Development of Laminated Bamboo Lumber: Review of Processing, Performance, and Economical Considerations

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Abstract: As focus is drawn toward more sustainable construction practices, use of bamboo as a structural building material is growing as a topic of interest. It is highly renewable, has low-embodied energy, and has the highest strength-to-weight ratio of steel, concrete, and timber. Composite lumber made from bamboo, termed laminated bamboo lumber (LBL), has gained the particular interest of researchers and practitioners of late, since it has bamboo's mechanical properties but can be manufactured in well-defined dimensions, similar to commercially available wood products. Its primary drawbacks are that it is difficult to connect and is more costly than competing, locally available materials. This paper presents the advantages and challenges of embracing LBL as an alternative building material. Experimental and analytical data on production, performance, economics, and environmental impact of bamboo and LBL are reviewed, synthesized, and further analyzed to present an overview of the viability of using bamboo as a structural material in North America. **DOI: 10.1061/(ASCE)MT.1943-5533.0000253.** *© 2011 American Society of Civil Engineers.*

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Introduction

As resource availability declines and resource demands increase in today's modern industrialized world, it is becoming increasingly necessary to explore opportunities for new, sustainable building materials (Meadows et al. 1992). Wood, for example, has recently gained popularity in the green building community because of its environmentally beneficial characteristics: wood is promoted as renewable, biodegradable, sequestering carbon from the atmosphere, low in embodied energy, and creating less pollution in production than steel or concrete (Falk 2009). Bamboo has similar environmental characteristics (van der Lugt et al. 2006; Lee et al. 1994; Rittironk and Elnieiri 2007; Nath et al. 2009). Most notably, it is highly renewable; bamboo stalks reach maturity in eight years. Its strength is comparable to that of wood. As such, it makes an appealing candidate as a structural material. With adequate research, it is conceivable that bamboo could become a sustainable alternative to current building materials in North America.

In a study by van der Lugt et al. (2006), an environmental life cycle analysis (LCA) of bamboo is presented in an effort to quantify the environmental effects of using bamboo as a construction material. The results of this analysis show that, in some applications, bamboo has achieved "factor 20" environmental impact, which means that it had 20 times less load on the environment than currently used alternatives. Environmental impact is expressed in units of environmental cost, which is defined as: "fictitious societal costs (monetary factors) connected to the prevention of environmental damage by certain interventions (e.g., emissions)" (van der Lugt et al. 2006). Lack of knowledge and experience with bamboo were seen as contributors to much inefficiency and unnecessary cost currently associated with bamboo construction. These inefficiencies and costs are expected to diminish as familiarity with this material increases.

Bamboo, being a hollow tube, is efficient in resisting bending forces, having a large ratio of moment of inertia to cross-sectional area. It is difficult, however, to create connections for this shape, and tubes cannot be used in applications where flat surfaces are required. Laminated bamboo lumber (LBL) resolves these deficiencies in the natural shape of bamboo because it is formed in rectangular sections that are more suitable for use in traditional structural applications. LBL has been created in research studies by using adhesive to join strands or flattened surfaces taken from the culm (i.e., bamboo stem). The result is a composite rectangular structural member having highly renewable characteristics that make it competitive, in this regard, with commonly used building materials.

This paper synthesizes state-of-the-art knowledge on LBL processing and resulting material performance in an effort to encourage further research and development of this sustainable material. Cost and environmental impact of manufacture are also discussed.

Background on Bamboo

Bamboo is a grass that is the fastest growing plant currently known (Liese 1987). In the United States, it is not officially recognized as a structural building material owing to the absence of any standard building code, preventing it from being accepted freely by the construction industry. It is mainly used for nonstructural applications such as flooring, fencing, furniture, crafts, and ornamental

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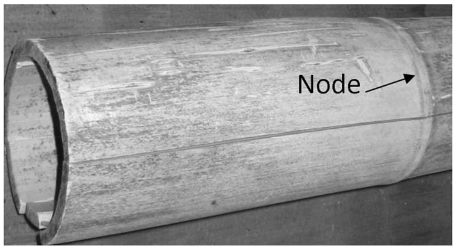

Fig. 1. 12.7-cm-diameter Moso bamboo (*Phyllostachys pubescens* Mazel ex J. Houz.) culm (Photo courtesy of M. Mahdavi)

purposes. In many countries in which it is native, bamboo *is* used as a structural building material. According to Liese (1987, 1992), there are about 700 species of bamboo, and the differences in properties among them are relatively small. These species will reach their maximum height, between 15 and 30 m (approximately 49–98 ft), within 2 to 4 months. It takes between 3 and 8 years for bamboo to reach its maximum strength properties. Diameters of this plant range from 5 to 15 cm (approximately 2–6 in.). Figure 1 shows a dry Moso bamboo culm.

