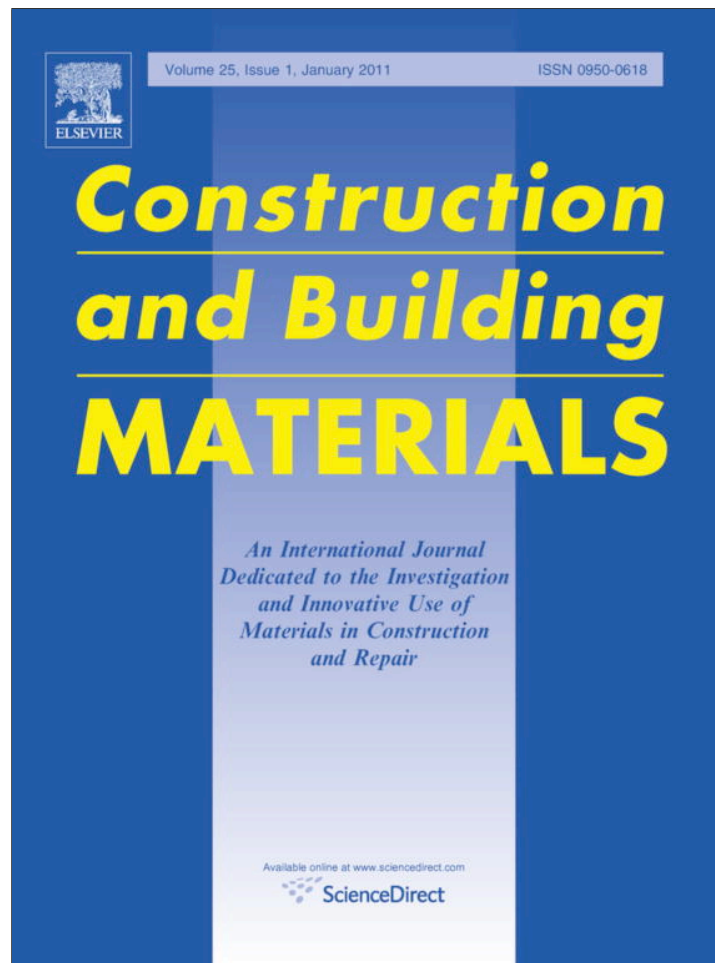


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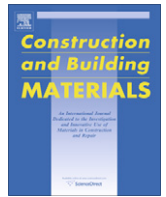
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A low-technology approach toward fabrication of Laminated Bamboo Lumber

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ABSTRACT

Depletion of natural resources has become a major concern in today's modern industrialized world centering much attention on sustainability of the built environment and sustainable alternatives to current development and construction practices. In the green building community, strong interest lies in natural and renewable building materials that can be used in structural applications. Just such a natural and renewable building material, called Laminated Bamboo Lumber (LBL), has recently been developed. This product, however, typically requires sophisticated fabrication equipment and energy intensive pressing processes that generally limit the possibility of local product fabrication. In an effort to foster local and thus more sustainable production of the product, this paper proposes a simple, practical and low-technology approach for LBL fabrication that could be carried out in any part of the world in which bamboo currently grows. Twelve 4-ply LBL specimens were fabricated using the proposed approach and the mechanical properties of the resulting LBL indicate that the end product is mechanically suitable for use in structural applications. The key contribution of this paper, therefore, is the conclusion that structurally reliable LBL can be fabricated using hand tools, screw-driven mechanical presses, and widely available, economical adhesives.

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1. Introduction

The term *bamboo* encompasses a collection of giant grass species [10]. In the western world, it is commonly used in non-structural applications, such as flooring, fencing, furniture and crafts, and for ornamental purposes. In many countries to which it is native, however, bamboo is used as a structural building material. For example, in Asia, bamboo has traditionally been used in low-rise buildings, short-span foot bridges, long-span roofs and construction platforms [1].

Bamboo has recently attracted considerable interest as a sustainable building material since it possesses mechanical properties similar to those of structural wood products, and, due to its fast growth rate, can support intensive and sustainable use in the building industry [2,10,8,6]. Bamboos grow faster than any other plant, and for most species, full height is reached within 2–4 months [4] with maturity coming in 3–8 years [2]. Bamboos also sequester large amounts of carbon, with Nath et al. [6] reporting an above ground carbon storage of 61.05 tons per hectare for village bamboos of northeast India. After a detailed quantitative lifecycle analysis, van der Lugt et al. [10] found the structural use of bamboo

to have less negative effect on the environment than that of other common building materials, such as steel or concrete.

