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ORIGINAL ARTICLE

Experimental study on flexural performance of glued-laminated-timber-bamboo beams

Qingfeng Xu · Yubing Leng · Xi Chen · Kent A. Harries · Lingzhu Chen · Zhuolin Wang

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Abstract Engineered bamboo, produced through the technique of gluing and reconstituting, has better mechanical properties than round bamboo and some wood products. This paper studies the flexural performance of laminated beams produced with timber and engineered bamboo. The six-layer beams were made from Douglas fir, spruce, bamboo scrimber and laminated bamboo, or a combination of these. It is confirmed that glued-laminated wood beams produced with wood of weak strength, like spruce, can be strengthened by gluing engineered bamboo lumbers on the outer faces, thus achieving better utilization of the fast growing economic wood species. Flexural failure of the laminated beams was primarily triggered by tensile fracture of the bottom fiber in mid-span, followed by horizontal tearing beside the broken surface. No relative slip between layers was observed before failure, therefore the flexural capacity of the laminated beams can be predicted using equilibrium and compatibility conditions according to the plane section assumption.

Keywords Engineered bamboo · Bamboo scrimber · Timber · Laminated beams · Flexural performance

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Q. Xu (✉) · Y. Leng · X. Chen · L. Chen · Z. Wang
Shanghai Key Laboratory of Engineering Structure Safety, Shanghai Research Institute of Building Sciences, No. 75 South Wanping Road, Shanghai 200032, China
e-mail: xuqingfeng73@163.com

Y. Leng
School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

K. A. Harries
Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA 15261, USA

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1 Introduction

It is essential to develop green and environment-friendly construction materials. Compared with conventional building materials like steel, concrete and masonry, bamboo and wood are both renewable and biodegradable materials with low carbon emission [1, 2]. The similarities between bamboo and wood, like high strength-to-weight ratios and excellent seismic performance, prompt researchers to consider whether it is possible to use the two materials together to achieve better mechanical performance.

New and innovative uses of wood have been developed in recent decades driven by the considerations of sustainability and energy savings [3, 4]. Similarly, in recent years, engineered bamboo materials have garnered increased attention, as studies comparing bamboo to timber have mostly concluded

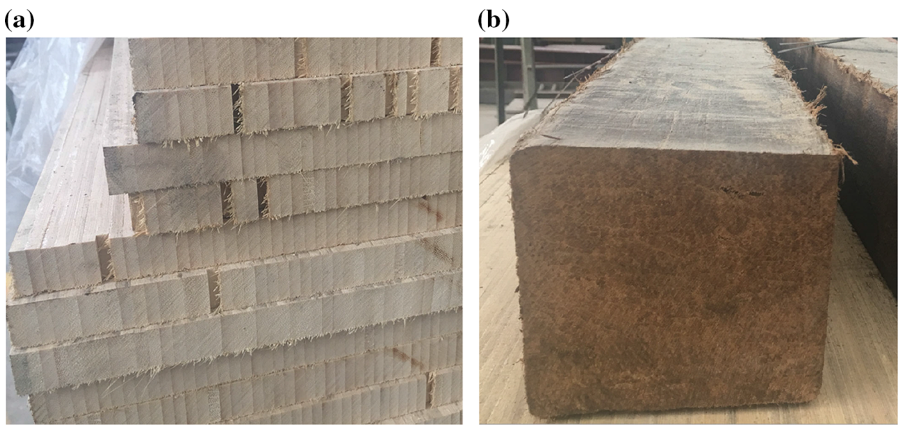


Fig. 1 Engineered bamboo constituent products: **a** laminated bamboo; and **b** bamboo scrimber

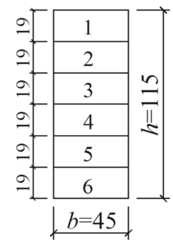
bamboo to be more sustainable and available than timber [5]. Despite its long history, round bamboo has limited structural applications due to its slenderness, natural variation, and limited geometrical sizes. Engineered bamboo, including laminated bamboo and bamboo scrimber, overcomes these shortcomings. The mechanical properties of engineered bamboo are comparable to, and in many respects better than comparable wood products [5–8].

Laminated bamboo is fabricated by cutting laminae from the bamboo stem and gluing them into rectangular cross sections; in this case the original bamboo wall cross section is maintained [6]. Bamboo scrimber, also called parallel strand bamboo, is fabricated by cutting bamboo into strips and gluing them parallel to each other, typically in a mould under pressure [9, 10]. In both materials, the process of gluing and reconstituting result in a material that is more stable and less variable than the constituent natural materials. The resulting engineered materials are believed to achieve better mechanical properties than timber and round bamboo. The laminated bamboo and bamboo scrimber products used in this study are shown in Fig. 1. In practice, both engineered bamboo and wood constituent materials are first fabricated into boards of desired thicknesses, and then processed into glue-laminated structural members by cutting and gluing under pressure at room temperature (cold press) [6, 9].

Some fast growing wood species, like spruce, typically exhibit relatively weak tensile and flexural strengths. It is proposed that glued-laminated wood beams produced with such weaker wood can be strengthened by gluing engineered bamboo lumbers at the outer faces, thus achieving better utilization of the fast-growing economic wood species. In glued laminated timber manufacture different grades of wood have been used together in the same member—with stronger harder wood as the outer layers (resisting flexure) and poorer quality wood in the middle (resisting shear) [11–15]. Other researchers have proposed similar approaches with weaker glued laminated beams reinforced with steel [16–18], FRP [18–23], natural fibers [24] and ultra-high performance concrete [25]. This study proposes an alternative to the use of (possibly less readily available) better wood species or other materials in the outer layers of such hybrid glued laminated members: engineered bamboo.