Physical Properties

According to Yu et al. (2008), the dimensional stability of Moso bamboo (*Phyllostachys pubescens* Mazel ex J. Houz) is dependent on "layer," referring to the location within the wall of the culm between the inner and outer radii. Similar to many wood species, the test results found specific gravity based on ASTM D2395 (values between 0.553 and 1.006) (ASTM 2002) and tangential shrinkage from green to oven-dry (values between 4.9 and 7.8%) to be greater at the outer layers, increasing with longitudinal position or height. Conversely, they observed a decrease in longitudinal shrinkage (values from 0.30 to 0.09%) with movement from inner to outer layers. It was determined that the effects that height and layer had on all properties (specific gravity, tangential shrinkage, and longitudinal shrinkage) were statistically significant and independent of one another.

Lee et al. (1994) reported results for specific gravity and orthogonal shrinkage of giant timber bamboo (*Phyllostachys bambusoides* Siebold & Zucc.). Specific gravity for this species was, on average, 0.52 (irrespective of layer or height). Radial shrinkage results were the most extreme (values between 7.1 and 27.7%), with the maximum radial shrinkage being twice as great as that of the tangential direction (values between 3.9 and 18.7%). Longitudinal shrinkage was negligible (values between 0.00 and 0.06%).

Mechanical Properties

Test results provided by Yu et al. (2008) indicated that longitudinal elastic modulus and tensile strength of Moso bamboo have clear dependency on radial position. It was found that elastic modulus and tensile strength at the outer layer (average, over height, of 26.9 GPa and 295.6 MPa, respectively) were almost triple those of the inner layer (average, over height, of 9.7 GPa and 113.4 MPa, respectively). Tensile modulus of elasticity had a mean increase across all layers of 12.8% as height increased from 1.3 to 4 m. The same mean change for tensile strength was only 1.25%, suggesting that tensile strength is not dependent on height.

The study by Lee et al. (1994) investigated the influences of moisture content, height, and the presence of nodes on mean strength and stiffness properties on giant timber bamboo. Contrary to Yu et al. (2008), it was found that strength properties increased with height—the dissimilarity likely being a result of the use of different bamboo species. Consistent with structural wood species, however, strength increased with decreasing moisture content. The data showed an increase in compressive strength, tensile strength, elastic modulus, and modulus of rupture (MOR) by 37.6, 19.4, 48.2, and 47.7%, respectively, when tested in air-dry conditions versus green conditions. For loblolly pine, the same properties increased by 102.9, 75.3, 27.9, and 75.3%, respectively. This suggests that the effect of moisture content on the mechanical properties of giant timber bamboo is less than the effects of moisture content on the mechanical properties of wood. Therefore, in considering bamboo for structural applications, the usual (as in current wood construction) precautions must be taken for dimensional stability in wet service conditions.

Table 1. Comparison of Bending Properties of Bamboo to Other Common Building Materials

Building materials	Specific gravity	Modulus of elasticity (MOE) (GPa)	Modulus of rupture (MOR) (MPa)	MOR to specific gravity ratio (MPa)
Giant timber bamboo[a]	0.52	10.7	102.7	197.5
Other bamboo[a]	—	9.0–20.7	97.9–137.9	—
Loblolly pine[b]	0.51	12.3	88	172.5
Douglas-fir[b]	0.45	13.6	88	195.6
Cast iron[c]	6.97	190	200	28.7
Aluminum alloy[c]	2.72	69	200	73.4
Structural steel[c]	7.85	200	400	50.9
Carbon fiber[c]	1.76	150.3	5,650.00	3,205.10

[a] Lee et al. 1998.
[b] Forest Products Laboratory 1999.
[c] Rittironk and Elnieiri 2007.

The presence of nodes (rings seen on bamboo poles—see Fig. 1) weakened the material and had the most significant influence on tensile strength, which decreased by 26.6% when nodes were present.

Table 1 compares giant timber bamboo and "other" bamboo species' properties with those of common raw building materials. Although giant timber bamboo is one of the weaker bamboo species listed, its properties are comparable to structural wood species such as Douglas-fir or loblolly pine. The data indicate that bamboo is stronger in bending than timber, and its strength-to-weight ratio (expressed as MOR/specific gravity) is greater than that of all materials listed except carbon fiber. Not only is bamboo fast-growing, but it is also highly efficient in comparison to other raw structural materials.

