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*REVIEW ARTICLE*

# A review of mechanical behavior of structural laminated bamboo lumber

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**Abstract:** The transition of the construction sector to sustainable development mostly depends on the environmental friendliness of building materials. This, in turn, calls for the development of new, strong, and sustainable materials that would be a worthy alternative for traditional materials, including wood. Over the past decade, laminated bamboo lumber (LBL) has received much attention from engineers, practitioners, and scientists for its attractive mechanical properties, comparable to and in some cases superior to hard and softwood. Moreover, the sustainability of LBL is characterized by its high carbon sequestration, fast time to harvest, high yield, and low energy consumption for processing. However, the behavior of LBL is not yet fully understood, which in turn affects the low awareness and application of the material by practitioners and engineers around the world. Since LBL has a promising future, this article will contribute to a better understanding of its mechanical properties and a more accurate design, taking into account the influencing factors. This article discusses the mechanical properties of three types of structural LBL, namely beams, columns, and sheathing panels. The previous works of researchers on the mechanical properties of structural LBL were reviewed, and thus the most common failure modes, the causes of the destruction of structural elements, and the factors that affect their behavior were discussed and described. This work will serve as a reference for current practitioners and future research.

**Keywords:** Laminated bamboo lumber; mechanical properties; column; beam; shear wall

## 1 Introduction

Currently, interest in bamboo as a building material is growing due to its sustainable characteristics [1-6]. Compared to wood, bamboo can grow up to 30 meters in 4 months and reach maximum strength in 3–8 years, which ensures fast and high yield [7-10]. According to life-cycle assessment (LCA) results, bamboo has the highest carbon sequestration than wood and requires less energy for processing, which reduces its environmental impact compared to traditional building materials [10, 11].

Since ancient times, bamboo has been used in many areas of human life, from household utensils to the construction of houses and bridges, due to its high earthquake resistance [12], as well as its

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distinctive mechanical properties, comparable to mild steel, cast iron, aluminum alloys, and wood [13-15]. For instance, the tensile strength and modulus of elasticity parallel to the grain of Moso bamboo (*Phyllostachys pubescens*) can reach up to 309 MPa and 27.397 GPa, respectively [16]. Bamboo also copes well with bending loads due to a large ratio of moment of inertia to a cross-sectional area [10]. Over the past decades, new engineering bamboo materials have been developed, such as laminated bamboo lumber (LBL), glued laminated bamboo (glubam), parallel strand bamboo (PSB), etc. so it became possible to use bamboo in various shapes, sizes and applications [17, 18]. According to previous studies, the physical and mechanical properties of engineered bamboo, as well as its sustainability and flexibility, are comparable to timber and glue-laminated timber products [19-23]. For example, building weight reduction can be achieved by using composites made of bamboo and steel or bamboo and concrete; glubam panels with mineral wool increase fire resistance; and the use of bamboo structures reduces energy consumption by 65% [12]. Recently, the use of LBL in the construction of buildings and structures has increased. For example, a private villa in Saudi Arabia (Fig. 1a) and a number of structures in China were constructed using LBL as structural and facing material (Fig. 1b-d).

(a) Private villa in Saudi Arabia (Zhenhua Xiong)
(b) Art exposition in Beijing (Zhenhua Xiong)

(c) Sentai office building in Ganzhou (Haitao Li)
(d) Zidong Pioneer Park in Nanjing (Zhenhua Xiong)

**Fig. 1.** Structures made of LBL.

Extensive research has been done to determine the feasibility of LBL in structural applications, such as beams to columns and other connections [24-30]. The state of the art in LBL and bamboo scrimber development was summarized and compared to structural timber and laminated veneer lumber (LVL) [31]. International codes for timber were investigated to consider the development of all-encompassing bamboo standards and building codes [32]. Technologies of full culm bamboo joints [33,34] and connections of engineered bamboo [35] were reviewed, application challenges and future research potentials were discussed.

This study aims to present a review of the mechanical performance of structural LBL such as beams, columns, and shear walls. Journals and conference articles were accepted for review, while book chapters, letters, notes, and short communications were excluded from the search according to the requirements. The requirements ensuring the consistency are: (1) an article is written in English; (2) published in a journal or conference proceedings; (3) include experimental, analytical, or numerical investigation; (4) the main focus of the article is to explore the mechanical behavior of structural LBL. According to Science Direct, there were 278, 153, and 174 research articles on “laminated bamboo beam”, “laminated bamboo column”, and “laminated bamboo shear wall”, respectively (Fig. 2).

As can be seen from Fig. 2, since 2006, there has been a growing trend in the development of engineered bamboo materials. Since 2011, there has been a sharp increase in research, indicating a high demand for engineered bamboo materials in Architecture, Engineering, and Construction (AEC) industry. This leap is associated with the transition of the world economy and the AEC sector to a sustainable path, which in turn gave an impetus to the development of environmentally friendly, energy-efficient, and strong alternatives to traditional building materials.