In this paper the flexural performance of 18 glued laminated beams is studied. Twelve beams are fabricated with a single material (i.e., Douglas fir, spruce, laminated bamboo and bamboo scrimber, three specimens with each material). The remaining 6 hybrid specimens consist of different material layers. In the hybrid beams, the outer layers, especially the outermost tensile layer, are produced with engineered bamboo lumbers, and the inner layers, are composed of spruce. Such a combination is referred to as 'composite sandwiches'. The objective of the study is to investigate whether the composite beams can achieve better flexural performance, compared with the laminated wood beams.

Table 1 Design of the test beams

Specimen	Numbering of the laminate						Cross section (mm)
	1	2	3	4	5	6	
DF1, DF2, DF3	Douglas fir (DF)						
Sp1, Sp2, Sp3	Spruce (Sp)						
BS1, BS2, BS3	Bamboo scrimber (BS)						
LB1, LB2, LB3	Laminated bamboo (LB)						
ST1	Sp	Sp	Sp	Sp	Sp	BS	
ST2	DF	Sp	Sp	Sp	BS	BS	
ST3	BS	Sp	Sp	Sp	BS	BS	
LT1	Sp	Sp	Sp	Sp	Sp	LB	
LT2	DF	Sp	Sp	Sp	LB	LB	
LT3	LB	Sp	Sp	Sp	LB	LB	

The uniaxial stress–strain relationships of the four constituent materials are first studied, to gain a better understanding of the flexural behavior of the resulting hybrid glued laminated beams.

2 Experimental investigations

2.1 Design of the test specimens

An experimental program was carried out to illustrate the flexural performance of the beams glued laminated with different materials. Six series of laminated beams with a total of 18 specimens were tested. The first (DF1 ~ DF3) and second series (Sp1 ~ Sp3) were produced with six layers of 19 mm thick Douglas fir and spruce, respectively. The third (BS1 ~ BS3) and forth series (LB1 ~ LB3) were produced with six layers of 19 mm thick bamboo scrimber and laminated bamboo, respectively. The fifth series (ST1 ~ ST3) included 3 specimens produced with bamboo scrimber at the tension face, spruce in the middle and varying materials at the compression face. The sixth series (LT1 ~ LT3) included 3 specimens with laminated bamboo at the tension face, spruce in the middle and varying materials at the compression face. The six layer laminates are described in Table 1.

By comparing the flexural behaviors of different series, the effectiveness of strengthening laminated wood beams produced with wood species of low strength with engineered bamboo is discussed. Such an approach is expected to result in better utilization of the fast growing and economical softwood species.

Test specimens having dimensions 115 mm deep × 45 mm wide × 2400 mm long were designed in compliance with ASTM D198-15 [26]. All specimens had identical dimensions with six 19 mm thick glued layers (Table 1). According to ASTM D198-15, shear span/depth ratios between 5 and 12 are recommended for evaluation of flexural properties; in this study a shear span of 690 mm, resulting in a shear span/depth ratio of 6.0 was used. The specific configurations of the laminated beams are shown in Table 1.

The adhesive used to bond the layers was AQUENCE SL 3184, produced by the Henkel Chemical Technologies; the bond line thickness is negligible.

2.2 Test set-up and instrumentation

Tests were carried out in a 100 kN capacity universal testing machine. The beams were simply supported on roller supports over a distance of 2070 mm and tested in four-point flexure with equal shear spans and constant moment regions of 690 mm. Tests were conducted under mid-span displacement control at a displacement rate of 5 mm/min. Figure 2 shows the loading geometry used. Loading was sustained until failure of the beam, after which the carrying capacity dropped dramatically.

Vertical displacements at mid-span, both loading points, and both supports were measured with displacement transducers. Strain gauges having a gage length of 55 mm, oriented parallel to the longitudinal axis of the beams, were placed on the bottom, top and lateral surfaces as shown in Fig. 2. Particular attention

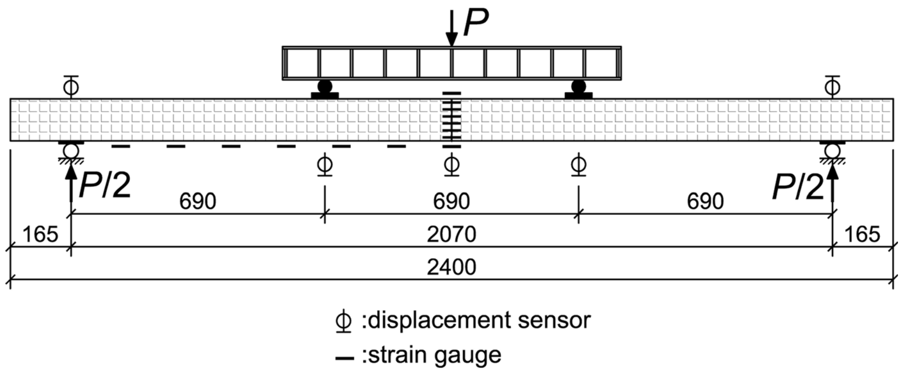


Fig. 2 Test set-up and instrumentation scheme

was paid to the strain distribution through the depth of the beam at mid-span, where each lamina was instrumented with a strain gage on the lateral face of the beam in addition to gages on the top and bottom of the beam. Load, displacement and strain data were simultaneously recorded through a dynamic data logger.

3 Material properties of constituent lamina

The mechanical properties of wood and bamboo are influenced by many factors. The physical properties and mechanical behaviors of the four constituent materials used in this study were tested individually under the same environmental conditions as the subsequent beam tests. Currently there are several standards for testing of bamboo as structural material, like ISO 22157 for determination of physical and mechanical properties of bamboo [27], and JG/T 199-2007 proposes testing method for physical and mechanical properties of bamboo used in building (in China) [28]. And ISO 22156: 2004 (reconfirmed in 2012) has recommended performance based limit state design of bamboo structures (round bamboo, split bamboo, glued laminated bamboo) or bamboo-based panels joined together with adhesives or mechanical fasteners [29]. Yet there is no standard test method for engineered bamboo products, so ASTM D143-14 [30], which is a standard test method for timber, was adopted. The moisture content, density, strength and modulus of elasticity under tensile, compressive and flexural conditions were determined for all four constituent material in the parallel-to-grain direction (the primary direction in which they were stressed in the beams).