Laminated Bamboo Lumber

Using bamboo in its natural cylindrical form poses several challenges. Most importantly, it is difficult to create reliable connections owing to geometry and the fact that bamboo is prone to splitting. Also, since bamboo is not perfectly straight and has a nonuniform cross section, practical issues, such as squeaky joints and thermal bridges, are a problem. Further, the fact that it is cylindrical makes it inefficient spacewise.

Laminated bamboo lumber is a relatively new concept that involves gluing together bamboo material in various forms (e.g., strands or mats) to form rectangular boards, similar to lumber. Despite its commercial potential, only a small body of research on LBL exists in the literature. Two patents exist—the first patent, by Chu, entitled "Bamboo board" [U.S. Patent No. 4,810,551 (1989)], describes a product that is similar in layup to plywood, and the second, by Plaehn, entitled "Parallel randomly stacked, stranded, laminated bamboo boards and beams" [U.S. Patent No. 5,543,197 (1996)], is similar in layup to parallel strand lumber (PSL). The second patent describes the composition of the beam as bonded bamboo segments—specifically, "bamboo stalks [that] are split open and dried in segments ranging from 1/4 to 3/4 in. in width to approximately 5–20 ft in length. The core may contain gaps as a result of the cross-sectional shape of the bamboo segments and the randomness of the stacking of the segments."

Processing Techniques

Method 1

Nugroho and Ando (2001) investigated a technique to process LBL by progressively crushing Moso bamboo culms using roller press crushers to create zephyr strand mats, displayed in Fig. 2. The mats were hot-pressed (between 150°C and 180°C) in order to achieve dimensional stability and to create a smoother surface with less irregularity and fewer voids, since spaces between strands likely weaken the material.

It was found that dipping specimens in boiling water for 1 min tended to aid in the flattening of fibers at low press temperatures (between 100°C and 130°C) but had less effectiveness at higher press temperatures (between 150°C and 180°C).

After hot-pressing, the mats were passed through a planer to remove their inner and outer layers that contain wax and silica that weaken adhesive bonding. The zephyr mats were coated with resorcinol-based adhesive and stacked on top of each other. Inner surfaces were bonded to inner or outer surfaces.

Three glue-spread rates were tested for optimal internal bond (IB) strength. IB strength was optimal when using a glue-spread rate of approximately 300 g/m^2 and joining outer to inner surfaces of the mats.

After adhesive was applied, the stacks of zephyr mats were cold-pressed until the adhesive was fully bonded. The product was then conditioned at 25°C and 65% relative humidity for at least two weeks. The final product is displayed in Fig. 3.

Method 2

Another technique was investigated by Rittironk and Elnieiri (2007) and Sulastiningsih and Nurwati (2009), whereby bamboo strips were produced by feeding culms through a splitter machine that cut the bamboo culm into slender strips. All surfaces of the strips were scraped and planed to remove wax and silica as well as to create rectangular cross sections. Adhesive was applied to the strips that were then neatly arranged next to and on top of one another to create the final product. Fig. 4 clearly depicts the cutting, planing, and lamination steps. Fig. 5 shows the final product.

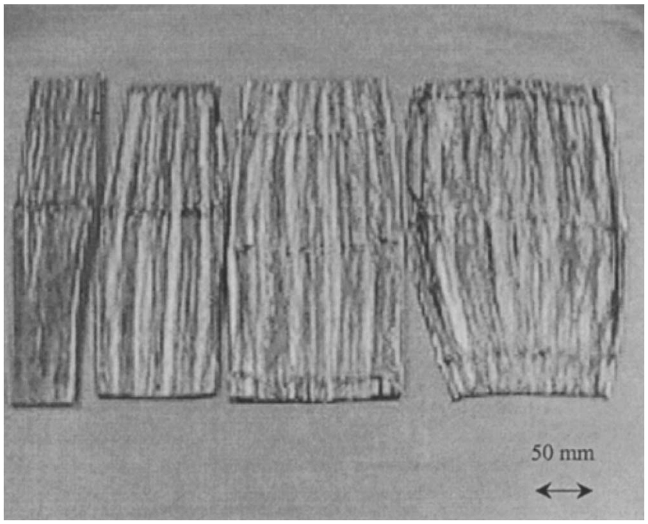

Fig. 2. Bamboo zephyr strand mat from Moso bamboo after pre-hot-pressed treatment. From left to right: treatment at temperatures of 100°C, 130°C, 150°C, and 180°C, respectively (Nugroho and Ando 2001; reprinted with permission from the *Journal of Wood Science*)

