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BAMBOO AS A CONSTRUCTION MATERIAL: STRENGTH ANALYSIS OF PARALLEL STRAND LUMBER FROM CALCUTTA BAMBOO (*Dendrocalamus strictus*).

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ABSTRACT

The aim of this work was to analyze the bending and compression strength of parallel strand lumber (PSL) made from Calcutta bamboo (*Dendrocalamus strictus*). In this study, a prototype PSL from Calcutta bamboo was manufactured and tested in the laboratory. Ultimate stress, stress at proportional limit and modulus of elasticity of the PSL from Calcutta bamboo were determined, and compared to structural composite lumber (SCL) from several timber species produced by other researchers and manufacturer in the US. The PSL produced were also exposed to accelerated aging process in order to assess its durability under extreme condition. The mechanical characteristics compare favorably to SCL produced in other studies and SCL products available in the US. The accelerated aging process was found to reduce the bending strength but no significant difference was detected in bending stiffness, and compression strength and stiffness. This is a promising indication of the suitability of Calcutta bamboo as the raw material for structural composite products.

KEYWORDS: Structural Composite Lumber, Parallel Strand Lumber, Calcutta Bamboo, *Dendrocalamus strictus*, Bending Strength, Compression Strength and Accelerated aging test.

INTRODUCTION

Dendrocalamus strictus is commonly recognized as Calcutta bamboo [1], but also known as male bamboo [2], and solid bamboo [3]. Calcutta bamboo is the most widely used bamboo in

India [4], especially for the paper industry. It is also used in house construction, basket making, mats, furniture, agriculture implement and tools handles. It is the most common specie of bamboo cited in the Indian forest and is available in every state in India [5]. This specie is also found in Burma, Bangladesh and Thailand, as well as being cultivated in Malaysia, Indonesia, Sri Langka and southern parts of the United States [1,6]. Calcutta bamboo thrives because it is adaptable to various types of habitat. Generally, it thrives in the inner region of the land that is beyond the effect of the sea breeze, and with low relative humidity. It flourishes in places with an annual rain fall between 75 to 500 cm, and in a maximum shade temperature as low as –5 ^{o}C, and up to 47 ^{o}C. It can grow in all types of soils, with good drainage characteristics, except water-logged soil such as pure clay or clay mixed with lime. Sandy soil or well-drained soil, or comparatively low rainfall, are the factors, which enable Calcutta bamboo to occupy even flat ground. It is said to be the most drought resistant species of bamboo [2]. Another factor contributing to the availability of Calcutta bamboo is its fast growth. Most bamboo, including Calcutta bamboo, matures quickly (15 to 18 cm daily increment), and can be cut-down in three-year cycles. Tewari [2] reported that the yield of Calcutta bamboo in one region in India was about 2 tons/hectare. The yield of Calcutta bamboo is increasing each year to fulfill the growing demand. The average diameter of Calcutta bamboo is small (3.0 to 4.0 cm). However, it has thick walls and a long culm that could provide longer strands suitable for the production of parallel strand lumber.

A parallel strand lumber (PSL) from timber is produced from long strands of veneer that are bound together with exterior-type plywood adhesive. PSL is grouped under structural composite lumber (SCL), alongside other products such as laminated veneer lumber (LVL) and oriented strand lumber (OSL) [7]. The manufacture of PSL involves veneer strands that are about 2.3 to 4 mm (0.1 to 0.16 in.) thick. The strands are about 12 mm (0.5 in.) wide and generally are 2.6 m (102 in.) long, but pieces as short as 61 mm (24 in.) can be included in the furnish [8]. The length of the veneer strand is limited only to the length of the bolt for the peeling process. The width of the strands must not be less than about 6 mm (0.25 in.), and the average length of the strands must be a minimum of 150 times the least dimension [9,10]. In the production of PSL in North America, Douglas-fir, southern pine, western hemlock and yellow-poplar are commonly used for PSL. The processing of PSL is similar to the early processing stage of plywood and LVL. Standard veneer peeling technology is used [11], until it reaches the clipping process. Clipping is done on veneer to produce strands with the width mentioned above. The strands are then coated with adhesive (phenol-formaldehyde or phenol-resorcinol-formaldehyde) and laid up randomly to form a long and continuous mat, which is then formed into a billet (lumber) in a continuous press. A microwave-type heating system is used to cure the adhesive in the thick billet. Temperature ranging from 180 ^{o}C to over 200 ^{o}C (360 ^{o}F to 400 ^{o}F) is needed. The maximum pressure applied is approximately 690 kPa (100 lb/in^{2}). The common commercial size of the PSL billet is 28 by 36 cm (11 by 14 in.) and 28 by 40 cm (11 by 16 in.) in cross section [7].