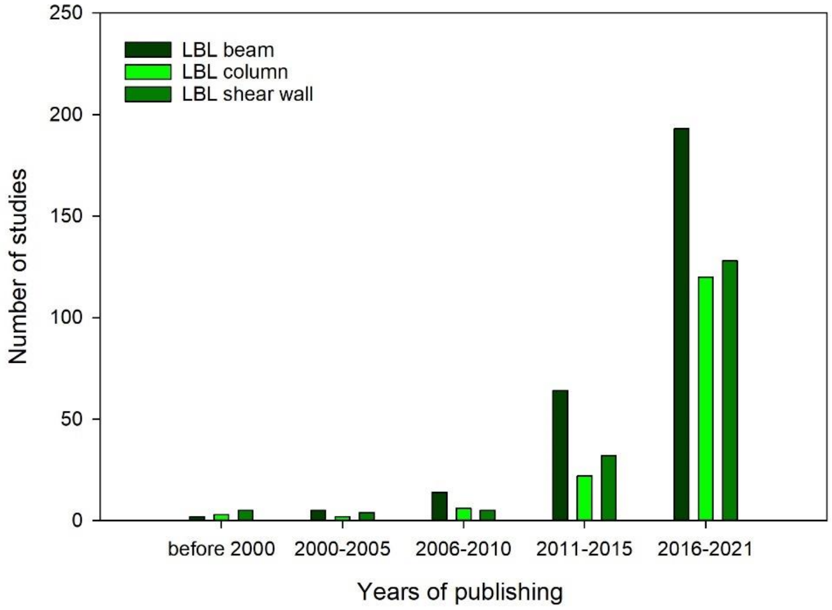


**Fig. 2.** Existing research on structural LBL per year via Science Direct.

**Table 1.** Summary of selected studies on structural LBL

| Study | Species | Glue | The spread rate, g/m$^2$ | Lamination method | Standard | Size, mm |
|---|---|---|---|---|---|---|
| Li et al. [36] | *Phyllostachys pubescens* | PF | 300 | - | - | 56×110×1950 |
| Jorissen et al. [37] | *Phyllostachys pubescens* | - | - | - | - | - |
| Correal et al. [38] | *Guadua Angustifolia kunt* | - | - | - | - | - |
| Lei et al. [39] | *Phyllostachys pubescens* | - | - | Hot press | ASTM D198<br>GB/T 50329-2012 | 40 to 80×120×2300<br>60/80×120×1150 |
| Li et al. [40] | *Phyllostachys pubescens* | PF | - | - | ASTM D198<br>GB/T 50329-2012 | 45 to 80×100×2400 |
| Su et al. [41] | *Phyllostachys pubescens* | - | - | - | GB 50005-2003<br>JG/T 199-2007<br>ASTM D143 | 80×160×2200 |
| Karyadi et al. [42] | *Malang, East Java, Indonesia* | UF | 268 | Cold clamped pressure | ASTM D198 | 89×89×3000<br>79×79×3000<br>71×107×3000<br>65×113×3000<br>65×98×3000<br>67×100×3000<br>71×107×3000<br>80×120×3000 |
| Zhou et al. [43] | *Phyllostachys pubescens* | PF | - | - | ASTM D143<br>ASTM D198 | 80×160×2100 |
| Mujiman et al. [44] | *Dendrocalamus asper* | PVA | - | Cold pressure | - | 70×100×900<br>70×100×2850 |
| Penellum et al. [45] | *Phyllostachys pubescens* | PUR | 180 | Manual clamping pressure | BS EN 408 | 60×120×2400 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Li et al. [46] | *Phyllostachys pubescens* | PF | - | Hot pressure | - | 73×73×1000 |
| Li et al. [47] | *Phyllostachys pubescens* | - | - | - | - | 100×100×1200 |
| Li et al. [48] | *Phyllostachys pubescens* | PF | - | Hot pressure | - | 80×80×850 to 1700 |
| Li et al. [49] | *Phyllostachys pubescens* | PF | - | Hot pressure | - | 100×100×400 to1800 |
| Luna et al. [50] | *Guadua Angustifolia kunt* | MUF<br>PF | - | Cold pressure | ISO 22156<br>ISO 22157 | 50×50×150 to 1250<br>100×100×250 to 2500 |
| Sharma et al. [23] | *Phyllostachys pubescens* | PF | - | - | EN 384<br>EN 408<br>ON ISO 13061 | 90×140×540<br>45×70×90 |
| Wang et al. [51] | *Phyllostachys pubescens* | PF | - | Hot pressure | - | 76×76×800 |
| Li et al. [52] | *Phyllostachys pubescens* | PF | - | - | ASTM D198 | 100×100×1200 |
| Correal et al. [53] | *Guadua Angustifolia kunt* | - | - | - | ASTM E72<br>ASTM E564<br>ASTM E2126 | 2400×1200 |
| Varela et al. [54] | *Guadua Angustifolia kunt* | MF,<br>UF | - | Cold pressure | ASTM D3043<br>ASTM E564<br>ASTM E2126 | 9×1200×2400 |
| Luna et al. [55] | *Guadua Angustifolia* | - | - | - | NTC5525<br>NSR-10 | 15×200×1300 |

Adhesives: PF – phenol-formaldehyde, UF – urea-formaldehyde, MF – melamine-formaldehyde, PVA – polyvinyl acetate, MUF – melamine-urea-formaldehyde, PUR – polyurethane, EPI – polymer-isocyanate.

Finally, 21 papers were adopted for review, from which 20 papers are published in the last 10 years, and 1 paper is of the 2007 year. It should be mentioned, that only studies that focus on the mechanical properties of structural LBL namely beams, columns, and shear walls were selected for review. Tab. 1 shows a summary of selected papers.

## 2 Production

Given the details of the literature reviewed, most studies have been done on structural LBL created from bamboo genus *Phyllostachys*, and only a few from *Guadua* and *Dendrocalamus*. According to previous studies [56-58], the species of bamboo affect the mechanical properties of the material, therefore, investigation of the mechanical behavior of structural LBL from equally popular bamboo genera like *Bambusa* and *Gigantochloa* is relevant.

In the literature, there are several methods of producing base bamboo material, such as dividing bamboo culm into two halves followed by flattening [31], dividing bamboo culm into grooves followed by flattening [59,60], roller flattening [61], dividing bamboo culm into grooves followed by complete separation into strips using a hammer [62], and dividing bamboo culm into strips followed by planing to obtain the uniform size. It should be noted that the flattening process is carried out at a pressure of 690 kPa for 1–4 min [10] and it can cause cracks in the base bamboo sheet [63], so the optimization of this method is a relevant topic.

Among the manufacturing countries, China is the leader in the production and supply of bamboo building materials. Fig. 3 briefly shows the process of manufacturing LBL in China.

For the production of LBL in China, 4-5-year-old bamboo culms are chosen and divided into strips. The strips are dried till the moisture content gets 8-12% and then planed to remove wax and silica from both sides and achieve a uniform size of the strips. The strips are then treated with carbonization or bleaching. Carbonization is the placement of strips in a chamber under a pressure of 120–130˚C to caramelize sugar and obtain a deep brown shade of the material [64]. Bleaching consists of placing bamboo strips in a solution of hydrogen peroxide at a temperature of 70–80˚C [64]. According to previous research [64, 65], both processing methods have an impact on the mechanical properties of the LBL, so this should be taken into account when determining the structural application of the final material. After processing, the strips are folded, glued, and pressed using cold or hot pressing to obtain a homogeneous material of the required size. It is worth noting that during hot pressing, bamboo is densified, which leads to a denser material with improved mechanical properties.