Due to bamboo's natural hollow tube shape, it is not possible to connect bamboo members with existing standard connections. Therefore, it has been of interest to make bamboo available in shapes more suitable to current structural applications. This interest led to the development of Laminated Bamboo Lumber (LBL), which is usually produced as a board of rectangular cross-section [3,7–9].

Generally speaking, LBL is fabricated by flattening bamboo culms and gluing them in stacks to form a laminated composite. While resolving geometric issues presented by the round, hollow culm, this process introduces new issues of cost, labor and need for sophisticated equipment. Moreover, the process adds embodied energy to the final product while erecting financial obstacles for LBL production in developing countries. It is speculated that limited LBL production causes reduced availability and increases the distance between supplier and consumer, leading to greater transportation burdens. It is hoped that development of a low-technology fabrication approach would allow creation of new value-added LBL products worldwide that would help local communities and drive economic growth in developing nations.

The objective of this paper is to examine a new low-technology approach for the fabrication of LBL in an effort to assess the feasibility of using this approach to produce an LBL product that is suitable for use in structural applications.

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2. Current Laminated Bamboo Lumber (LBL) fabrication techniques and properties

LBL is a fairly new material with only a limited body of associated research. Further research on, and promotion of, LBL is required in order for this environmentally friendly material to gain popularity for use in structural projects. Here, a brief background is presented on current fabrication techniques, mechanical properties and feasibility of LBL. Detailed methods of LBL fabrication and performance information are available in the literature [7,9,3].

2.1. Fabrication

In order to fabricate LBL, bamboo culms (poles) must first be flattened. Then, with fibers oriented longitudinally, the culms are stacked in layers in the presence of adhesive to form a laminated composite. Bamboo culm is naturally strong in its cylindrical shape and high pressures are required to flatten it. Lee et al. [3] reported that placing a bamboo culm under a hydraulic laboratory press at a pressure of 690 kPa sustained for 1–4 min, depending on the thickness and curvature of the culm, was effective in achieving flattened bamboo. However, the stacked layers were later placed under a pressure of 1380 kPa in the presence of adhesive during the lamination process, which could have greatly contributed to the flattening of any curvature remaining after the first attempt. Therefore, it seems best to take 1380 kPa as a reference for the amount of pressure needed to flatten bamboo culm, if pressing is the desired flattening approach. It is important to note that during the flattening process, many cracks are formed between and parallel to bamboo fibers that can negatively affect the final product strength.

The inner and outer surface layers of bamboo poles contain wax and silica which do not allow adhesive to bond well to the surfaces. Therefore, these layers must first be removed. A planer is often used for this [8,7,9,3].

Previous literature provides important information on adhesive application and stacking arrangements of the flat sheets or “mats”. Lee et al. [3] clearly show from their test results that increase in glue spread rate results in a product with higher bending strength. Nugroho and Ando [7] found a significant drop in glue bond strength at interfaces formed by joining two outer faces of bamboo culm.

2.2. Mechanical properties

Table 1 compares the reported average values of mechanical properties, Modulus of Elasticity, MOE and Modulus of Rupture, MOR, of similar sized small coupons of LBL, 2600Fb-1.9E Eastern Species Laminated Veneer Lumber (LVL) and 2900Fb-2.0E Eastern Species Parallel Strand Lumber (PSL). LBL properties from three dif-

Table 1
Average values of LBL's mechanical properties reported by previous studies shown in comparison to those of LVL and PSL.

Product	MOE (GPa)	MOR (MPa)	Species
LBL ^a	8.0	86.3	<i>Phyllostachys pubescens</i>
LBL ^b	11.6	81.2	<i>Phyllostachys pubescens</i>
LBL ^c	10.0	95.1	<i>Gigantochloa apus</i>
LBL ^c	9.8	87.8	<i>Gigantochloa robusta</i>
LVL ^d	11	93.5	Eastern species
PSL ^d	11.6	90.3	Eastern species

^a Lee et al. [3].

^b Nugroho and Ando [7].

^c Sulastiningsih and Nurwati [9].

^d Mahdavi et al. [5].

ferent studies are included [3,7,9]. All values are similar to one another suggesting that, ignoring cost and connection challenges, LBL could be considered an alternative to LVL and PSL in structural applications.