3.1 Parallel-to-grain tension and compression behavior

Tensile properties were determined using specimens cut from undamaged regions of the beams, and the specimen sizes were adopted according to ASTM D143-14. Two strain gauges were adhered on opposite faces at the center of the specimens to evaluate the tensile modulus of elasticity. For each material, four tests were conducted in a universal testing machine under displacement control, with a loading rate of 1 mm/min.

Two specimen sizes were used to determine compression properties. Small clear specimens having a section size of 20 mm × 20 mm, approximately equal to the thickness of a single laminate, and height 30 mm in parallel-to-grain direction, were used to mitigate any influence of the glued surfaces. Six tests were conducted in displacement control, with a loading rate of 1 mm/min. Larger specimens having a section size of 35 mm × 35 mm and height 120 mm in the parallel-to-grain direction, which included a glued surface were also tested. The larger dimension is supposed to better reflect the actual compression behaviors of the glued laminate. Three specimens were tested. Four strain gauges were adhered to the center of the four lateral surfaces of the larger specimens to evaluate the compression modulus of elasticity. For these specimens, load was first applied to 30% of the predicted compression strength, and unloaded to 10% of the strength. The load was then

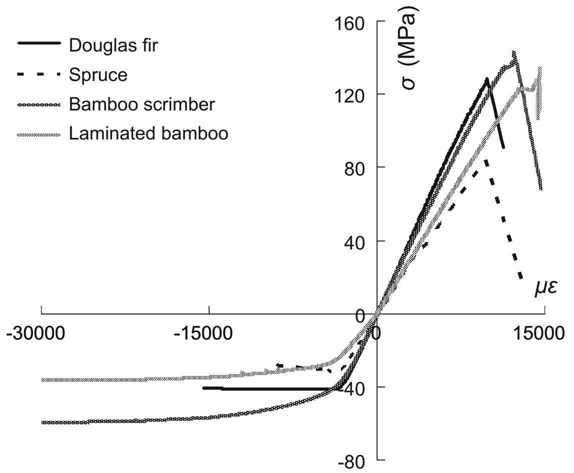


Fig. 3 Stress–strain relationships of the four constituent materials

cycled twice with the strains recorded in these cycles being used to calculate compression modulus. After the third cycle, loading was continued under displacement control at a rate of 1 mm/min until compression failure—defined as the compression capacity dropping below 80% of the ultimate capacity.

Figure 3 presents the resulting stress–strain relationships of the four constituent materials. All materials exhibited linear elastic behaviors under uniaxial tensile conditions until tensile fracture. While in the compressive direction, nonlinear behavior was obvious before reaching the compression strength. For Douglas fir, linear compressive behavior was maintained up to a proportional limit of about 90% of the strength at which point a plateau is observed. The compressive capacity was maintained until the strain reached about 15,000 $\mu\varepsilon$. The compressive behavior of spruce is similar before yielding, but the strength dropped gradually after the peak was achieved. The compressive capacity fell to 85% of the ultimate strength at 10,000 $\mu\varepsilon$.

The bamboo scrimber and laminated bamboo showed somewhat different compressive characteristics. The ratio between the proportional limit and the ultimate strength was smaller, but the 'plastic' plateau lengths were far longer. Specifically, the stress–strain curve of the bamboo scrimber showed a proportional limit about 65% of the ultimate strength. Then in the nonlinear segment, the stress increased gradually and the compressive strength was reached at about 20,000 $\sim$ 25,000 $\mu\varepsilon$. The compressive capacity did not decrease significantly until reaching a compressive deformation of about 4% of the total height. The compressive behavior of laminated bamboo was similar, with a proportional limit about 75% of the ultimate strength. The compressive capacity was reached at about 20,000 $\mu\varepsilon$, and the total compressive deformation before the load fell 20% from the peak was as large as 10% of the block height. Both the engineered bamboo products showed excellent ductile behavior in compression.

3.2 Flexural properties

Specimens having cross sections of 20 mm × 20 mm and length 300 mm in the parallel-to-grain direction were cut from the undamaged regions of the test beams. The third point flexural specimens were tested over a 240 mm simple span to determine the flexural strength and modulus. Six tests were conducted in a universal testing machine under displacement control of 1 mm/min. The applied load was cycled between 300 and 700 N three times, and the displacements measured in the last two cycles were used to calculate the flexural modulus of elasticity from Eq. (1), in which ΔP is the difference between the upper and lower limit of the load (400 N); Δu is the corresponding difference in displacement determined from cross-head travel; b, h, l are the section width, section depth and span length (20 × 20 × 240 mm) respectively. After the last cycle, loading was continued under displacement control of 5 mm/min until flexural failure.

$$E_{\mathrm{m}} = \frac{23(\Delta P)l^3}{108bh^3(\Delta u)} \quad (1)$$

The constituent material properties are summarized in Table 2. The following conclusions can be drawn from the material test results. (1) The flexural strengths lie between the tensile and compressive strength. (2) Comparing f_{c} and f_{c}', where f_{c} and f_{c}' are the compressive strength from specimens of 20 mm × 20 mm × 35 mm and of 35 mm × 35 mm × 120 mm respectively, demonstrates that the compressive strength of the four materials are all influenced by the presence of gluing surfaces although the associated strength decrease of spruce is almost negligible. The compressive strength of Douglas fir and bamboo scrimber decreased by about 9 and 14%, respectively, in the presence of a gluing surface