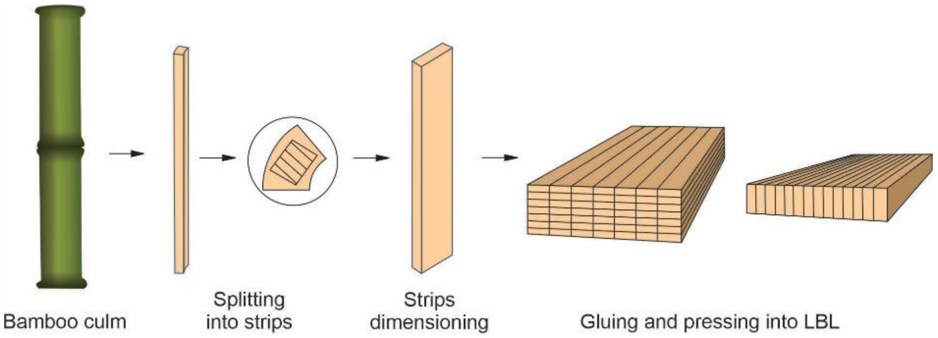


**Fig. 3.** The manufacturing process of LBL.

Despite the relatively low energy consumption for the production of LBL compared to conventional materials such as cement and steel, the processes of carbonization, drying, cold or hot pressing are the most harmful parts that affect the environment and make LBL more energy-intensive than wood and plywood [12,66]. Moreover, the use of adhesives that contain urea increases acidification and ozone depletion potentials [67]. Therefore, the development of the low-technology production of LBL is a topic of great interest. Existing studies on the environmental evaluation of LBL production and the construction of houses using engineered bamboo have not compared the potential for energy demand and other environmental indicators of LBL with the results of LCA of similar bamboo- and wood-based materials.

Based on the literature reviewed, PF is the most common adhesive used for gluing bamboo strips. It should be noted that different adhesives affect the physical and mechanical properties of LBL [68-70]. According to previous studies, the specimens created with polymer-isocyanate (EPI), PUR, hybrid polymer adhesive (HPA), and PVA failed more often along the glue line than the specimens glued with MUF, as well as PF [68, 69]. At the same time, EPI appeared to be unsuitable for the creation of LBL to be used in structural applications due to delamination caused by the inability of EPI to transfer loads [68]. Generally, the amount of glue required for gluing LBL is determined by the manufacturer. Nevertheless, the glue spread rate turned out to be one of the influencing factors on the mechanical properties of small-sized LBL, so in future studies, internal bond strength should be discussed in terms of using LBL for structural purposes.

## 3 Mechanical Behavior of Structural LBL

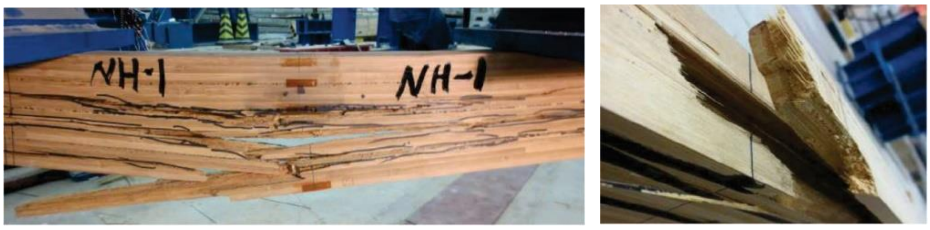
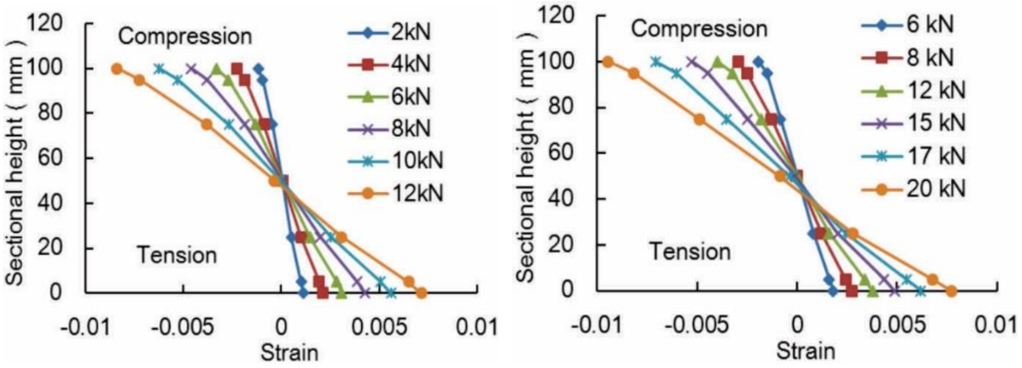
### 3.1 Beams

(a) Side surface (b) Bottom surface

**Fig. 4.** The failure mode for the LBL beams under bending load (extracted from Li et al.’s [36] paper).

The LBL beams are structural members subjected to lateral loads, that is, forces or moments having their vectors perpendicular to the axis of the bar. During the tests, the process of destruction of the LBL beams was similar to small bending specimens and was characterized by a bottom tensile fracture (Fig.

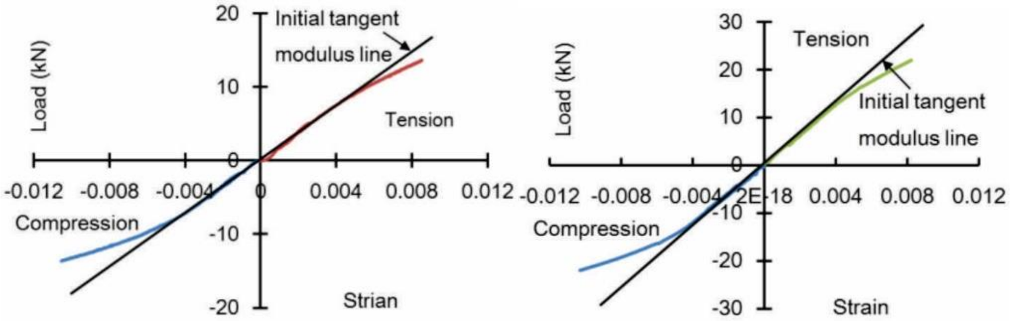
4).