3. Experimental methodology

Many of the methods that have been used in the past for LBL production require equipment that may not be available or feasible to acquire in some places where bamboo commonly grows. For example, planers and hydraulic presses – for the purposes of flattening culms and removing inner and outer surface layers – or bamboo splitting machines may be difficult to finance by residents of a rural area in China or India. Simple alternatives to using these tools are necessary in these cases. After some preliminary investigation, it was found that hammering culm can be just as or more effective than a press in flattening culm and creating mats. Also, using coarse sandpaper was found to be very effective in removing inner and outer surface layers. While these alternatives are more labor intensive, they make the process adaptable and available to people in regions where heavy machinery is not readily available.

3.1. Fabrication of LBL specimens – the proposed approach

For this study, Moso bamboo (*Phyllostachys pubescens*, Mazel ex J. Houz), approximately 13 cm in diameter, was used to fabricate twelve 4-ply LBL specimens which were then tested to measure bending stiffness and strength in accordance with ASTM D143 – Standard Test Methods for Small Clear Specimens of Timber. The following discussion outlines the detailed fabrication approach.

3.1.1. Cutting bamboo culm into segments of desired length

Dry bamboo poles were cut into segments 81.3 cm in length, 5.1 cm longer than the length of the final specimen. The extra length was to allow for losses due to cutting and any adjustments that may be necessary.

3.1.2. Sanding outer surfaces of bamboo segments

Previous studies have shown that the concentration of fibers decreases from the outer layers toward the inner layers of bamboo culm [11]. Therefore, care was taken to remove only as much as necessary when sanding the outer surface, so as to preserve as much of the high strength material near the outer surface as possible. This was based on the speculation that removing too many layers with high fiber density would decrease the overall average fiber density and could possibly weaken the material.

Wax and silica are non-fibrous materials. During sanding, when fibrous material begins to appear it is a sign that wax and silica layers have been removed and sanding should stop, otherwise fibers will be damaged. Fig. 1 shows a partially sanded outer surface of dry Moso-bamboo culm. The fibrous and non-fibrous layers are visually distinguished.

3.1.3. Flattening bamboo into mats

Splitting bamboo culm longitudinally into smaller pieces makes the process of flattening the culm much easier. Naturally occurring longitudinal cracks (Fig. 2) can assist with manually splitting the culm. Since Moso bamboo is very weak in the direction perpendicular to the fibers and tangential to the perimeter of the cross-section, longitudinal cracks form very easily. For dry culms, cracks often form naturally; otherwise, a few strikes with a hammer (Fig. 3) will generate a longitudinal crack with fair ease. These cracks can be opened easily by hand, or by using a pry bar.

After culms were split, they were placed on a hard, flat surface with the inside of the culm facing down. They were then further flattened by hammering. The flattened mat, after completion of hammering, is shown in Fig. 4.

It is not possible to determine the widths of the mats prior to hammering. Therefore, after all mats were created, compatible groups of four mats were visually organized. Compatibility was determined based on width and node location. Nodes are rings that exist on a bamboo pole at varying distances from one another (see

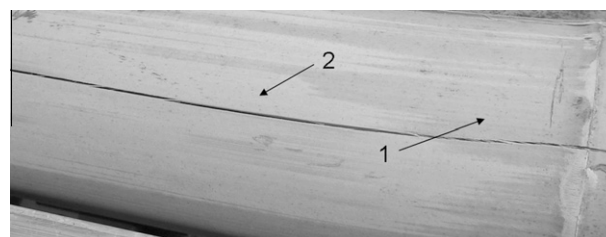


Fig. 1. Partially sanded outer surface of dry Moso bamboo culm; (1) Non-fibrous wax and silica that must be removed; (2) Fibrous material.



Fig. 2. Splitting Moso-bamboo culm.

Fig. 4). Existing literature reports that nodes are significantly weaker than material between nodes [2,9]. Based on this observation, mats of similar width were grouped and nodes were staggered by layer, to avoid concentration of weak points as much as possible.

3.1.4. Sanding inner surface

After bamboo mats were created, their inner surfaces were sanded (Fig. 5) using a rotary sander. Removal of wax and silica from the inner surface was found to be more difficult than its removal from the outer surface even though the culm had previously been flattened, indicating that the inner surface material is of different character than that of the outer surface.