Composite lumber expected to perform in structural applications has to be evaluated in order to provide safety and reliability. The standard ASTM D5456 [10] provides procedures to develop design properties and quality assurance methods for SCL. This standard evaluates the mechanical properties, the response of the materials to the end-use environment, and establishes and conforms the quality according to the standard performance specification.

Calcutta bamboo has been tested for its various physical and mechanical properties and the results were reported in the previous work [12,13]. These results have been compared with selected timber species in an effort to assess the technical feasibility of using bamboo in structural composite products. Several timber species that are commonly used for composite products were compared to Calcutta bamboo. These timber species have been used successfully for composite products, interact well with the common wood-adhesives, and the production technology is well known. Thus, the similarities, or differences, between bamboo and wood were used to judiciously select the manufacturing parameters for a prototype bamboo composite.

EXPERIMENTAL

Materials

Calcutta bamboo was acquired from a Southern Asian distributor. Average length of the culms was 5.5 m (18 ft), and the average moisture content as received was about 10%. The average thickness of the culm wall was 0.97 cm (0.38 in) and the average oven-dry density was 643 kg/m^3 (40.1 lb/ft^3). The adhesive used was a liquid phenol formaldehyde (PF-PSL) obtained from Georgia Pacific Resins, Inc. The viscosity of PF at 25 $^oC \pm 0.5$ ^oC was 2200 cps, pH value of 11.2, 51% solid content, and specific gravity of approximately 1.18.

Methods

Upon arrival, the bamboo culms for the prototype PSL were cross-cut into 0.6 m (2 ft.) long segments. The length was limited by the size of the hot-press available. The culms were then manually split along the longitudinal axis into 4 to 6 parts using a hand cutter. The split culm was then reduced into strips of 2.5 mm (0.1 in.) to 5.0 mm (0.2 in.) thickness and with various widths ranging from 6 mm (0.25 in. to 20 mm (0.75 in.). The strip thickness was achieved using an abrasive planer, which removed the waxy outer layer of the culm. The strips were dried to a moisture content of approximately 5%. The PF adhesive was applied using a single-side roll-coater. The PF resin was added with an extender ratio of 95% neat PF and 5% extender (wheat), which increased the viscosity of the adhesive to 2800 cp. The adhesive mix was spread at a rate of approximately 200 g/m^2 to form a single glue-line. Adhesive was applied to both surfaces of the strips. The strips were later laid-up parallel to each other in a forming box to a dimension of 1.9 cm by 61 cm by 61 cm (0.75 in. by 24 in. by 24 in.). Typically 7 layers of strips were needed. The weight of the bamboo strips used in one mat was 5000 g, while the average adhesive mix consumption was approximately 730 g. The mat was pressed at a temperature of 120b^oC for 15 minutes. Pressing was done on a step-wise basis. Initial pressure was applied with the press closing to a position of 2.5 cm at 1 minute. After one minute, the ram continued closing to achieve a thickness of 1.9 cm (0.75 in.). The maximum pressure was 5500 kPa (800 psi) before the mat relaxed to approximately 1000 kPa (145 psi). Seven boards were pressed and then allowed to cool. The boards were later cut for the mechanical properties determination. The specimens were conditioned at 20 ^oC with 65% RH for three weeks prior to testing. Bending and compression tests were performed in accordance with ASTM D5456 [10], while the accelerated aging test (24-hour soak) were carried out in accordance to ASTM D 1037-96a [14]. Dimensions for bending and compression test were 1.9 cm by 4.0 cm by 40.0 cm and 1.9 cm by 1.9 cm by 8.4 cm, respectively. At least 30 specimens were prepared for each test. The mechanical properties determined were compression stress at proportional limit (σ_{pl}), ultimate compressive stress (σ_{ult}), and compressive modulus of elasticity (E), and bending stress at proportional limit (SPL), bending modulus of rupture (MOR) and bending modulus of elasticity (MOE). The mechanical tests were conducted on a universal testing machine (MTS 810). Bending tests were conducted at a cross-head speed of 5 mm/min (0.2 in. /min), while compression tests were at 2.5 mm/min (0.1 in. /min). Moisture content was measured after the test, as well as the relative density of each specimen, which was used in the analysis of covariance.