With increasing deflection, cracks appeared on the tensile side with nodes, joints, and other defects of bamboo, since the tensile strength of bamboo was sensitive to the concentration of stresses in the area with defects [37,71]. Internal joints had more influence on specimens in tangential bending direction (TBD) than in radial bending direction (RBD) by increasing the stiffness and reducing the failure load [36], and the modulus of rupture (MOR) and modulus of elasticity (MOE) of the LBL beam with edgewise orientation were 12% and 9% higher than equivalent parameters for flatwise orientation [38]. When the deflection got very big and the outmost layer of the bamboo fiber pulled out, the beam failed due to a longitudinal splitting along the grain. The authors calculated the deflections for the ultimate load point which were more than 60 mm and far bigger than the value 8.4 mm (L/250) prescribed as the maximum allowable deflection by the Chinese wood structure design specification (GB50005-2003). Therefore, the critical design criteria for the LBL beams should be deflection rather than strength [39].



(a) Specimen LBLB45-1 (45-mm width)  (b) Specimen LBLB70-2 (70-mm width)

**Fig. 5**. Typical strain profile development for the mid-span cross-section (extracted from Li et al.'s [40] paper).



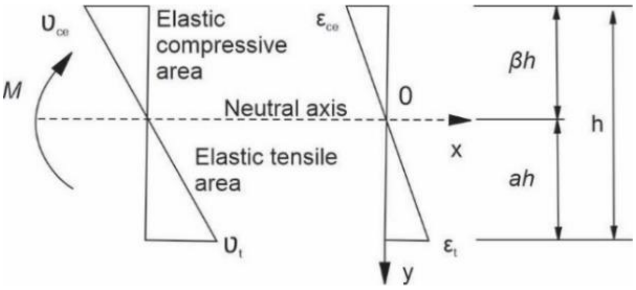
(a) Specimen LBLB45-1 (45-mm width)  (b) Specimen LBLB70-1 (70-mm width)

**Fig. 6.** Typical load-strain curves for the mid-span cross-section (extracted from Li et al.'s [40] paper).

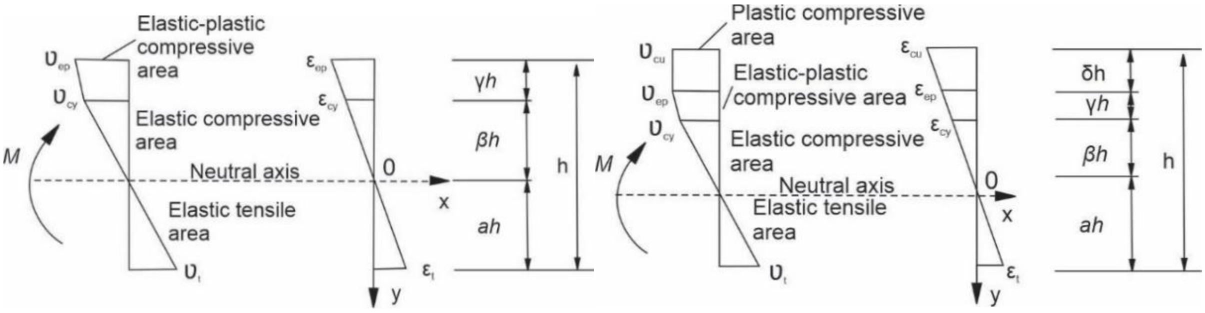
According to previous studies, the width of the LBL beams did not affect the ultimate tensile strain, bending strength, and MOE [40], and the effect of length was insignificant. As can be seen from Fig. 5, all the strain profiles follow the same law, and the strain across the cross-section of the LBL beam was linear throughout the loading process, following the standard beam theory regardless of the length and the width of the specimen [39,41].

The destruction process of the LBL beams demonstrated an initial elastic phase, non-linear deformation, and then brittle failure initiated by rupture on the tension side of the beam [40]. Fig. 6 shows the typical load against the strain for the mid-span cross-section of specimens, according to which the MOE for both the compression and the tension was equal to each other both in RBD and TBD regardless of the width of the LBL beams [36,40].

The stress was distributed linearly across the cross-section of the beams during the testing process [40], therefore the LBL beams followed the standard beam theory. Many studies proposed stress-strain relationship models for calculating the flexural capacity of LBL beams. All the models were based on similar conditions such as compliance with the plane cross-section assumption, the MOE for both compression and tension was equal, tension zone remained in a linear elastic stage, the outermost fiber of the tension zone reached the ultimate tensile strength, the compression zone experienced the ideal elastic-plastic state, and the stress in the plastic compression zone maintained a compressive proportional limit strength [14,39,43]. Based on stress-strain relationships for LBL Li, et al. [36] identified three possible failure modes of the LBL beams (Fig. 7), according to which during failure Mode 1 all bamboo fibers in the compressive zone were still in the elastic stage, while in Mode 2 some bamboo fibers in the compressive zone were in the plastic-elastic stage and some in the elastic stage, and in Mode 3, some bamboo fibers in the compressive zone were in the fully plastic stage, some in the elastic-plastic stage and some in the elastic stage.



(a) Mode 1



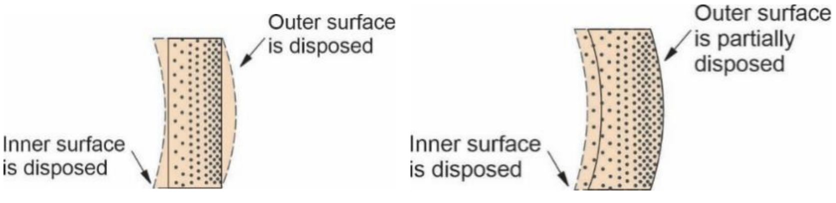
(b) Mode 2 (c) Mode 3

**Fig.7.** Strain-stress distribution at the ultimate failure state for LBL beams in different modes (reproduced according to Li et al. [36]).

Based on testing results according to full-scale structural timber standards, Sharma, et al. [23] concluded that edgewise orientation of LBL beams slightly increased bending strength and local MOE by 14% and 6-13% and constituted 61.7 – 66.7MPa and 9093 – 10412 MPa, respectively. While for flatwise, the same parameters were 56.6 – 58.6 MPa and 8612 – 9178 MPa, respectively.

Karyadi and Susanto [42] compared the performance of box-section and solid beams and figured out, that the box-section beams were more efficient in receiving the transversal load compared to the solid beam for the same amount of materials, since when the ratio between the section height and section width was less or equal to 1.50, the ability of the beam to resist the load increased proportionally with the increase of inertia moment for the same amount of material.