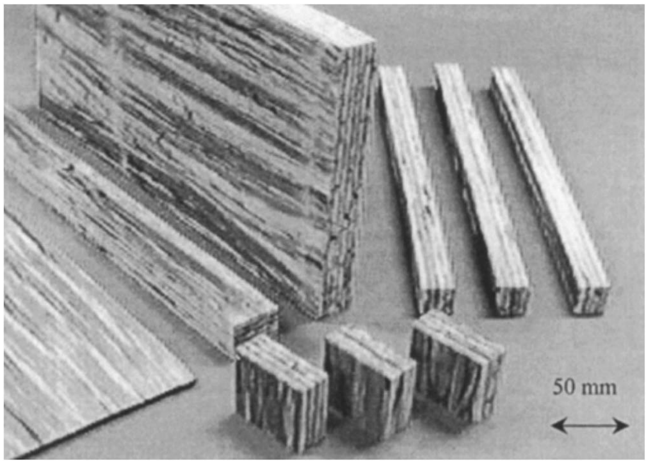

Fig. 3. Samples of laminated bamboo lumber (LBL). In the front are specimens of IB (internal bonding) strength. In the background are, from left to right: bamboo zephyr mat, LBL board, and bending testing specimens (Nugroho and Ando 2001; reprinted with permission from the *Journal of Wood Science*)

Based on the approach by Sulastiningsih and Nurwati (2009), strips were left to air-dry at room temperature for one week after they were cut. Air-dried strips were then immersed in a boron solution and left to dry in the sun until their moisture content reached 12%. Bamboo sheets were produced by placing bamboo strips side-by-side and edge-gluing them using tannin resorcinol formaldehyde (TRF) extracted from black wattle (*Acacia mangium* Willd.) bark mixed with wheat flour. Sheets were then stacked on top of one another, keeping grains parallel, using the same adhesive, and clamped with no heat for 4 h.

Method 3

A third technique was investigated by Lee et al. (1998). The procedure began by splitting Moso bamboo culms in half longitudinally. These splits were then flattened at a pressure of 690 kPa for 1—4 min. The curvature and thickness of the bamboo splits determined whether or not to increase or decrease the amount of time during which pressure was applied. The inner and outer layers of the flattened bamboo were passed through a planer in order to remove the wax and silica contained in these layers. Resorcinol-based adhesive was applied to the surfaces of the flattened and planed bamboo splits. They were then carefully stacked on top of one another, and the stack was placed under a pressure of 1,380 kPa for 12 h. The resulting product was then conditioned at 25°C and 65% relative humidity for at least two weeks.

LBL Structural Performance

Comparison of LBL Processing Methods

Products of Method 1 (Nugroho and Ando 2001), Method 2 (Sulastiningsih and Nurwati 2009), and Method 3 (Lee et al. 1998) were tested in accordance with JIS Z-2113 (Japanese Industrial Standards 1997), ASTM D1037 (ASTM 1993), and ASTM

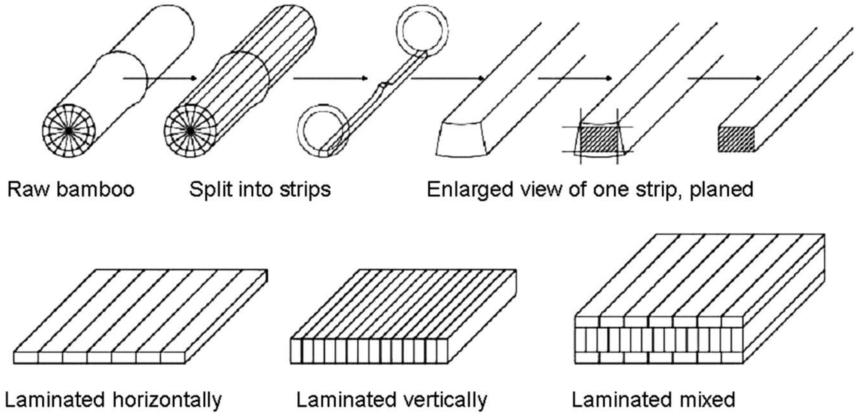

Fig. 4. Manufacturing process of laminated bamboo lumber using bamboo strips (Rittironk and Elnieiri 2007; reprinted with permission from CRC Press/Taylor and Francis Group)

