diameter of bolt; $T$ is the tensile strength of GluBam; $\alpha \beta$ is the coefficient obtained by regression.
Zhou et al. [55]	Manual for design of timber structures (Chinese)	
Dai [57]	European Yield Model (EYM)	
Wang [58]	European Yield Model (EYM)	

It can be seen that scholars have done some research on the calculation method of engineered bamboo bolted joints, but most of the existing studies just follow the codes and standards for timber structure. For the design of engineered bamboo bolted joints, there is no unified design theory and calculation system yet. Although both wood and engineered bamboo are bio-materials, there are some differences in their structure and mechanical properties. Thus, the specifications that conform to the characteristics of engineered bamboo materials should be developed as soon as possible.

### 3 Carpentry Joints

#### 3.1 Tenon-mortise joint

Tenons and mortises made by carpenters realize the connections of components in Chinese ancient timber architectures. It is characterized by the fact that no metal parts are used in the objects, which reflects the ancient Chinese culture and wisdom. Tenon-mortise joint is a kind of connection method that tenon is pressed into the mortise. The convex part is called tenon, and the concave part is called mortise. It has strong semi-rigid characteristics and has the ability to resist tension, compression, bending and torsion. However, under the long-term load, tenons may be pulled out or broken, and mortise may be damaged [71]. There are many kinds of tenons, among which rectangular tenon, round tenon, and oval tenon are the common forms. Because of the relatively simple and fast processing technology, they are widely used in solid wood furniture manufacturing enterprises.

Scholars have carried out experimental research and analysis on the performance of tenon-mortise joint in bamboo structure. In order to study the pull-out resistance of tenon-mortise joints of LBL, Li [72] comprehensively considered the influence of gluing method, tenon shape, joint area, the diameter of round tenon, insertion depth, and magnitude of interference. It was found that the pull-out resistance reached the maximum when both tenon and mortise were coated with glue; the larger the joint area between tenon and mortise, the larger the pull-out resistance and the bending strength; the pull-out resistance of rectangular tenon joint is larger than that of round tenon joint; the influence of the diameter of round tenon, insertion depth and magnitude of interference on the joint strength decreased in turn.

Xu [73] studied the influence of tolerance parameter  $\alpha$  and  $\beta$  of LBL oval tenon on pull-out resistance

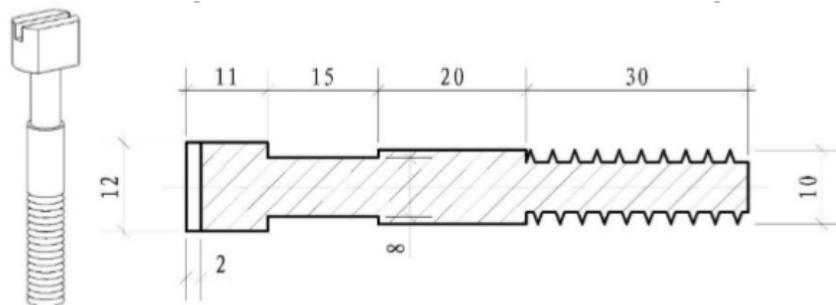
( $\alpha$  and  $\beta$  are the difference between the width of mortise and tenon, the difference between the thickness of mortise and tenon respectively), and obtained the relations between the two parameters and the ultimate pull-out resistance through fitting the experimental data. Huang [74] found that in a certain range, the tensile strength of oval tenon increased with the increase of  $\alpha$  and  $\beta$ , but decreased when  $\alpha$  was greater than 0.4 mm or  $\beta$  was greater than 0.1 mm; polyurethane adhesive was superior to white emulsion in enhancing the pull-out strength of tenon, which illustrated that selection of adhesive with strong bonding ability could effectively improve the pull-out strength of tenon; the bending strength of oval tenon made by PBSL was far higher than that of oval tenon made by common solid wood.

It can be seen that although some scholars have carried out some research on tenon-mortise joints made by engineered bamboo, and considered many influencing factors, but the current tenon-mortise joints mainly aimed at bamboo furniture. There is a lack of research on the tenon-mortise joint for utility in bamboo building structures.