Mujiman, et al. [44] improved the shear and flexural strength of the LBL beams by modifying the shape of the cross-section of the lamina (curved) rather than the ordinary rectangular shape of the lamina (Fig. 8). The research results showed that in general, the LBL beams with curved lamina were more durable, rigid, and ductile compared to the beams with rectangular lamina. The average shear and bending strength of the LBL beams with the curved lamina of 7 mm thick were much better than that of 9 mm thick of curved lamina, constituting 2.72 and 68.80 MPa, respectively [44].



(a) Rectangular (b) Curved

**Fig. 8.** The disposed part of the bamboo in making the laminas [44].

The researchers proposed several factors as critical design criteria for calculating bamboo beams in design such as the cross-sectional stiffness [22] or deflection [39,40]. In addition, the characteristic MOE should be used for design purposes, rather than the mean [40]. Penellum, et al. [45] proposed a model of predicting the bending stiffness of LBL by "ImageJ" analysis based on "composite rule of mixtures" [45]. It should be noted, that the elastic transformed section method for the prediction of bending stiffness turned out to be ineffective and required further refinement to draw meaningful conclusions on the effect of strip orientation [45]. The work also showed that the bending stiffness variations previously attributed to solely the preservative treatment method were caused by a difference in the size of the constituent strips [45]. Zhou, et al. [43] developed the calculating models for ultimate bending moment, and ultimate bending deflections by using the progressive method in the calculation process of ultimate load-carrying capacity to trace the inelastic processes of the specimens.

**Table 2.** Bending performance of the LBL beams compared to similar bamboo- and wood-based beams

| Beams | Species | Size, mm | Bending ∥, MPa | Bending ⊥, MPa | MOE ∥, MPa | MOE ⊥, MPa |
|---|---|---|---|---|---|---|
| LBL [36, 39, 40, 42] | *Phyllostachys pubescens* | 56×110×1950<br>40 to 80×120×2300<br>60 to 80×120×1150<br>45 to 80×100×2400<br>79×79×3000 to 80×120×3000 | 55.82 – 109.73 | - | 8730 – 11499 | - |
| Glubam [66, 72] | *Phyllostachys pubescens* | 84×450×6000 to 100×400×9000 | 99 | - | 10500 – 11200 | - |
| LVL [73] | *Heritiera spp.* | 50×60×1080 | 55.6 | 10.046 | 9973 | 1601.49 |
| LVL [73] | *Pometia spp.* | 50×60×1080 | 71.96 | 14.993 | 12043 | 2364.58 |
| LVL [74] | *Douglas-fir* | - | 54.2 – 71.7 | - | 15400 – 19300 | - |
| Glulam [75] | *Hevea brasiliensis* | 20×60×1200 | 75.14 | - | 8166.79 | - |
| WPC [76] | *Pine* | - | 26.1 | 16.7 | 4100 | 2660 |
| Douglas-fir [74] | | - | 85 | - | 13400 | - |
| Teak [74] | | - | 80 | - | 9400 | - |

Notes: WPC – wood plastic composite.

Tab. 2 shows the comparison of mechanical properties of the LBL beams compared to similar bamboo- and wood-based beams. As can be seen, the bending strength and MOE of the LBL beams are comparable with similar bamboo-based material glubam. The bending strength of the LBL beams can surpass those of LVL and glulam, but the MOE of the former is slightly lower than that of the latter except for glulam. According to Tab. 2, the bending performance of the LBL beams is similar to hardwoods like teak. The variability in strength values of the LBL beams can be explained by different types of adhesives, shapes of cross-section, strips orientation, the thickness of lamina, and species type used for its production.

### 3.2 Columns

Three failure modes were recorded for the LBL columns under compression along the grain: splitting, cracks extension along the compression, and propagation of the longitudinal cracks between bamboo laminates along the loading direction (Fig. 9) [46]. In both eccentric radial and tangential directions, the specimens showed the same failure modes [47].

(a) Mode 1 (b) Mode 2 (c) Mode 3

**Fig. 9.** Failure modes of the LBL columns under compression (extracted from Li, *et al.* [46] paper).

According to Li, et al. [47], LBL columns with different heights under axial compression obtained

2 failure modes: a squashing or crushing failure for short columns and a buckling failure for long ones. This was since the ultimate strength of long columns was less than that of the material, and the main factor affecting their load-bearing capacity was the slenderness ratio. At the same time, the load-bearing capacity of short columns was determined by the compression strength of the material. Fig. 10 shows the typical failure modes for short and long columns.

Under both tangential and radial eccentric compression directions, the strain across the cross-section of the LBL columns had similar linear properties, so they could follow the standard normal section bending theory [46,47]. Regardless of the lengths of the LBL columns determined by Li, et al. [48], the lateral deflection curves were close to the sine line, and the strain across the cross-section of the LBL column was linear throughout the loading process, following standard normal section bending theory.

Side surface Top surface Bottom surface

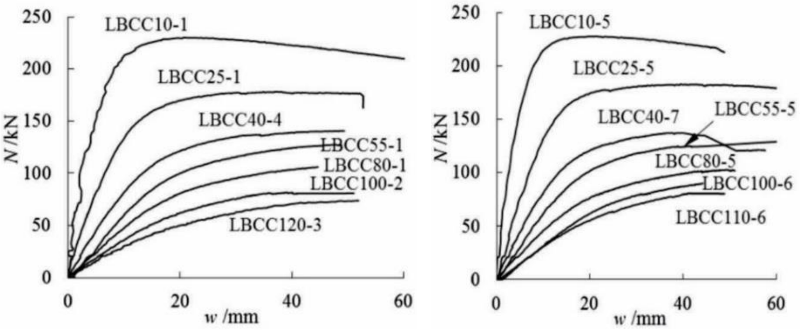
(a) Short columns

Side surface Top surface Bottom surface

(b) Long columns

**Fig. 10.** Failure modes of the LBL columns under compression (extracted from Li, et al. [47] paper).

Fig. 11 a, b shows the typical load-middle deflection curves for the LBL columns with different eccentricities under two eccentric directions. Initially, the specimens were in the elastic stage, followed by non-linear behavior regardless of the direction. When the peak load was reached, the lateral deflection increased and after the load was decreased, it kept growing till the failure of the specimens. It can be seen, that specimens with low eccentricity behaved plastically, while the specimens with high eccentricity showed increased lateral deflections before achieving the peak load.