RESULTS AND DISCUSSION

Strength properties of bamboo PSL before and after the accelerated aging process are illustrated in Table 1. These comparisons were based on the adjusted mean value using relative density as the covariant. The analysis of variance indicated that bending MOR (F-value = 8.38) and MOE (F-value = 36.1), were significantly reduced when exposed to the accelerated aging process, while the bending stress at proportional limit was not significantly changed (F-value = 3.05).

Table 1. Mean bending and compression properties of the initial and adjusted values before and after the accelerated aging process of bamboo parallel strand lumber.
*Relative density was used in the property adjustment.
Average relative density for the bending and compression tests were 0.73 and 0.75, respectively.

Description	Bending (MPa)			Compression (MPa)		
	SPL	MOR	MOE	σ_{pl}	σ_{ult}	E
Initial	71.9	133	$12.3x10^3$	47.9	66.3	$7.68 x10^3$
Std. Dev.	*17.6*	*32.6*	*$1.71x10^3$*	*7.4*	*8.2*	*$1.64 x10^3$*
Adjusted*	66.9	126	$11.7x10^3$	47.4	65.8	$7.51 x10^3$
Exposed	51.1	85.1	$7.97x10^3$	45.6	65.4	$6.83 x10^3$
Std. Dev.	*7.6*	*21.2*	*$1.11 x10^3$*	*6.8*	*8.5*	*$1.20 x10^3$*
Adjusted*	58.3	95.6	$8.93 x10^3$	46.2	66.1	$7.06 x10^3$

None of the compression strength values, σ_{pl} (F-value = 8.38), σ_{ult} (F-value = 36.1) and E (F-value = 36.1) were significantly reduced when exposed to the accelerated aging process. The mean SPL was 71.9 MPa ($1.04x10^4$ psi), while the PSL exposed to the accelerated aging process was 51.1 MPa ($7.40x10^3$ psi). The mean SPL, when adjusted for relative density was 66.9 MPa ($9.71x10^3$ psi), while the adjusted value exposed to the accelerated aging process was 58.3 MPa ($8.46x10^3$ psi). The mean unexposed MOR was 133.0 MPa ($1.93x10^4$ psi), while the exposed MOR value was 85.1 MPa ($1.23x10^4$ psi), which is 64% of its original value. When adjusted for relative density MOR for the unexposed and exposed specimens were 126 MPa ($1.83x10^4$ psi) and 95.6 MPa ($1.39x10^4$ psi), respectively. Mean bending MOE was 12.3 GPa ($1.79x10^6$ psi), while the exposed bending MOE was reduced 35% to 7.97 GPa ($1.16x10^6$ psi). When it was adjusted using relative density, the values for bending MOE of the initial and the exposed specimens were 11.7 GPa ($1.69x10^6$ psi) and 8.93 GPa ($1.29x10^6$ psi), respectively, which was a 23% reduction.

The mean compression stress at proportional limit (σ_{pl}) of bamboo PSL was 47.9 MPa ($6.94x10^3$ psi), while the PSL exposed to the accelerated aging process was 45.6 MPa ($6.61x10^3$ psi). The adjusted σ_{pl} of PSL was 47.4 MPa ($6.87x10^3$ psi), while the adjusted value for the PSL exposed to the accelerated aging process was 46.2 MPa ($6.70x10^3$ psi). The adjusted value of ultimate compression stress (σ_{ult}) and compression MOE for the exposed specimens were also found to be not significantly different from the unexposed specimens. The mean σ_{ult} was 66.3 MPa (9.62x10^3 psi), while the exposed σ_{ult} value was 65.4 MPa (9.49x10^3 psi). The adjusted σ_{ult} for the two values were 65.8 MPa (9.54x10^3 psi) and 66.1 MPa (9.59x10^3 psi) respectively. Mean compression MOE was 7.68 GPa (1.11x10^6 psi), while the exposed compression MOE was 6.83 GPa (9.91x10^5 psi). When it was adjusted using relative density, the values for compression MOE of the initial and the exposed specimens were 7.51 GPa (1.09x10^6 psi) and 7.06 GPa (1.02x10^6 psi).

Comparison of the strength and stiffness of bamboo PSL was made to published values for some commercial and laboratory produced structural composite lumber (SCL) products. Table 2 illustrates the derivation of the preliminary allowable properties for bamboo PSL produced in the laboratory. Adjustment of the allowable properties for PSL considered a 5% exclusion limit and the general adjustment factors for hardwood that are specified in ASTM D-2915 [15]. The general factors include an adjustment for normal duration of load and safety factor. The 5% exclusion limit was applied to MOR and σ_{ult}. MOE was based on the average value [16]. Preliminary allowable properties for structural composite lumber, such as LVL, tested by some researchers in Table 3 were also derived according to ASTM D-2915, except that the general adjustment used was for softwood. These values are for comparison purposes only and are not to be used in design.