Table 2 Material properties (COV in brackets, %)

Material	Natural density (kg/m^3)	Moisture content (%)	Compressive properties (MPa)			Tensile properties (MPa)		Flexural properties (MPa)	
			f_c	f_c'	E_c	f_t	E_t	f_m	E_m
Douglas fir	553 (1.1)	11.8 (2.1)	44.2 (5.8)	40.1 (5.0)	12,900 (8.2)	125.6 (6.3)	13,600 (12.2)	93.5 (4.4)	15,800 (11.2)
Spruce	426 (2.8)	12.5 (4.7)	30.9 (2.7)	30.4 (5.1)	9830 (9.0)	85.5 (4.2)	8720 (10.6)	72.5 (4.3)	12,100 (9.2)
Bamboo scrimber	1117 (3.4)	10.0 (7.9)	70.6 (5.2)	60.0 (3.7)	13,600 (3.2)	126.1 (14.3)	12,200 (13.1)	114.3 (12.6)	14,700 (11.7)
Laminated bamboo	580 (3.4)	7.9 (5.8)	49.1 (2.5)	36.1 (2.5)	7270 (2.0)	114.6 (13.6)	10,000 (16.7)	113.3 (4.7)	12,900 (11.5)

f_c = compressive strength from specimens of 20 mm × 20 mm × 35 mm; f_c' = compressive strength from specimens of 35 mm × 35 mm × 120 mm; f_t (f_m) = tensile (flexural) strength; E_c (E_t, E_m) = compressive (tensile, flexural) modulus of elasticity

whereas the strength of laminated bamboo was reduced about 27%. Considering that the structural members all contain gluing surfaces, the tested strengths f_c' are more representative of the available compressive strength in the glued laminated members.

4 Glued laminated flexure test results

4.1 Failure processes and patterns

The failure modes are summarized in Table 3, and the following describes details of the observed failures. Photos of the failures of all specimens are shown in Online Resource 1. The load here means the total concentrate load P.

1. Douglas fir specimens
   Evidence (sound emissions) of fiber fracture became frequent after an applied load 14–15 kN. Finally the bottom fibers fractured in mid-span, and the fractured surface extended through the bottom 2–3 laminates (layers 6, 5 and 4). Finally the laminates tore horizontally through the wood material from the fracture tip. In specimen DF1, in addition to the horizontal tearing cracks, delamination occurred between the 4th and 5th, and 5th and 6th layers. Failures of specimens DF2 and DF3 exhibited tensile fracture and horizontal tearing in the wood but not delamination. DF2 failed in a sudden manner, resulting in a horizontal tearing crack passing through the whole span, so the deformation was unrecoverable. The horizontal tearing cracks in DF3 were dense but none extended to the beam end, so the deformation recovered rapidly after unloading.
2. Spruce specimens
   Evidence of fiber fracture occurred at around 5–6 kN and became frequent after 8–10 kN. The specimens eventually ruptured by tensile fracture of the bottom fibers in mid-span. In specimen Sp1 a horizontal tearing crack appeared after the tensile fracture surface developed to the top of the 6th layer. The failure modes of Sp2 and Sp3 were similar. After tensile fracture of the bottom two layers, the tearing crack developed diagonally, passing through wood and glue lines, splitting the beam into two parts, so the deformation was unrecoverable.

Table 3 Some test results and predicted flexural capacities of the beams

Specimen	Test results								Calculation results			
	Failure mode	P_{ser} (kN)	P_{cr} (kN)	Δ_{cr} (mm)	E_0 (MPa)	y_{t_exp} (mm)	P_{u_exp} (kN)	Δ_u (mm)	y_{t_cal} (mm)	M_{u_cal} (kNm)	P_{u_cal} (kN)	$\frac{P_{u\_exp}-P_{u\_cal}}{P_{u\_exp}}$
DF1	① + ③	2.8	9.5	28.3	9260	50.7	17.5	75.2	51.5	5.24	15.2	− 13.2
DF2	① + ②	2.1	5.8	23.6	6770	46.4	16.0	124.1	51.5	5.24	15.2	− 5.0
DF3	① + ②	2.6	7.6	25.5	8230	53.3	15.6	71.4	51.5	5.24	15.2	− 2.6
Sp1	① + ②	2.3	8.0	27.8	7960	58.9	12.7	52.6	53.1	3.74	10.8	− 14.7
Sp2	① + ④	2.3	5.9	21.8	7450	47.0	10.1	44.5	53.1	3.74	10.8	7.3
Sp3	① + ④	2.4	7.2	25.2	7900	49.3	13.5	56.2	53.1	3.74	10.8	− 19.8
BS1	③	2.5	9.8	33.6	8060	50.0	19.0	85.5	49.0	7.38	21.4	12.5
BS2	③	2.2	9.2	33.7	7540	52.4	17.1	76.0	49.0	7.38	21.4	25.0
BS3	① + ②	2.2	9.6	36.4	7290	49.9	19.5	104.0	49.0	7.38	21.4	9.6
LB1	① + ②	1.5	9.5	50.4	5200	51.4	17.0	118.0	43.3	5.86	17.0	− 0.2
LB 2	① + ②	1.7	10.2	48.0	5860	46.2	17.9	111.9	43.3	5.86	17.0	− 5.2
LB 3	① + ②	1.8	9.6	44.0	6020	47.5	17.8	110.6	43.3	5.86	17.0	− 4.7
ST1	① + ② + ⑤	2.1	5.3	21.2	6920	45.2	14.0	95.9	38.9	5.01	14.5	3.7
ST2	① + ③ + ⑤	1.9	6.5	28.2	6360	46.2	16.3	138.2	39.6	5.49	15.9	− 2.9
ST3	① + ②	2.2	9.2	34.0	7480	45.0	20.6	132.4	41.8	6.08	17.6	− 14.5
LT1	⑥ + ③ + ②	1.9	6.6	29.2	6230	51.2	14.1	105.3	40.3	4.87	14.1	0.1
LT2	① + ② + ⑤	2.1	9.7	36.0	7430	55.3	17.0	131.0	41.8	5.33	15.4	− 9.1
LT3	① + ②	1.9	9.2	41.6	6110	50.8	17.7	107.7	41.4	5.25	15.2	− 14.0