3.1.5. Lamination process

3.1.5.1. *Longitudinal gaps.* During flattening of the culms, fibers separate from each other forming longitudinal gaps which, if not mitigated, can give rise to a final LBL product that is susceptible to horizontal shear failure. Therefore, it is necessary to understand the mechanism that causes gaps and their effect on strength properties. Once these are understood, cracking can be controlled in order to avoid potential shear failures in beam applications.

Nodes have a higher resistance to transverse splitting than do the fibers between nodes. Therefore, after the culm is flattened, the gaps between fibers increase in size as the distance from the node increases. The sizes of these gaps dictate the shapes and sizes of gaps that will be present in LBL after lamination is completed.

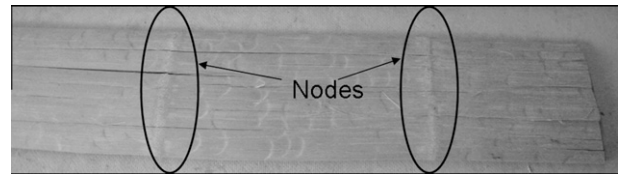


Fig. 4. Flattened bamboo mat.

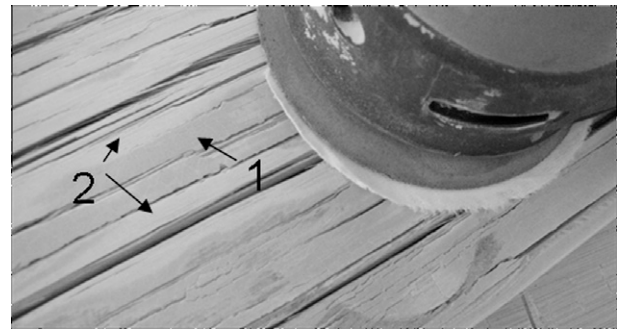


Fig. 5. Sanding inner surface of flattened culm; (1) Non-fibrous waxy material on the inner surface, which is more difficult to remove than the same existent on the outer surface; (2) Fibrous material.

Longitudinal gaps decrease cross-sectional area and can lead to significant stress concentrations depending on the type and orientation of loading and supports. In a trial test, a specimen (shown in Fig. 6) was created without any attempt to mitigate gaps being made. Although bending stresses predominated for this specimen (owing to a span to depth ratio of 14), the failure mechanism was horizontal shear cracking at a load that was far lower than expected. The gaps existing at mid-depth of one support location (i.e. in the high shear zone) of the beam reduced the beam's horizontal shear capacity to the point that the full bending capacity could not be realized. Note that the gaps with significant size, on the right end of the beam, were not concentrated at mid-depth as were the gaps on the left end of the beam. Data in Table 2 quantifies the failure of the specimen shown in Fig. 6.

It was discovered that limiting the size of gaps during the fabrication process can prevent beam shear failure and significantly enhance beam load capacity. One way of limiting gaps is to apply lateral pressure to each layer of the stack in addition to, and simultaneous with, the vertical pressure that is applied. This was achieved by tying loops of nylon strings around the mats and tightening them to create an arch (Fig. 7). As the arch in the mat decreases due to vertical pressure, the string tightens applying lateral confinement pressure to each individual layer and closing the gaps between separated fibers. What is important here is to apply lateral pressure using a method that does not cause separation of layers or occupation of too much interfacial surface area in one concentrated region. It is noted that tying nylon string achieves this for this study, but could be difficult to execute in large scale operations; in this case, a more systematic mechanical process to achieve lateral pressure would be preferred.

3.1.5.2. *Applying adhesive, stacking and pressing.* The mats were glued together using Georgia Pacific Resorsabond® 4242/4553 slurry adhesive. Although it is known from previous reports [3] that higher glue spread rates result in higher strength, it was of interest to maintain efficiency and sustainability as much as possible. Therefore just enough adhesive was applied to wet all surfaces with a thin layer. Based on a study by Nugroho and Ando [7] outer surfaces do not bond well with one another. Therefore, the stacks were arranged so that the inner surfaces of the middle layers formed the centermost interfaces, and the inner surfaces of the outer layers contacted the outer surfaces of the inner layers (Fig. 8).