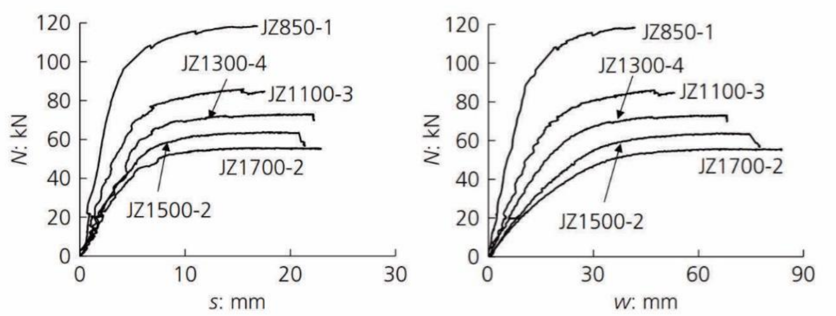


(a) Radial eccentric direction (b) Tangential eccentric direction

**Fig. 11.** Load-displacement curves for the LBL columns with different eccentric directions (extracted from Li, et al. [47] paper).

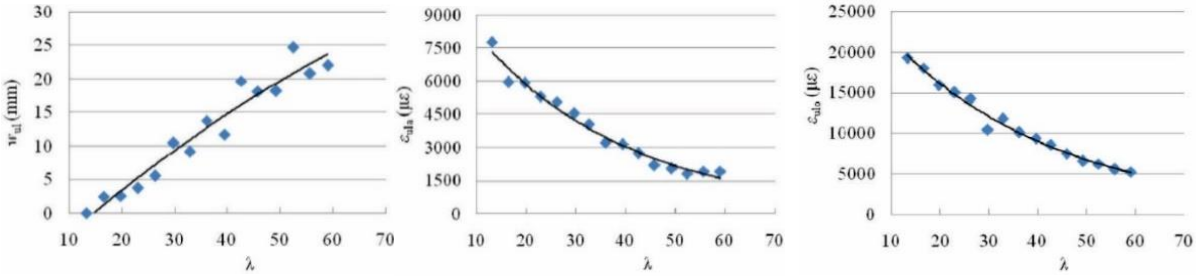
According to the results, the mechanical properties for two eccentric directions were the same, therefore, they could follow the same design rules. The authors proposed the calculation of the ultimate bearing capacity of the LBL columns by the radial eccentricity influencing coefficient φe, since the values of the ultimate mid-height lateral deflection and the absolute ultimate longitudinal strain increased with an increase in the eccentricity ratio [46,47].

Fig. 12 shows the typical load-displacement curves for the LBL columns with different slenderness ratios.



(a) Load-longitudinal displacement curves (b) Load-middle deflection curves

**Fig. 12.** Typical load-displacement curves comparison (extracted from Li, et al. [48] paper).



(a) Ultimate middle lateral deflection (b) Lateral strain (c) Longitudinal strain

**Fig. 13.** Influence of slenderness ratio on the ultimate strain and deflection (extracted from Li, et al. [49] paper).

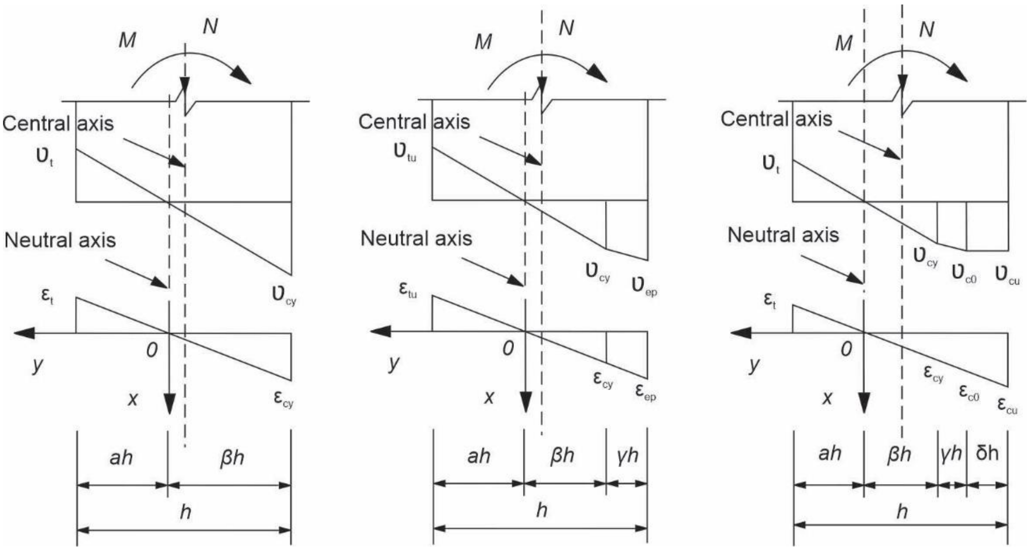
Regardless of the length, the LBL beams showed linear behavior in the initial stage followed by non-linear, and when the peak load was achieved, both the longitudinal displacement and the lateral deflection increased with subsequent failure. The displacement was bigger in longer columns. Similarly, the values for lateral middle deflections were larger than those for longitudinal displacement. Based on the results, the authors proposed the slenderness ratio as an approach for the design of LBL columns since it affected the bearing capacity of the columns [49]. As can be seen from Fig. 13, an increase in the slenderness ratio increased the lateral deflection (Fig. 13 a) corresponding with the peak load and decreased the ultimate lateral strain (Fig. 13 b) and longitudinal strain (Fig. 13 c) [49, 50].

Based on the results of the study [49], elastic buckling theory could be applied for columns of longer length, while non-linear finite element modeling (FEM) analysis – for columns of mid and low slenderness ratios. The authors proposed the equation for the calculation of ultimate bearing capacity considering the stability coefficient φ of LBL columns [49].

According to Sharma, et al. [23], the edgewise oriented LBL columns showed an increase in compressions strength perpendicular to grain and a decrease in local MOE, constituting 12.0 – 12.1 MPa and 1197 – 1219 MPa respectively. While in compression parallel to grain, the LBL columns showed buckling failure with the bending strength and local MOE of 39.5 MPa and 8166 MPa, respectively.

From the literature reviewed, the compression behavior of the LBL columns was characterized by elastic behavior at the beginning of loading, plastic deformation, and a decrease in the rigidity of the columns with increasing load [46-48,51]. The failure began with a tensile fracture since defects as mechanical connections or natural nodes detrimentally affected the tensile resistance of the material more than the compression [46-48,51]. And bending failure always happened for all the column specimens under two eccentric directions compression [48].