Table 2. Derivation of allowable properties for PSL from Calcutta bamboo.
*5% exclusion level not applied on MOE.
** General adjustment for hardwood.

Properties	Mean values (MPa)	5% exclusion limit* (MPa) Mean - 1.645(STD)	General adjustment factor**	Allowable Properties (MPa)
Compression stress (σ_{ult}.)	65.8 *(8.2)*	52.3	1/2.1	24.9
MOR	126 *(32.6)*	72.3	1/2.3	31.4
MOE (x10^3)	11.7 *(1.71)*	11.7	1/0.94	12.4

Table 3. Bamboo PSL preliminary allowable properties compared to other structural composite lumber products. All allowable properties are for comparison only, not for design, except the properties given by manufacturer.
[1]Allowable properties given by the source.
[2]Allowable properties derived for the data from the source.
[3]Allowable properties given by manufacturer.

Species/product	Source/ producer	σ_{ult} MPa (psi)	MOR MPa (psi)	MOE MPa (psi)
Calcutta bamboo BPSL		24.9 (3.61 x10^3)	31.4 (4557)	12.4 x10^3 (1.80 x10^6)
Lodgepole pine LVL[1] *Pinus contorta*	[17]	20.4 (2.99 x10^3)	21.1 (3054)	13.4 x10^3 (1.95 x10^6)
Interior Douglas-fir LVL[1] *Pseudotsuga menziesii*	[17]	21.1 (3.06 x10^3)	24.6 (3563)	15.3 x10^3 (2.22 x10^6)
Douglas-fir LVL[2] *Pseudotsuga menziesii*	[18]	25.5 (3.69 x10^3)	30.9 (4478)	17.2 x10^3 (2.49 x10^6)
1.8E Parallam PSL[3]	Trus Joist	17 (2.5 x10^3)	16.5 (2400)	12 x10^3 (1.8 x10^6)
2.0E Parallam PSL[3]	Trus Joist	20 (2.9 x10^3)	20.0 (2900)	14 x10^3 (2.0 x10^6)
1.5E Timberstrand LSL[3]	Trus Joist	13 (2.0 x10^3)	15.5 (2250)	10 x10^3 (1.5 x10^6)

From Table 3, the estimated allowable compression parallel to grain (σ_{ult}) for the bamboo SCL was 24.9 MPa ($3.61x10^3$ psi), which was higher than all other SCL products except the Douglas fir LVL produced by Kunesh [18]. The most distinctive failure mode involved in compression parallel to grain of the bamboo PSL was splitting. Other less significant failure modes were shear and end-rolling.

The estimated allowable MOR also showed a higher value compared to other SCL in Table 3. MOR for bamboo PSL was 31.4 MPa ($4.56x10^3$ psi), which is the highest value reported in Table 3. The most prevalent failure mode in bending was horizontal shear. Some tension failure occurred, but no other mode of failure was observed.

The estimated allowable MOE for bamboo PSL is lower compared to most of the values in Table 3, except the LSL manufactured by Trus Joist . The MOE value of bamboo PSL is approximately the same as the 1.8E Parallam produced by Trus Joist.

In general, the properties of the bamboo parallel strand lumber made from Calcutta bamboo compared quite favorably with the SCL given in Table 3, although MOE was lower compared to the PSL and some of the LVL. Since the strength properties (MOR and σ_{ult}) are superior, bamboo PSL could be effectively used as compression and bending members. However, due to its modest MOE, as well as its high relative density (~0.78), bamboo PSL could have difficulty meeting deflection requirements.

CONCLUSIONS

Composite products with acceptable mechanical properties can be produced from Calcutta bamboo. Mechanical properties of the bamboo parallel strand lumber compares favorably to commercial SCL, although there are a few exceptions. Although only the bending and compression properties were determined, this was a promising indication of the suitability of Calcutta bamboo as the raw material for many structural and nonstructural composite products. This research determined general trends and specific performance values of the bamboo PSL produced in the laboratory. Further effort is needed to determine more precisely the individual composite products that could be made from Calcutta bamboo and the application of the technology on an industrial scale. As an alternative to timber, Calcutta bamboo surely offers a promising future.

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