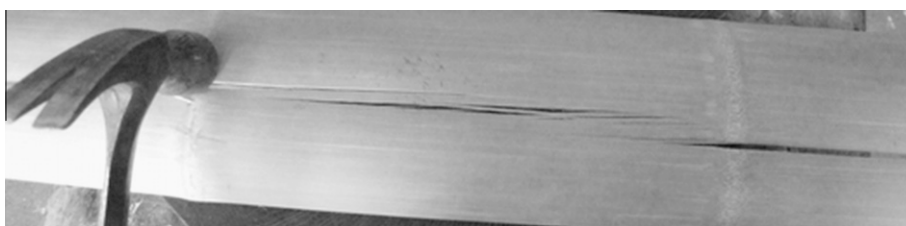


Fig. 3. Hammering piece of bamboo culm flat.



Fig. 6. LBL specimen that failed in horizontal shear due to a large longitudinal gap at the center of its cross-section; (a) Cross-section of specimen at its left end showing concentration of cracks at center; (b) Shear failure on left portion of specimen; (c) Right portion of specimen, which is not damaged; (d) Cross-section of specimen at its right end showing a critical concentration of transverse gaps in the layers.

Table 2
Loads and stresses applied to specimen shown in Fig. 6 at failure.

Peak load (N)	Max bending stress at failure (MPa)	Max shear stress at failure (MPa)	E (MPa)
4119.8	49.1	1.8	6487

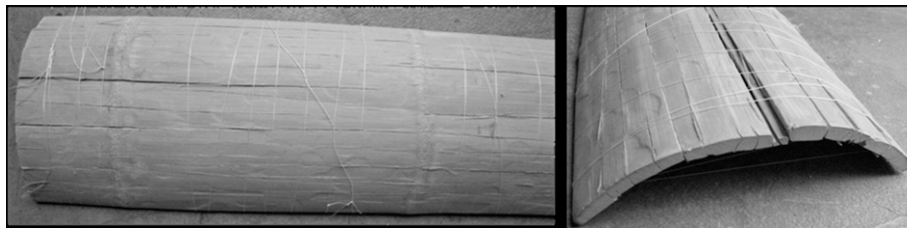


Fig. 7. Wrapping loops of nylon string around mats to apply lateral pressure to each mat during the lamination process.

Outer surface
Inner surface
Outer surface
Inner surface
Inner surface
Outer surface
Inner surface
Outer surface

Fig. 8. Arrangement of mats.

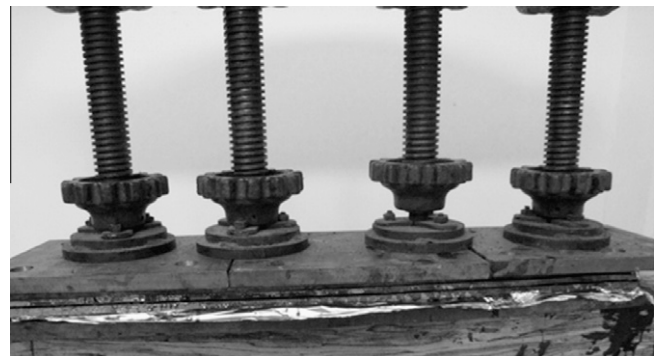


Fig. 9. Mechanical pressing device used to apply vertical pressure to a stack of glued bamboo mats.

After the layers were wrapped with nylon string, glued and stacked, the billet was placed under pressure using a basic mechanical press and left for 24 h (Fig. 9). The exact amount of applied pressure was not measured; rather, adequacy of pressure was determined visually by continuous interfacial surface contact and glue squeeze-out. After 24 h, the billets were removed and left in the laboratory to cure for 4 days.

3.1.6. Cutting and testing specimens

A total of twelve specimens were cut out of the 4-ply billets with dimensions according to ASTM D 143–94 primary method. The specimens were then subjected to three-point bending using a 133 kN capacity MTS universal testing machine as shown in Fig. 10. A digital Linear Variable Displacement Transducer (LVDT) was used to record displacement.

4. Results

Table 3 contains the physical and mechanical properties of LBL produced during this study. All specimens failed due to bending stresses; no de-lamination or shear failure was observed.

5. Discussion

Table 4 compares the results of this study with previous research studies. Moisture content, number of plies and dimensions



Fig. 10. Failed laminated bamboo lumber specimen in three-point bending.

for all specimens were similar, minimizing strength differences due to moisture and size. The modulus of elasticity of LBL produced in this study is on par with, and its MOR is slightly lower than, the values reported for specimens produced by other researchers in previous studies.