Li, et al. [52] identified three failure modes of the LBL columns under compression and proposed stress-strain relationship models for each. According to the results, Mode 1 was characterized by the linear behavior of fibers both in tension and compression, and the failure happened due to the splitting of the glue (Fig. 14 a). In Mode 2, the compression zone was characterized by the elastic-plastic behavior of fibers (Fig. 14 b). And in Mode 3, the outermost compression zone achieved full plastic capacity but the remaining portion experienced elastic-plastic stress conditions at failure (Fig. 14 c).



(a) Mode 1 (b) Mode 2 (c) Mode 3

**Fig. 14.** Stress-strain distribution for the LBL columns [52].

Based on a detailed analysis of failure modes of the LBL columns under eccentric compression, Li, et al. [52] proposed equations for predicting the ultimate resistance of columns. The test results of the LBL columns under axial and eccentric compression made by Wang, et al. [51] were in good agreement with previous studies, stating that eccentricity was one of the main influencing factors for the ultimate bearing capacity of LBL columns. The results showed, that the ultimate load for the specimens with the eccentricity values of 30 mm and 110 mm decreased by 65.2% and 88.4%, respectively [51]. It should be noted, that the LBL columns with box- and solid- sections under compression had an elastoplastic performance with high ductility with an average MOE for solid short columns of 5924 MPa, and a box section of 4653 MPa [50].

When comparing the LBL columns with glulam [77] and PSB [78-80] columns, it turned out that they have similar behavior, characterized by bending brittle failure, and by the dependence of the ultimate load-bearing capacity on the slenderness ratio.

### 3.3 Shear Walls

Wooden frame buildings have good seismic resistance as their lateral systems can dissipate energy without significant loss of lateral capacity. Lateral systems are usually wooden shear walls made of a wooden frame, sheathed with wood or wood-based materials, such as (oriented strand boards) OSB, and plywood. With the development of sustainable technologies, bamboo shear walls have become a comparable eco-friendly alternative.

Previous studies compared sheathing panel materials, their aspect ratio (AR), and edge nail spacing since these factors affect the shear wall performance under lateral loads. Correal and Varela [53] examined and compared 3 building modules such as one-story module, two-story module, and two-story module with wall finish, the shear walls of which were made of LBL, OSB, and plywood. Under the shake table test, the modules exhibited light damage on the wall and the wooden frame structure without finishing, and significant cracking appeared on the corners of the windows and at the joints between the structural and non-structural walls of the exterior and interior finishing (Fig. 15).

Varela, et al. [54] compared the cyclic performance of shear walls made of LBL, OSB, and plywood with different edge nail spacing 2, 4, and 6 inches and wall AR 1:1 and 2:1. As shown in Fig. 16 a, the failure mode was associated with the removal of nails from the panels, although the punching of the panels with nails also took place. It is worth noting that the nail driving schedule for walls with AR 2:1 was performed in a staggered order and the nails were driven into both double end studs instead of one to improve load transfer to the end posts since monotonic and cyclic tests of shear wall with a distance between the edges of the nails 3 inches and 2 inches and AR 1:1 showed localized failure in the form of tension in the two end studs to which the clamps were attached, which in turn affected the load-displacement behavior after the peak. All cyclic tests demonstrated localized fatigue failures of sheathing nails regardless of the type of wall (Fig. 16 c).

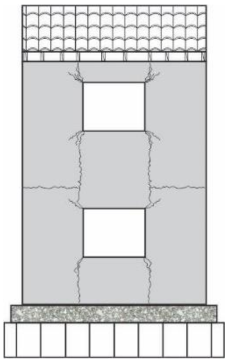


**Fig. 15.** Cracking pattern in exterior stucco after the tests [53].

(a) Monotonic tests with LBL bamboo panels

(b) Monotonic tests with OSB and plywood panels

(c) Cyclic tests regardless of the type of panel

**Fig. 16.** Typical observed failure modes (extracted from Varela, et al. [54] paper).

At the same time, for OSB and plywood walls, tearing and punching with nails with further damage to the panel itself was observed more than for LBL walls (Fig. 16 b). This could be since the LBL panels have a higher density, which prevented the breaks and slippage that were observed in wood-based panels.

Based on the results of studies made by Correal and Varela [53] and Varela, et al. [54], it can be concluded that shear wall sheathing with LBL had similar load-displacement behavior to shear walls sheathing with OSB and plywood. Shear walls with LBL panels were affected by the edge nail spacing in the same manner as OSB and plywood. According to results, AR didn't affect peak shear strength values of the walls and energy dissipations, but an increase in the number of nails increased the strength of the wall. The authors recommended using adequate anchorage and force transfer details for walls with AR 1:1 and closely spaced nails due to the low capacity of the framing members. A decrease in nail spacing decreased the displacement ductility capacity and the dissipation of energy by walls, while the stiffness and maximum load-carrying capacity of the wall increased. The peak shear strength values for all panels were found to be comparable, and it is worth noting that the higher density of the LBL panels allowed them to dissipate more energy and save themselves from significant damages compared to OSB and plywood. The results of the shake table test showed limited damages on shear wall sheathing with the LBL panels after a strong earthquake simulation. According to both studies, stiffness, maximum load capacity, and ductility of the LBL sheathed shear walls were not affected by the AR of the wall. But nail spacing and sheathing panel materials had a significant effect on shear wall performance under lateral loads.

Luna and Takeuchi [55] investigated the behavior of LBL frames with K-bracing and stiffened with the LBL panels under lateral load. According to load-displacement curves obtained from the tests, frames with K-bracing exhibited elastoplastic behavior, while the elastic behavior of frames with panels was divided into two zones such as accommodation of frames and elastic region. Both structures showed that the frames had great ductility. The maximum lateral drift allowed in Colombia by the earthquake-resistant building code is 1%, the value for which, the two types of structures tested were still in the elastic behavior area.