The failure modes of ①: tensile rupture of the bottom fiber; ②: horizontal tearing; ③: delamination; ④: diagonal splitting; ⑤: compressive buckling of the top fiber; and ⑥: tensile rupture of the middle layer

3. Bamboo scrimber specimens
   The sound of fiber fracture was not heard until near final failure. Specimens BS1 and BS2 ruptured due to delamination. Specimen BS1 first failed between the 4th and 5th layers, and finally also failed between the 2nd and 3rd layers. In specimen BS2 the glued surface failed between the 2nd and 3rd layers, and extended to the beam end. The bottom fiber was not broken. Specimen BS3, on the other hand, failed due to tensile fracture followed by horizontal tearing; thus the deformation was also recovered after unloading.
4. Laminated bamboo specimens
   The failure mode of the three specimens was quite similar—the bottom fiber fractured in tension at mid-span and horizontal tearing cracks formed thereafter. Tensile rupture of the bottom fibers occurred at several sections. Importantly, the vertical gluing surfaces of the constituent bamboo slats also fractured.
5. Hybrid Specimens with bamboo scrimber at tension face
   In this group of specimens, having a spruce core, the tension layers were replaced with bamboo scrimber and the compression layer with Douglas fir or scrimber (ST2 and ST3, respectively). As expected, flexural capacities improved successively from ST1 to ST3. The three specimens finally failed by tensile fracture of the bottom fibers. In ST1 in which only the bottom layer was replaced with bamboo scrimber, the bottom layer as well as the fifth spruce layer ruptured, with a horizontal tearing crack forming in the fifth layer, and finally the fourth spruce layer was also fractured at another section. Additionally, obvious compressive deformation occurred in the top spruce layer. In ST2, after tensile fracture of the bottom layer, the gluing surface between the 4th and 5th layer failed, and the top layer of Douglas fir buckled. Specimen ST3 failed due to tensile

fracture of the bottom layer, followed by horizontal tearing.

6. Hybrid Specimens with Laminated bamboo at tension face
In this group of specimens, also having a spruce core, the tension layers were replaced with laminated bamboo and the compression layer with Douglas fir or laminated bamboo (LT2 and LT3, respectively); the flexural capacities were also obviously improved. In specimen LT1 the 4th and 5th spruce layers were fractured, but the bottom laminated bamboo layer was not. A horizontal tearing crack developed in the second layer, and the gluing surface between the 5th and 6th layers was also broken. Specimens LT2 and LT3 failed due to tensile fracture of the bottom laminated bamboo layer, accompanied by horizontal tearing cracks. LT2 also showed compressive buckling deformation in the top Douglas fir layer.

Except for the few specimens that failed by delamination and diagonal splitting, those which failed due to tensile fracture, showed immediate deformation recovery once the load was removed.

4.2 Load-deformation responses

Figure 4 shows some typical load-deformation curves of the specimens, and the detailed load-deformation curves of all the specimens are shown in Online Resource 2. The key test results are summarized in Table 3. In Table 3, the initial modulus of elasticity E_0 refers to the modulus before the proportional limit. Neglecting shear deformation, and considering the cross section to be an equivalent homogeneous material, the equivalent elastic modulus can be estimated as:

$$E_0 = \frac{23 P_{cr} l^3}{1296 \Delta_{cr} I} \tag{2}$$

in which P_{cr} and Δ_{cr} refer to the proportional limit load and the corresponding mid-span deflection, l is the beam span length and I is the moment of inertia of the section.

The following conclusions can be drawn from Fig. 4 and Table 3.

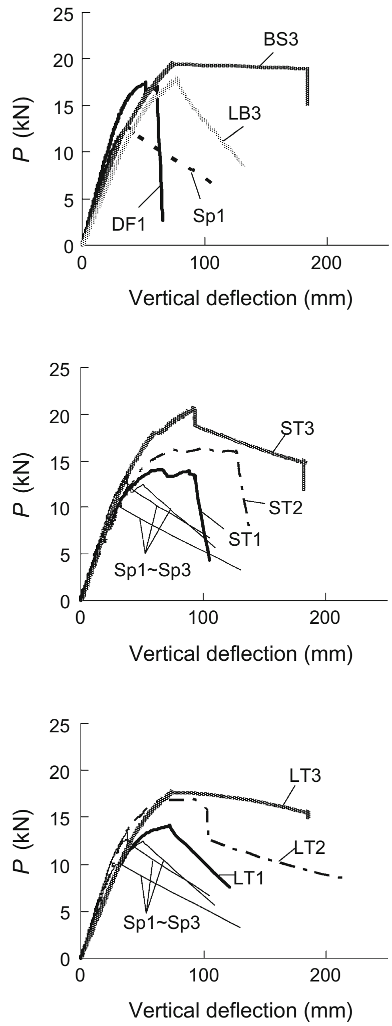


Fig. 4 Some typical load–deflection responses of the specimens

1. For the specimens produced with a single material, the flexural capacities are proportional to the strength of the material. Once the bottom fiber was broken or the glued surface failed, the carrying capacities dropped immediately.
2. In specimens ST1 ~ ST3, with the addition of the bamboo scrimber tension layers, the flexural capacities increased. The strength of ST3 is even slightly larger than that of BS1 ~ BS3. It may be owing to the improvement of the adhesive quality, but it still need further study to reveal the carrying mechanism of the laminated composite beams produced with more than 2 materials.