### 3.2 Nail/Screw Joint and Truss Plate Joint

There are a few studies on nail connection and truss plate connection of engineered bamboo in the existing literature. The nail connection has dispersed force transmission, and its performance cannot meet the needs of the connection of larger components. Huang [74] studied the screw joints of PBSL furniture and analyzed the influence of screw type, hole diameter, and screw-in depth on the joint strength. The results showed that the screw-in depth and hole diameter had a significant influence on the pull-out resistance, while screw type had no apparent effect. Through the experiment, Li et al. [75] concluded similarly to Huang. It was found that with the decreasing of diameter of guiding hole and the increasing of screw-in depth, the joint strength was obviously increased. Li et al. [75] obtained the relation curves between screw type, hole diameter, screw-in depth and pull-out resistance respectively, and suggested that the suitable diameter of guiding hole was 80% ~ 90% of the diameter of the screw.

Zhang [76] optimized the thread parameters of the special screw (Fig. 13) for LBL by orthogonal test. The effects of the diameter of the hole, the depth and direction of screw insertion, and the number of disassembling and assembling of screw joints on the mechanical properties were discussed. The results showed that the joint strength decreased with the increase of the times of assembly and disassembly, and the two had a negative linear correlation. Chen et al. [77] found that the screw diameter, screw type and loading rate had no obvious influence on withdrawal resistance. However, the diameter of hole had significant influence, and suggested that the size of pilot hole should be 60~85 % to the diameter of the screw. Sinha et al. [78] studied the lateral bearing capacity of edge connection and plate connection (Fig. 14) of LBL-OSB by static load test. The results showed that the bearing capacity of LBL-OSB nail joints is similar to that of conventional fir-OSB nail joints, and the bearing capacity of edge connection before yielding was higher than that of plate connection.



**Figure 13:** Schematic of special screw by Zhang [76]

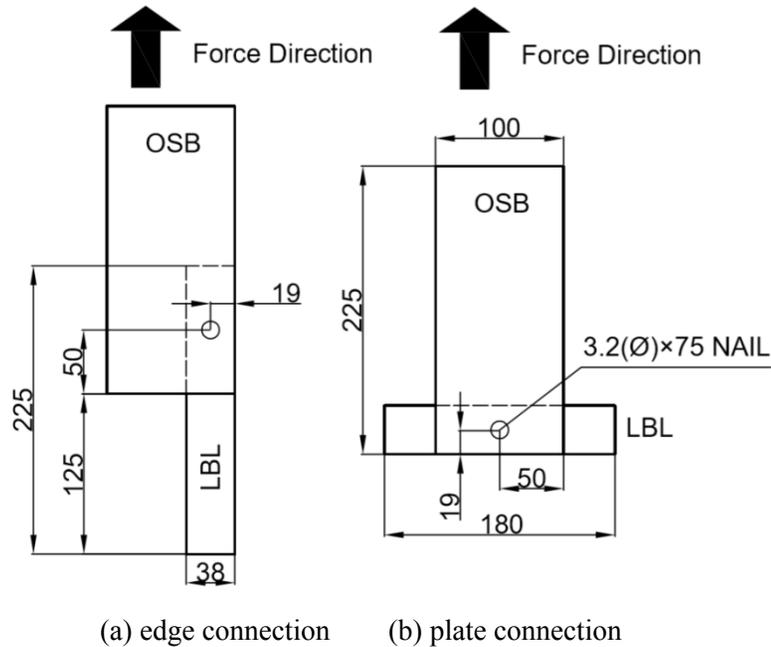


Figure 14: Schematic of connection geometries by Sinha [78]

Truss plate joints are made of galvanized steel sheet by one-way teeth beating. They are often used in light timber trusses with the characteristics of fast and convenient construction. However, the truss plate joint may also be the weak area of the whole truss, and its bearing capacity determines the bearing capacity of the whole truss. Wu [79] carried out tensile test on the joints with four connection conditions, of which the orientation between load and the main fiber direction of GluBam, load and main direction of truss plate was different (Fig. 15). Four failure modes, which were bamboo panel failure, tooth plate pull-out, tooth breakage and mixed mode of three, were observed. By comparing the ultimate strength of GluBam truss plate joints with timber truss plate joints, it was found that the joints had good ultimate strength. The tensile strength, shear strength and ultimate strength at special angles of the joints were also tested, which proved the applicability of the truss plate joints in engineered bamboo structures.