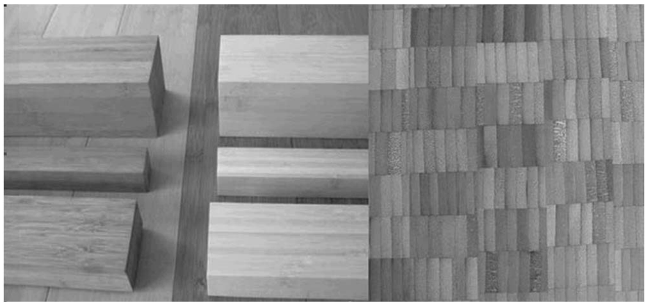

Fig. 5. (Left): Laminated bamboo lumber from manufacturer in China, shipped to United States for many building finishing products (Image courtesy of 4windsbamboo.com); (right): Close-up of bamboo lumber section made up of many strips laminated together (Rittironk and Elnieiri 2007; reprinted with permission from CRC Press/Taylor and Francis Group)

D198 (ASTM 1994), respectively. Table 2 displays selected results of these tests for purposes of comparing the effectiveness of the three methods.

The effect of varying ply arrangement for Moso bamboo was considered in Method 1, based on inner versus outer surface contact at interfaces where mats meet in the presence of adhesive. Tested specimens were 4-ply, so, for each specimen, there were three interfaces, one at the center and two on either side of the center. Three variations were tested: Type I, in which inner surfaces of culm were glued to outer surfaces at all interfaces; Type II, in which outer surfaces of culm were glued together at the center interface, and inner surfaces were glued together at the outer interfaces; and, Type III, in which inner surfaces of culm were glued together at the center interface, and inner surfaces were glued to outer surfaces at the outer interfaces. Method 2 considered two different bamboo species: bamboo tali [*Gigantochloa apus* (Schult. & Schult. f.) Kurz] and awi mayan (*Gigantochloa robusta* Kurz). For Method 3, a 2 × 3 factorial design was used considering two moisture contents and three glue-spread rates with Moso bamboo.

For all methods, bending specimens were small (e.g., 2.5 cm × 2.5 cm × 81.3 cm for Method 3 as shown in Table 2) with a similar test configuration. The size effect is known to influence the bending strength of structural composite lumber (Sharp and Suddarth 1999) and, thus, could be a potential point of discrepancy for this comparison; however, based on this previous work, the coupon dimensions were deemed similar enough in scale to not be a significant concern. Another notable point is that Method 2 used a different bamboo species than Methods 1 and 3, which could be a source of discrepancy in the results. Fiber orientation was oriented longitudinally for all specimens.

Important among these results is the significantly lower dimensional stability of LBL produced by Method 1 and the clear dependence between glue-spread rate and the modulus of rupture for Method 3. The use of heat treatment by Method 1 during flattening processes sets it apart from Methods 2 and 3. Apart from a slightly higher MOR possessed by Method 3's LBL, the properties of products manufactured using Methods 2 and 3 are similar. Among the three processes, Method 3 is the simplest and least cost-/resource-intensive. This fact, along with data presented in Table 2, are strong evidence that Method 3 is the most efficient and potentially sustainable process that will yield a strong, dimensionally stable product that is suitable to structural applications.

Comparison of Bending Strength of LBL with Other Structural Composite Lumber Products

To provide a direct comparison of LBL mechanical properties with commercial structural composite lumber products, laboratory tests were conducted on 20 2600Fb-1.9E Eastern Species laminated veneer lumber (LVL) specimens and 20 2900Fb-2.0E Eastern Species PSL specimens manufactured by iLevel (Weyerhaeuser Co.) Specimens were sawn to dimensions in accordance with ASTM D143 (ASTM 1999) secondary specimens ($2.5 \times 2.5 \times 40.6\ \text{cm}^3$) and tested in 3-point flexure. This specimen size and test configuration were chosen to be consistent with that of the LBL specimens of Method 3 to allow direct comparison of strength values and to avoid discrepancies owing to size or load configuration effect. Specimens were tested in the vertical lamination (joist) orientation. All tests were performed using a 150 kN capacity MTS universal testing machine. Load was applied under displacement control mode at a constant rate of 1.3 mm/min to achieve failure in, on average, 5 to 8 min. Specimens were conditioned to ambient laboratory temperature and relative humidity producing an average moisture content of approximately 6%.