Comparing specimen ST1, having only one tensile layer replaced by bamboo scrimber, with Sp1 $\sim$ Sp3, the flexural capacity increased slightly but the ductility at failure was obviously improved. ST2 showed even better ductile performance. This can be explained by the constitutive behavior of the materials in the compression zone. At the moment of flexural failure, according to the constitutive behavior in Fig. 3, plastic stress distribution rather than linear elastic stress distribution existed in the compression zone. In ST1 and ST2 the compression zone was produced with spruce or Douglas fir, both of which showed almost bi-linear constitutive behavior. Thus at the moment of flexural rupture, the strength of the compression zone had been fully exploited. The ductile behavior of spruce and Douglas fir in compression contributed to the ductile behavior of ST1 and ST2, respectively.

However, for bamboo scrimber under compression, the proportional limit is lower but the compressive strength is not reached until 20,000–25,000 $\mu\varepsilon$, which is much larger than the tested compressive strain at failure. In other words, the bamboo scrimber in the compression zone has not reached its ultimate compression strength. That is why in the load–deflection curves, ST1 and ST2 showed a long yielding segment before final rupture, while in ST3 the failure point occurred during the ascending segment.

The compressive strength of Douglas fir is smaller than that of bamboo scrimber, thus the flexural capacity is improved from ST2 to ST3, since flexural failure is dependent on yielding of the compression zone.

3. The flexural capacities of LT1 $\sim$ LT3 presented the same trend: the use of laminated bamboo lumber resulted in an increase of flexural capacities. The flexural capacity of LT3 was comparable to LB1 $\sim$ LB3. Since the compressive strength of Douglas fir and laminated bamboo was close, the flexural capacities of LT2 and LT3 were also close, but due to the smaller compressive modulus of elasticity of laminated bamboo, LT3 showed larger deformation at failure.

4.3 Serviceability limit loads

In general the resistances of both bamboo and wood members are limited by the deformation requirements, imposed by the serviceability limit state. For ordinary flexural members, the serviceability deflection limit ranges from $L/150$ to $L/300$ (where L is the span length) [31]. The serviceability limit for the tested specimens was selected to be $L/250 = 8.3$ mm and the load to cause this deflection, P_{ser}, is reported in Table 3.

It is found that P_{ser} determined for specimens ST1 $\sim$ ST3 does not increase significantly with the increase of the bamboo scrimber layers. Their service loads are even smaller than that of the spruce beams Sp1 $\sim$ Sp3. This may be a limitation in the adoption of hybrid structural members. On one hand, the adhesive used in the specimens was generally adopted to glue timber layers. Its bonding capacity between bamboo layers need to be further tested. According to some current data, the bonding between bamboo scrimber layers has not reached a quality as high as timber layers, due to its hardness. On the other hand, it is supposed that in the composite beams, there exists a stress gradient between different material layers. The stiffness is decreased by the stress concentration caused by the stress gradient. The use of new and efficient bonding process between bamboo scrimber layers may solve this problem.

As the flexural moduli of spruce and laminated bamboo are similar, the bending stiffness of specimens of LT1 $\sim$ LT3 is not expected to increase obviously. In fact, it is found that the service loads of the laminated bamboo beams LB1 $\sim$ LB3, as well as the composite beams LT1 $\sim$ LT3, are all smaller than Sp1 $\sim$ Sp3. This is probably due to the low compressive modulus of laminated bamboo, which stems from the influence of the gluing surfaces. Generally, the serviceability limit loads of the tested beams are much smaller than their ultimate capacities (about 1/6–1/11). And it should be noted that the conclusions here were only applicable to short-term serviceability limit states, and the long-term behavior, which is more complex, need further study.

4.4 The normal strain distribution in mid-span

Figure 5 presents the normal strain distribution along the mid-span section in specimens ST3 and LT3 under different load levels. These two specimens were both failed by tensile fracture of the bottom fiber and horizontal tearing beside the fracture surface, which is the most common failure mode. Other failure modes include tensile fracture followed by diagonal splitting

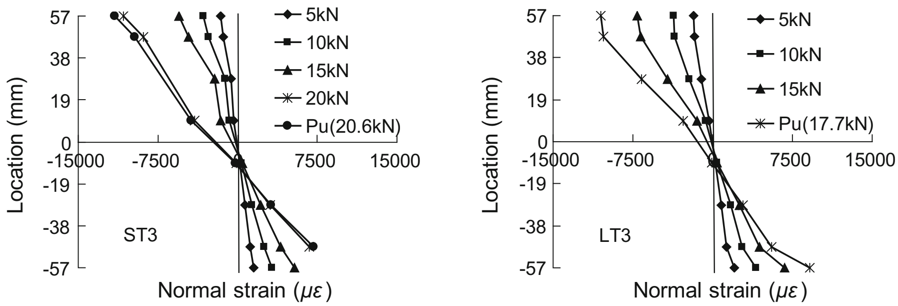


Fig. 5 The normal strain distribution along the mid-span section in specimens ST3 and LT3

(specimens Sp2 and Sp3), tensile fracture followed by delamination (specimens DF1, ST2 and LT1), and purely delamination (specimens BS1 and BS2). The normal strain distribution along the mid-span section of other typical failure modes are provided in Online Resource 3. The horizontal axis represents the strain values and the vertical axis represents the measuring position. The zero point refers to the midpoint of the cross section.

It is evident that the strain is distributed linearly until reaching the ultimate load P_u. The Bernoulli beam assumption that plane sections remain plane after bending, is applicable to the laminated beams under various failure modes. A few points showed some deviation at the ultimate state due to sudden rupture or local material crushing, although this did not affect the overall deformation characteristics. As the load increased, the neutral axis moved downward (except for the specimens Sp1, Sp3 and BS3), indicating that plastic deformation occurred in the compression zone.