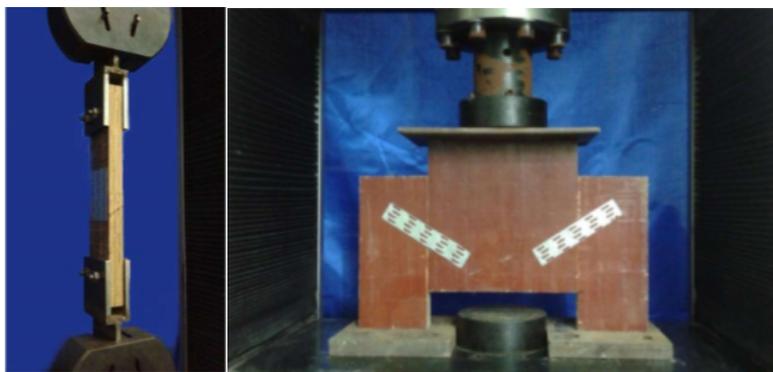


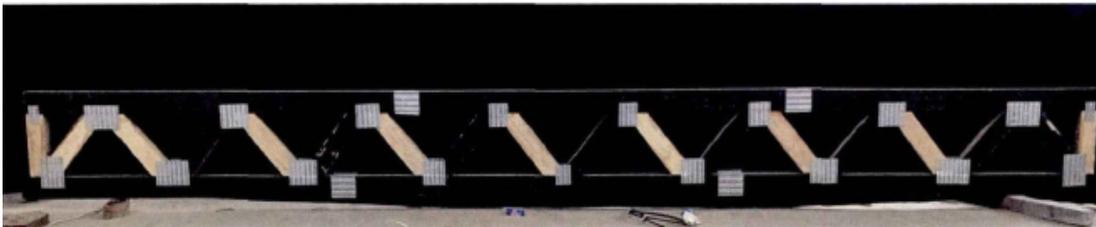
Figure 15: Truss plate joint test by Wu [79]

Peng [17] studied the strength of GluBam truss plate joints at ten different angles through tensile tests. The results showed that the strength of joints was higher than that of the timber truss plate joints at most angles. Static loading tests were carried out on four GluBam trusses with 3 m span and 5.6 m span as well (Fig. 16). The ultimate bearing capacity, load-displacement curves and strain of some components were

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843 obtained. The results showed that the truss had a large strength reserve. The trusses were destroyed by the  
844 failure of the truss plate joints, which belonged to brittle failure.  
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853 (a) GluBam trusses with 3 m span



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862 (b) GluBam trusses with 5 m span

863 **Figure 16:** Test specimen of Peng [17]

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866 In summary, scholars have already conducted some research on the connection performance of  
867 engineered bamboo for different forms, and discussed the effect of various factors. However, compared  
868 with wood, the number of the experiment and theoretical depth are still insufficient. The mechanical  
869 properties of engineered bamboo joints have yet to be further studied.  
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#### 871 **4 Engineering Example**



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887 (a) Double-curved lattice structure



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896 (b) Double-curved lattice structure

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(c) Steel member joint with special configuration



(d) LBL component with slot

**Figure 17:** LBL building with special geometry at 2019 the Beijing International Horticultural Exhibition (reproduced with permission of Zhenhua Xiong)

Figure 17 displays the construction process of LBL building with special-shaped, which was presented at 2019 the Beijing International Horticultural Exhibition. In order to meet the requirement of the spatial form, the double-curved lattice structure was adopted according to the mechanical properties of LBL. The internal and external arches adopt the multi-point connection at the top instead of the conventional vertical connection between the internal arch and purlin. The greatest advantage of this method is to avoid the tensile stress in the perpendicular to grain direction, but to transform it into the tensile stress along the grain direction through the special joint, so as to make better use of the material. The multi-point connection increases the reliability of the structure connection as well.