Results of these tests are provided in Table 3. The LVL properties are consistent with those published in the Wood Handbook (Bergman et al. 2010). (PSL properties are not provided in this reference). Table 3 also indicates the bending properties of LBL specimens made using Method 3 (Lee et al. 1998) at 10% moisture content with a glue-spread rate of $420\ \text{g/m}^2$. The 4% difference in moisture content of the PSL/LVL specimens versus the LBL specimens may contribute partly to the observed differences of

Table 2. Physical and Mechanical Properties of Three Bamboo Processing Methods

LBL product			MC (%)	Specific gravity	Thickness swell (%)	Linear exp. (%)	MOE (GPa)	MOR (MPa)
Method 1[a] 4-ply LBL (2 × 2 × 32 cm^3)	Mat layup	Type I	—	0.9	12.1	0.5	11.9	83.5
		COV (%)	—	—	30.6	25	13.1	10.3
		Type II	—	0.9	12.4	0.5	12.1	86
		COV (%)	—	—	6.7	37.5	9.7	10.1
		Type III	—	0.9	11.9	0.5	10.9	74
		COV (%)	—	—	31.2	35.4	9	5.7
Method 2[a] 3-ply LBL (7.6 × 1.5 × 41 cm^3)	Species	*G. apus*	13.1	0.8	2.5	0.1	10	95.1
		COV (%)	8.9	1.3	11.7	9.1	8	9.7
		G. robusta	12.8	0.7	4.1	0.1	9.8	87.8
		COV (%)	12.3	2.8	16.9	14.3	5	13.8
Method 3[a] (2.5 × 2.5 × 40.6 cm^3)	Glue-spread rate (g/m^2 for a single glue line)	220	10	0.6	4.4	0.3	8	86.3
		COV (%)		—	18.9	26.7	9.5	11.9
			15	0.6	5.2	0.4	8.1	85.2
		COV (%)		—	20.1	30.3	14	21
		320	10	0.6	3.3	0.2	8.4	97.7
		COV (%)		—	13.4	22.5	10.2	7.5
			15	0.6	4.2	0.5	8.3	91.9
		COV (%)		—	15.3	31.5	13.6	13.5
		420	10	0.6	2.2	0.1	9.1	107.2
		COV (%)		—	14	30.3	11.7	10.1
			15	0.6	2.5	0.1	8.7	104.8
		COV (%)		—	15.4	41.6	8.5	6.4

Note: MC = moisture content.

[a] Sources: Method 1—Nugroho and Ando 2001; Method 2—Sulastiningsih and Nurwati 2009; Method 3—Lee et al. 1998.

Table 3. Flexure Properties of LBL versus LVL and PSL

Material		Count	MOE (GPa)	MOR (MPa)
LBL[a]	mean	24	9.1	107.2
	COV (%)	—	11.7	10.1
LVL	mean	20	11	93.5
	COV (%)	—	5.7	9.8
PSL	mean	20	11.6	90.3
	COV (%)	—	11.9	15.1

[a] Lee et al. 1998.

the three samples; bending properties for clear wood tend to increase with decrease in moisture content (Bergman et al. 2010). Although SCL is known to resist moisture effects more effectively than clear wood, for purposes of comparison, if the LVL/PSL specimens had been tested at the higher moisture content of 10%, slightly lower values may have resulted.

The average bending strength of LBL is 14.7% and 18.7% higher than that of LVL and PSL, respectively. The stiffness, however, is substantially lower than either LVL or PSL (21% and 27.5%, respectively). While the variability in resulting test data for LBL is similar to that of LVL, the variability in data for PSL bending strength is higher than that of LVL by an average of 81.4%, likely owing to the influence of macrovoids in PSL for small specimens.

Economic Considerations

Based on its mechanical and physical properties, bamboo has very high potential to compete with other structural materials. Companies are beginning to emerge with the capability of producing economically viable, commercial size LBL. One Chinese company, Advanced Bamboo Technologies, LLC, recently developed a commercial-size LBL product to compete with dimensional lumber called Glubam. It has been used in China in residential applications as beams and columns. Another U.S. company, Cali Bamboo, has recently introduced a laminated bamboo product for posts and rails in dimensions of up to 3 in. × 3 in. × 10 ft. From a production standpoint, a bamboo plantation produces three times as much biomass as the average timber productive forest (van der Lugt 2006). Its rapid growth and high strength-to-weight ratio suggest that it can be instrumental in the sustainability movement.