## 4 Discussion

Most of the materials from the articles reviewed were made from bamboo species *Phyllostachys*. Other genera of bamboo, such as *Bambusa*, *Dendrocalamus*, *Gigantochloya*, and *Guadua* can be used to create full-size LBL, and their mechanical behavior should be investigated and compared. According to the results of the review, not all types of adhesives are suitable for the production of structural LBL. The EPI appeared to be unable to transfer loads, which led to the destruction of the beam in the form of LBL delamination. In addition, past studies have pointed to the influence of adhesives types and their spread rates on the physical and mechanical characteristics of small-sized LBL, which calls for considering these influencing factors in terms of using LBL for structural purposes. Processing methods, such as carbonization and bleaching, and lamination methods, such as cold and hot pressing, also affect the physical and mechanical properties of the material and can be considered as factors determining the types of structural applications of the final product.

Despite the low environmental performance compared to conventional materials such as cement and steel, structural LBL was inferior to wood and plywood in environmental compatibility due to the highly intensive production. Moreover, the use of adhesives containing harmful substances also caused damage to the environment in the form of acidification and ozone depletion. Therefore, the development of a low-technology approach to LBL production and the use of environmentally friendly adhesives is a topic of great interest.

Currently, there are several review studies on engineering bamboo such as the basic mechanical properties of small-sized LBL, connections of the full culm bamboo and engineering bamboo, testing and design standards. However, there is not enough research on fire resistance of structural LBL, the effect of the processing methods, and fire retardant treatments on mechanical properties, as well as physical properties, such as durability, adhesion strength, dimensional stability, resistance to weather conditions, and aging.

Despite the presence of the ASTM D5456 standard, which included LBL (called laminated veneer bamboo) in the list of lumbers, the reviewed studies conducted experiments based on international and national codes used for timber. This is due to the wide demand for bamboo materials, which in turn is accompanied by a growing study of its mechanical and physical properties. The latest research results and calculation models of LBL based on wood standards should be reflected in the new editions of ASTM D5456 promptly and become the foundation for the development of a comprehensive standard for LBL.

According to the literature reviewed, the bending strength and elastic modulus parallel to grain of the LBL beam are 55.82 – 109.73 and 8730 – 11499, respectively, and resemble the behavior of hardwoods. The width and the length of the material had no effects on the behavior of the beam under bending, therefore, it could follow the standard beam theory. The investigators proposed 3 types of stress-strain relationships according to 3 possible failure modes of the LBL beam. The shape, thickness, and direction of the lamina affected the mechanical properties of the beam. For instance, the LBL beams with curved lamina were more durable, rigid, and ductile compared to the beams with rectangular lamina, and the specimens made of 7 mm thick lamina had higher bending strength than specimens with 9 mm thick laminas. At the same time, edgewise orientated LBL beams had slightly higher bending strength and local MOE than those of flatwise oriented beams. These influencing factors must be taken into account when producing the material for a particular end-use. Several methods for calculating the load-bearing capacity of the beam were proposed, in which the deflection of the beam was a critical design criterion.

The behavior of LBL columns was similar to that of PSB and engineered wooden columns. Under both tangential and radial eccentric compression directions, the strain across the cross-section of the LBL columns remained linear during the loading process, following the standard beam theory. The researchers developed 3 types of stress-strain relationships according to 3 possible failure modes of the LBL column. According to the results, the lamina direction had an impact on the behavior of the LBL columns under compression: the edgewise oriented LBL columns had a higher compression strength perpendicular to grain and lower local MOE. In addition, factors such as the stability coefficient, the slenderness ratio, and the eccentricity ratio affected the lateral deflection, lateral and longitudinal stresses in the columns, so they should be taken into account when calculating the bearing capacity of the columns.

Despite attractive mechanical characteristics, structural LBL also had disadvantages in the form of nodes and joints, which significantly reduced the mechanical characteristics of both beams and columns. This was because, with increasing deflection, cracks appeared on the tensile side with nodes and joints, since the tensile strength of bamboo was sensitive to the concentration of stresses in the area with defects.

The LBL panels had similar behavior to traditional OSB panels and plywood under lateral loads. Due to its density, LBL coped with energy distribution better than conventional materials, which made it the best for use in seismically hazardous areas. According to the results, the diameter of the screw and the distance between the screws and the nails significantly affected the behavior of the panels, while the influence of the aspect ratio was not observed.

## 5 Conclusion

According to the reviewed studies, LBL has great potential and can serve as a worthy alternative for conventional building materials. Even though modern research and the structural application still face the problems of high cost and high intensity of production, as well as the influence of nodes and joints on the mechanical properties, the average strength of structural LBL is similar to other bamboo- and wood-based materials and resembles the mechanical characteristics of hardwoods.

The mechanical properties of structural LBL were extensively studied, the most common failure modes, the causes of the destruction, and the influencing factors that correspond only to LBL were determined and discussed, which in turn will become the foundation for the development of design values for structural LBL. However, several factors still need to be addressed. The influence of bamboo species, adhesives and their spread rates, lamination methods, and clamping forces on small-sized LBL should be discussed in terms of structural applications of LBL members. Due to the growing demand for structural LBL, its modern production methods are becoming more intensive, which negatively affect the environment. Therefore, to retain the sustainability of the material, it is necessary to pay attention to low-technology and safe production with the corresponding use of environmentally friendly adhesives and reduction in energy consumption. Environmental evaluation of structural LBL based on LCA with local inventory databases and subsequent comparison with traditional materials will help in determining those production factors that need to be optimized. With the growing research interest, as well as the emergence of new bamboo-based materials, further testing based on timber standards is necessary in order to determine the properties, bamboo-based influencing factors, and create all-encompassing test and design standards similar to those used for wood.

The reliability of LBL structures is determined not only by the level of safety, comfort, and compliance with sanitary, hygienic, and fire resistance requirements but also by the retention of material properties during a long time of operation. Therefore, the influence of processing methods and fire retardant treatments of structural LBL on its physical and mechanical properties, durability, resistance to temperature fluctuations, humidity, and aging is a topic of great interest. Also, it is necessary to study the environmental impact associated with the treatment of LBL products.

The attractive characteristics of structural LBL have been demonstrated in numerous studies. In addition to the distinctive strength, structural members made of LBL can be created in any cross-section, shape, and meet different heights and spans of structures. The high cost of LBL members may delay its widespread use in the AEC sector, but the growing research interest, the development of low-cost and sustainable production methods, and, as a result, an increase in demand, will help structural LBL become a beneficial option in the construction of public and residential buildings. With the research progress in LBL, the integration of existing results will help to create the most innovative solutions that are profitable in terms of structural applications, cost, and environmental compatibility.

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## Conflicts of Interest

The authors declare no conflict of interest.

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