(a) Building skeleton



(b) Steel member joint with special configuration



(c) Connection between curved column and floor



(d) Building skeleton

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**Figure 18:** LBL ‘Lotus Pavilion’ in Jinggangshan City (reproduced with permission of Zhenhua Xiong)



(a) Construction process



(b) Construction process



(c) Connection between LBL column and floor



(d) Details of steel member joint

**Figure 19:** LBL office building in Ganzhou City (reproduced with permission of Chaokun Hong)



(a) Bamboo villa



(b) Connection between corner column and beam

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(c) Connection between middle column and beam (d) Connection between main beam and secondary beam

**Figure 20:** Earthquake-resistant bamboo villa in Nanjing Forestry University (Built in 2008, reproduced with permission of Chaokun Hong)



(a) Tenon-mortise joint



(b) Tenon-mortise joint



(c) Tenon-mortise joint



(d) PBSL villa

**Figure 21:** PBSL villa in Fengxin County (Built in 2008, reproduced with permission of Haitao Li)



**Figure 22:** A tenon-mortise joint sample made of LBL (reproduced with permission of Haitao Li)

Figure 18 displays the construction process of the ‘Lotus Pavilion’ made of LBL in Jinggangshan City, China, which was constructed by Ganzhou Sentai bamboo company LTD. Figure 19 displays the construction process of office building made of LBL in Ganzhou City, China, which was constructed by Ganzhou Sentai bamboo company LTD. Figure 20 displays the joint details of earthquake-resistant bamboo villa made of PBSL in Nanjing Forestry University, which was built by the research team led by Academician Zhang Qisheng of Nanjing Forestry University and Academician Lv Zhitao of Southeast University. From above, it can be drawn that the joint configuration of engineered bamboo structure is similar to that of timber structure, and specific configuration of joint can help create more structural and spatial types to meet the practical and artistic requirements of modern architecture. Figure 21 displays the joint details of a PBSL villa in Fengxin County, China, which was constructed by Jiangxi Feiyu Bamboo Stock Co. LTD. Figure 22 is a tenon-mortise joint sample made of LBL.

In summary, many attempts have been made on the application of engineered bamboo in construction. From the existing engineering examples, no matter from the perspective of aesthetic appearance, environmental interest and economic benefits, engineered bamboo has more space for development in the future. However, many enterprises produce engineered bamboo only on the basis of experience without general standards, which leads to differences in material properties of different enterprises and even different batches. Therefore, academia, industry and policymakers must improve their collaboration and communication to make the standardization of structural bamboo products and bamboo-based products be smooth [65].

## 5 Conclusion

Since the beginning of the 21st century, the world has paid significant attention to the sustainable development of the construction industry. Bamboo, as a green and renewable building material, provides the buildings with the characteristics of energy-saving and environmentally friendly. Additionally, the excellence in seismic performance, assembly performance and livability of bamboo has the potential to promotes its application in engineering construction to a wider range. With the rise of modern bamboo structure, scholars have carried out significant research on the manufacturing technology, physical and mechanical properties of engineered bamboo, but research on connection behavior is far from enough.

1. The physical and mechanical properties of materials in the connector need to be uniform and stable. However, many enterprises produce engineered bamboo only on the basis of experience without general standards, which leads to differences in material properties of different enterprises and even different batches. Therefore, formal general standards for manufacturing need to be developed in the future.

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2. The mechanical property of bolted joints is very complex. Scholars have considered many impact factors such as flexural strength of bolts, the embedding strength of members, specific gravity, bolt diameter, end distance, edge distance, loading direction, moisture content, grain direction, external temperature et al. However, it is still not enough. More influence factors like the permutation of bolts, working situations need to be considered deeply. Besides, the existing conclusion has yet to prove its universality.

3. Most of the existing studies just follow the codes and standards for timber structure, and make corresponding adjustments and improvements through regression and fitting method. The stress mechanism of the existing connection forms is not clear enough. Although engineered bamboo structures are analogous to timber structures, it is necessary to conduct a large number of experiments and theoretical studies to establish a unified design theory and calculation system that conform to the characteristics of engineered bamboo materials.

4. The current research on carpentry joints is mainly aimed at bamboo furniture. Nevertheless, some application of carpentry joints in engineered bamboo buildings has existed. At present, there is a lack of research on carpentry joints for utility in bamboo building structures. Thus, more research in this aspect should be carried out.

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