One strong barrier to the commercial success of bamboo is its cost. Rittironk and Elnieiri (2007), "after extensive data gathering and calculation," have reported the price of LBL to be four times that of conventional lumber, and 1.6 times that of glue laminated lumber. Since much of the bamboo in the United States is imported, shipping is a large component of the cost. Also, the lack of standardization for LBL and its noncommercialized manufacturing processes contribute to inefficiency and leads to cost increases. Further research and development will likely provide remedies to these issues.

In a study by De Flander and Rovers (2009), the idea of replacing other construction materials with bamboo was considered from a supply perspective. In this study, a scenario was quantitatively analyzed in which bamboo would be used as a "modern" material; a material that would replace construction materials such as brick, concrete, and wood. Using production data and the mechanical properties of bamboo, it was approximated that one hectare of bamboo is required to produce one medium-sized (175 m^2 total floor area) bamboo-frame house. Data for Colombia's current and potential bamboo-farming resources were examined to estimate potential supply quantities for this resource. In this study, potential farming resources are defined without regard to the possible consequences of bamboo-farming in areas of Colombia where they are not currently grown; it is acknowledged that

"…it is necessary to make a zoning with greater detail to be able to make political, economic, and technical decisions related to the promotion of the cultivation and management of this species with greater certainty." With this considered, it was determined that, if only 10% of all land that is currently used or could be used in the future for growing bamboo were to be harvested, it would yield enough structural bamboo material (after discarding unusable product) to produce 200,000 average-sized (175 m^2 total floor area), bamboo-framed houses. Paired with the fact that bamboo can grow in many parts of the world, this suggests, from a supply perspective, that there is a significant market potential for structural bamboo. Added to the fact that more attention is starting to be given to biobased construction materials such as wood, this will increase demand for bamboo as well. The writers propose that it would be strategic for North American resource management to direct more focus toward bamboo forestation with the aim of developing and standardizing/sustainable construction materials.

Environmental Impact Considerations

In a study by Bonilla et al. (2010), the emergy (embodied energy) accounting methodology (Odum 1996) was used to evaluate the sustainability of bamboo production in Australia, China, and Brazil. The methods of evaluation were not limited to these countries; with proper data, they could be applied to other regions to determine whether or not the production of bamboo is, in fact, sustainable when taking all factors (labor, fuel, materials, natural resources) into consideration. Because of the very efficient employment of labor in China, one would expect this country to be able to produce bamboo with the most efficiency and sustainability. It was surprising, therefore, that China's production of bamboo is the least sustainable among the countries studied. This ranking was based on the ratio between output and environmental impact. It considered the very important, yet often neglected, fact that efficiency does not necessarily represent sustainability; just because a process consumes less does not necessarily mean that what is consumed can be recovered. Therefore, one of the newer ideas that this study presented was that efficiency should be evaluated with respect to the *type* of energy input (renewable, nonrenewable, and purchased), not just the total number of joules required. Based on this approach to efficiency evaluation, Brazil and Australia ranked first and second, respectively. It is also important to note that, though Brazil had the least overall efficiency in production, it was able to provide the most sustainable supply of the three countries examined.

In order to gain a better understanding of how bamboo and bamboo products compare to other building materials based on environmental performance, an environmental life cycle analysis of giant less-thorny bamboo (*Guadua angustifolia* Kunth) from Costa Rica in its original form was performed and presented by van der Lugt et al. (2006). This study uses the principle of environmental cost as a measure of the environmental effects associated with using a material in structural application. This measure for bamboo is then compared to other materials that are commonly used in construction. Environmental cost is defined as "fictitious societal costs (monetary factors) connected to the prevention of environmental damage by certain interventions (e.g., emissions)" (van der Lugt 2006). Environmental load is a unit representation of environmental cost in millipoints (mPts). One millipoint represents 10^{-3} euro of environmental cost. The environmental costs considered for bamboo were associated with processing, preservation, land transport, and sea transport. The vast majority of bamboo's environmental load/cost was seen to be associated with transportation; assuming 1 kg bamboo culm, including transport from Costa Rica to the Netherlands as part of the production process, the load resulting from land and sea transportation was found to be approximately two times and 29 times greater than that of processing the material, respectively. It is important to note that these numbers compare total magnitudes particular to the study and do not imply, for instance, that sea transport is less efficient than land transport.