Table 3
Mean physical and mechanical properties of 4-ply LBL.

Descriptive statistics	MOE (GPa)	MOR (MPa)	Moisture content (%)	Specific gravity
Mean	9.3	76.5	15.81	0.51
Standard deviation	594.06	4.58	0.01	0.02
COV	6.39%	5.99%	5.73%	4.42%
Minimum	8601.75	67.71	0.14	0.45
Maximum	10543.76	85.75	0.18	0.53

Table 4
Comparison of mean mechanical properties of fabricated LBL with those of specimens tested in previous research studies.

Species	#-Ply	Specimen dimensions (cm)	MOE (GPa)	MOR (MPa)	Moisture content (%)
<i>Phyllostachys pubescens</i>	4	3.5 ^d × 5.08 × 76.2	9.3 (6.4) ^e	76.5 (6.0)	15.81 (5.5)
<i>Phyllostachys pubescens</i> ^a	4	2 × 2 × 32	10.9 (9.0)	74 (5.7)	–
<i>Phyllostachys pubescens</i> ^b	–	2.54 × 2.54 × 40.64	8.1 (14.0)	85.2 (21.0)	15
<i>Gigantochloa apus</i> ^c	3	–	10 (8.0)	95.1 (9.7)	13.07 (1.2)
<i>Gigantochloa robusta</i> ^c	3	–	9.8 (5.0)	87.8 (13.8)	12.81 (1.6)

^a Nugroho and Ando [7].^b Lee et al. [3].^c Sulastiningsih and Nurwati [9].^d Average width, since 4-ply specimens vary in width.^e Numbers in parentheses are the percent coefficient of variation of the corresponding mean values.**Table 5**
Comparison of mean mechanical properties of fabricated LBL with those of laminated wood specimens tested in previous studies.

Product	Species	Specimen size (cm)	MOE (GPa)	MOR (MPa)
LBL	<i>Phyllostachys pubescens</i>	3.5 ^d × 5.08 × 76.2	9.3	76.5
PSL ^a	<i>Eastern species</i>	2.54 × 2.54 × 40.64	11.6	90.3
LVL ^a	<i>Eastern species</i>	2.54 × 2.54 × 40.64	11	93.5
LVL ^b	<i>Lauan (Shorea species)</i>	4 × 4 × 80	10.2	74.7
LVL ^c	<i>Southern yellow Pine</i>	2.54 × 2.54 × 40.64	10.1	67.3
LVL ^c	<i>Sweet gum</i>	2.54 × 2.54 × 40.64	11.4	81.5
LVL ^c	<i>Yellow poplar</i>	2.54 × 2.54 × 40.64	9.6	62.3

^a Mahdavi et al. [5].^b Nugroho and Ando [7].^c Lee et al. [3].^d Average width; thickness of ply layer varies.

Table 5 compares the mechanical properties of the fabricated LBL specimens to those of laminated wood products. The wood products show a wide range of strength and stiffness properties. From the data displayed it is apparent that, among the species listed, LBL shows significantly lower MOR only in comparison to the PSL and LVL produced from *Eastern Species*. The stiffness of LBL is slightly lower than that of all wood products listed in Table 5.

6. Conclusions

The intent of this study was to develop a simple and sustainable approach for LBL fabrication, which would retain the favorable structural performance of the final product. Fabrication processes were simplified as much as possible and manual techniques were used in place of heavily mechanised ones. Promising test results show that the mechanical properties of the final LBL product were comparable to other similar bamboo and laminated wood products. This study demonstrates that a simple, low-technology approach can lead to the production of a strong, sustainable product for use in structural applications. The advantage of such a low-technology approach to the manufacture of LBL is that, using

such a process, it would be possible to manufacture the LBL close to where the bamboo is grown and where the LBL would be used in small scale construction. Such proximity of the raw material, structural material fabrication, and use of the structural material can dramatically reduce the embodied energy generated by material transport.

Further research is required to perfect the approach presented and permit scale-up to small scale commercial manufacture. One area that could be improved is in applying lateral pressure to layers of LBL. In this study, loops of nylon string were used only to close major gaps that are likely to cause unexpected shear failure. Despite the fact that the proposed approach was successful, application of lateral pressure to layers should be explored quantitatively in an effort to gain a better understanding of its effect on strength properties.

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