5 Analysis of the flexural capacities

The following conditions and assumptions are considered in the analysis.

1. The normal sections in the constant moment region remain plane until reaching ultimate capacities, which is confirmed by Fig. 5.
2. The adhesive surfaces are capable of transmitting the stress between adjacent layers and no slippage occurs at the adhesive surfaces.
3. Flexural failure is triggered by tensile rupture of the bottom fiber. Failure of delamination is currently not considered. Thus the calculating method may overestimate the flexural capacities of the specimens failing by delamination.
4. The tensile behavior of the four materials is linear elastic until tensile fracture. The compression behavior is nonlinear beyond the proportional limit. According to the tested strains, the upper part of the compression zone exhibits plastic deformation.

For both wood and engineered bamboo, the strengths tested from the small clear specimens are greater than that in full-scale structural members, due to the various kinds of defects, as well as the influence of the adhesive surfaces. The influences of natural defects, drying defects and size effect should be considered when using the strengths tested from small clear specimens. The influence of long-term loading does not need to be considered here. The Chinese design manual for timber structures [32] has suggested specific reduction factors for each influence. For tensile and compressive strengths, different combination of the above factors should be adopted.

For Douglas fir and spruce, the reduction factor for compressive strength only considers the influence of natural defects (0.8). The reduction factor for tensile strength considers the influence of natural defects (0.66) and size effect (0.75), resulting a net reduction factor of 0.5. The constitutive relationship for Douglas fir and spruce after reduction is shown in Fig. 6.

For engineered bamboo materials, current experimental data is insufficient to recommend reduction factors. Therefore reduction factors of wood provide the basis for selecting values for engineered bamboo. The production processes of cutting, laminating and reconstituting, engineered bamboo products mitigates

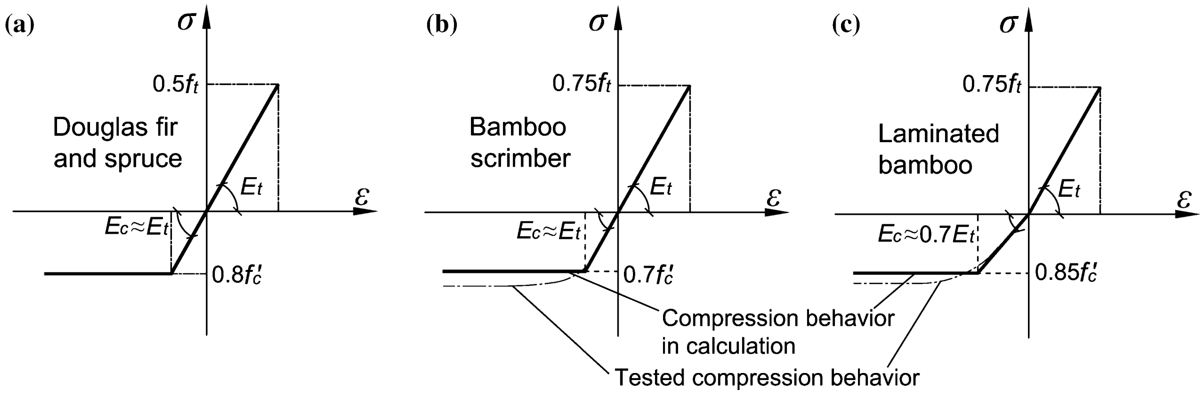


Fig. 6 Tensile and compressive behavior in structural members of the four materials

the influence of natural defects. Thus for engineered bamboo, the reduction factor for tensile strength contains only the influence of size effect (0.75). On the other hand, the compressive strengths should also be revised due to the observed nonlinear behaviors. According to the tested constitutive behaviors, the proportional limit of bamboo scrimber and laminated bamboo under compression is $0.65f_c'$ and $0.75f_c'$ respectively. The bilinear curves in Fig. 6 can approximately describe the stress distribution in the compression zone.

For Douglas fir, spruce and bamboo scrimber, the difference between the tensile and compressive elastic moduli is negligible. While for laminated bamboo, test results show that the compressive elastic modulus is approximately 70% of the tensile elastic modulus.

The stress distribution of a normal section at the ultimate limit state can be described according to the revised stress–strain relationships in Fig. 6. For the beams laminated with a single material, neglecting the influence of the adhesive surfaces, the normal stress and strain distribution can be approximated as shown in Fig. 7a. Three coefficients, k_c, k_t and α_E, are introduced. k_c and k_t are the reduction factors for the compressive and tensile strengths shown in Fig. 6. α_E is the ratio between compressive and tensile elastic modulus with $E_c = \alpha_E E_t$. For laminated bamboo $\alpha_E = 0.7$, and for the other three materials $\alpha_E = 1.0$.

The equilibrium of stress in Fig. 7a gives:

$$0.5k_t f_t \cdot y_t = 0.5k_c f_c' \cdot x + k_c f_c' \cdot (h - x - y_t) \tag{3}$$

Considering the ratio between the compressive and tensile elastic modulus:

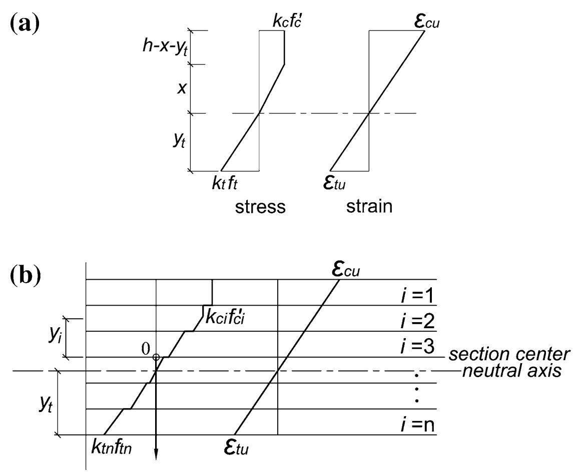


Fig. 7 Normal stress and strain distribution at ultimate state: **a** beams produced with a single material; and **b** composite beams

$$\frac{k_c f_c'}{x} = \alpha_E \frac{k_t f_t}{y_t} \tag{4}$$

Substituting Eq. (4) into Eq. (3), the depth of the tensile zone can be found:

$$y_t = \frac{h}{0.5\frac{k_t f_t}{k_c f_c'} + \frac{0.5}{\alpha_E} \cdot \frac{k_c f_c'}{k_t f_t} + 1} \tag{5}$$