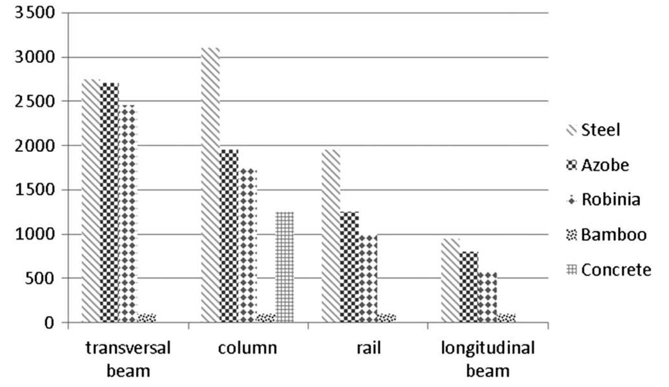

Fig. 6. Index of annual environmental costs of different elements of a bridge (Data from van der Lugt et al. 2006)

Fig. 6 shows a comparison of the environmental cost of bamboo, two species of wood—azobé (*Lophira alata* Banks ex Gaern.) and locust (*Robinia sp.*), steel, and concrete for different applications in a bridge. In this figure, the abscissae refer to categories of structural elements, and the ordinates indicate an index of environmental costs— the environmental load of each material divided by the lowest environmental load (possessed by bamboo in all cases), then multiplied by 100. The data show that the sustainability of bamboo is far better than all of the alternatives considered. In comparison to some materials, it has achieved "factor 20" environmental improvement. The reader is referred to the source paper by van der Lugt (2006) for details on this assessment.

A further study in the paper compared the annual monetary costs of various elements of a bridge (beams, columns, and rails) made from bamboo, timber, concrete, and steel. In addition to environmental costs, this study took all other incurred expenses, such as maintenance, assembly/disassembly, and material disposal, into consideration with respect to life span. Steel was found to be the most economical choice, mainly because of its long life span. Concrete was only considered for the columns and fared poorly (only moderately cheaper than *Robinia*). It was found that bamboo has a shorter life span and, because of its irregularity in shape, labor costs for assembly and disassembly were high. However, this is expected for a new material with which professionals and laborers are not yet familiar. With the development and implementation of codes and standards (like those that are already in place for steel, concrete, and wood) and as bamboo's usage as a structural material becomes more widespread, the additional expenses described are expected to decrease significantly. Bamboo competed well with wood in structural performance, however; it was on a par with azobé and better than *Robinia* in terms of annual cost.

Conclusions

Test results show that the strength and stiffness of bamboo are comparable to those of wood, making bamboo capable of replacing wood in structural applications from a load-carrying standpoint. Also, the strength-to-weight ratio of bamboo is far better than those of structural steel, aluminum alloy, cast iron, timber, and concrete, showing that it has a very efficient load-bearing capability. Use of bamboo in structural applications has been shown to have the least environmental load and cost (excluding additional costs such as assembly/disassembly, maintenance, and material disposal) by a large margin. It is reasonable to conclude that it could be economically, environmentally, and, perhaps, structurally beneficial to use bamboo as a wood alternative. Challenges must be considered and dealt with appropriately.

Challenges

1. Normal precautions should be taken for moisture and dimensional stability as would be done for wood.
2. Adhesives do not bond well to bamboo without adequate surface treatment.
3. Bamboo connections are difficult to design because of its irregular shape and tendency to split in the direction that is perpendicular to fibers.
4. Bamboo's cost is competitive in its natural form but significantly more expensive than alternatives in its processed form.
5. Construction and engineering professionals around the world are not yet adequately familiar with modern bamboo structure design.
6. Formal codes and standards have not yet been developed.

Solutions

The techniques discussed in this paper for the development of LBL help resolve challenges 1–3. Also, owing to the well-defined dimensions of LBL, geometry will not be an obstacle when developing connections. Challenge 6 will be resolved through the efforts of researchers and practitioners as further success is seen in their work on this topic. A large portion of bamboo's cost is associated with transportation resulting from a lack of local resources. This will be resolved as demand for bamboo increases, encouraging the development of local plantations. Many of the inefficiencies involved with bamboo construction will be reduced as challenge 6 is gradually overcome by further research and practice. This will reduce the cost resulting from inefficiency (challenge 5).

Future Work and Research

Further research is required to develop a method for producing a robust LBL product that overcomes the challenges discussed. Duration of load effects on LBL strength must be investigated, and research, design, and testing are needed to develop connections that are capable of withstanding the requirements of structural applications in which wood is currently used. Standards and codes must be developed in order to ensure efficiency and safety of design. General, technical, and economic information on bamboo should be distributed and made easily accessible to the public and especially to practitioners. Encouragement and, perhaps, incentive for the creation of bamboo plantations would help to make bamboo readily available to members in the industry who are interested in providing sustainable solutions.

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