Thus the flexural capacity is obtained as:

$$M_u = k_c f_c' \cdot b \cdot \left[(h - x - y_t)\left(\frac{h}{2} + \frac{x}{2} + \frac{y_t}{6}\right) + \frac{x}{3}(x + y_t) \right] \tag{6}$$

in which b is the width of the beam.

For the timber-bamboo composite beams, the normal section still remains plane but there exists a stress gradient between different material layers. Using the coordinate axis shown in Fig. 7b, the origin of the coordinate is at the center of the section, and y_i refers to the coordinate of the center of the ith layer. The tensile and compressive capacities of the material of the ith layer are $k_{ti}f_{ti}$ and $k_{ci}f_{ci}'$, respectively. The relationship between the tensile and compressive elastic modulus gives $E_{ci} = \alpha_{Ei}E_{ti}$.

According to the stress distribution in Fig. 7b, the stress at the center of the ith layer is

$$\sigma_i = k_{tn}f_{tn}\frac{y_i - (0.5h - y_t)}{y_t} \cdot \frac{E_{ti}}{E_{tn}} \quad \text{if} \quad y_i \geq 0.5h - y_t \tag{7a}$$

$$\sigma_i = k_{tn}f_{tn}\frac{y_i - (0.5h - y_t)}{y_t} \cdot \frac{E_{ci}}{E_{tn}} \geq -f_c' \quad \text{if} \quad y_i < 0.5h - y_t \tag{7b}$$

Considering the equilibrium condition that

$$\sum_{i=1}^{n} \sigma_i t_i = 0 \tag{8}$$

the depth of the tensile zone y_t can be solved. In practice, the value of y_t can be determined through trial and error. And the flexural capacity of the composite section can be obtained as:

$$M_u = b\sum_{i=1}^{n} \sigma_i t_i \cdot \left(y_i + y_t - \frac{h}{2}\right) \tag{9}$$

The predicted flexural capacities and test results are shown in Table 3. Table 3 also lists the serviceability limit load, P_{ser}, the proportional limit load, P_{cr}, and the corresponding mid-span deflection, Δ_{cr}. E_0 is the equivalent elastic modulus obtained with Eq. (2). y_{t_exp}, P_{u_exp} and Δ_u are the depth of the tensile zone, ultimate load and the corresponding mid-span deflection obtained from experiment. y_{t_cal}, M_{u_cal} and P_{u_cal} are the calculated depth of the tensile zone, ultimate bending moment and ultimate load.

The method overestimates the flexural capacities of the bamboo scrimber beams, especially specimens BS1 and BS2, as the two specimens failed by delamination rather than flexural rupture. The quality of the adhesive surface cannot keep up with the increase of the material strength, or the adhesive used does not work well with bamboo scrimber.

6 Conclusions

In this study, the flexural performance of laminated beams produced with timber and engineered bamboo was studied. The beams had 6 layers made from Douglas fir, spruce, bamboo scrimber and laminated bamboo, or the combination of them.

The tensile, compressive and flexural performance of the 4 materials: Douglas fir, spruce, bamboo scrimber and laminated bamboo were firstly tested. They all exhibited linear elastic behaviors under uniaxial tensile conditions until fracture. While in the compressive direction, nonlinear behavior was obvious before reaching the compression strength. For Douglas fir and spruce, the linear behavior was maintained up to 90% of the compression strength, followed by a yielding plateau. The compressive behavior can be described as almost elastic perfectly-plastic. Bamboo scrimber and laminated bamboo reach the proportional limit earlier, but showed much better deformation ability and ductile behavior under compression than wood.

Flexural failure of the laminated beams was primarily triggered by tensile fracture of the bottom fiber, followed by horizontal tearing beside the broken surface. A few specimens failed by delamination, diagonal splitting or compressive buckling of the top fiber after fracture. And two bamboo scrimber beams failed by delamination before fracture. It is found in the tests that the flexural capacities of the composite beams, produced with engineered bamboo in the bottom 2 layers and the top layer, is comparable to the capacities of the engineered bamboo beams. The flexural capacities of the laminated wood beams produced with fast growing economic wood species of low strength, like spruce, can be effectively improved by bonding engineered bamboo lumbers on the outer surfaces.

The Bernoulli beam assumption that plane sections remain plane after bending, is applicable to the laminated beams, even in the beams produced with different material layers. According to the plane section assumption, the flexural capacities of the laminated beams can be estimated through equilibrium and compatibility conditions. In calculating the capacities of the structural members, the strengths tested from the small clear specimens should be revised, considering the influences of natural defects, drying defects and size effect.

In this study only short-term behaviors were considered. In further research the long-term behaviors of engineered bamboo specimens and bamboo-timber hybrid specimens need to be investigated, which depend on the long-term behavior of both the gluing surfaces and the constituent materials. Different material may have different creep behavior, thus the resisting mechanism and deformation pattern under long-term load remain to be further explored. The bonding capacity between engineered bamboo layers is another problem to consider. Improving the bonding quality between engineered bamboo layers will further improve the mechanical behavior of engineered bamboo and hybrid specimens.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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