Stranding Moso and Guadua Bamboo. Part I: Strand Production and Size Classification

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Giant timber bamboos, such as moso (*Phyllostachys pubescens*) and guadua (*Guadua angustifolia*) are potentially well-suited to the production of engineered strand-based structural composite building materials. There is no information available for guadua, but moso bamboo is known to produce good-quality, strand-based composites. However, economically viable commercial production of these composites is hindered by the lack of an efficient, automated method for converting culm stock to strands, and very little technical information is available regarding strand production and quality. In this study, moso and guadua culm characteristics and tissue re-saturation behavior likely to affect stranding were measured and compared. Strand size classification and the thickness and width distributions from stranding re-saturated moso and guadua quartered culm pieces using a CAE 6/36 single-blade disk flaker were determined. While node frequency was lower in guadua than in moso, the diaphragms and embedded wall tissue were much thicker and tougher, with strong negative effects on strand quality. When cut to a target thickness of 0.65 mm, moso bamboo produced strand thickness frequency distributions close to those found in sampled mill strands of trembling aspen, while guadua caused high wear on blades and yielded a greater proportion of excessively thick, broken, and very rough strands.

Keywords: Bamboo; Processing; Furnish quality; Disk flaker; Oriented strand board

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INTRODUCTION

Bamboo is one of the fastest-growing renewable woody plants and is one of the world's most widely used building materials. Over one billion people live in dwellings built from bamboo (De Flander and Rovers 2009). These are mostly primitive, traditional, short-lived structures based on poles, woven strip mats, and thatching primarily inhabited by the poor. Bamboo is a member of the grass family, Poaceae/Graminaceae, which has approximately 1,225 known species (Austin and Ueda 1972), of which only a few grow sufficiently large-diameter (up to 6 inches) and have tall stems as to be suitable for processing into similar kinds of engineered composites as small wood logs. Due to deforestation, bamboo is emerging as a significant non-wood forest resource to replace wood in construction and other uses in several countries where it is native across the tropical and sub-tropical belt in Asia, Africa, and Latin America (Leise 1998; Fu *et al*. 2001). Raw bamboo rounds are unsuitable for modern wood-based construction systems because of their propensity for longitudinal splitting and flaws, highly variable geometry, and mechanical properties within and across culms. This makes it difficult to fit bamboo rounds in the narrow range of properties required for lignocellulosic composites used in the construction of large, modern structures (Van der Lugt *et al*. 2006; Correal and Ramirez 2010; Harries *et al*. 2012). A wide range of reconstituted lumber and panel products has been developed over many decades to overcome the natural variability in wood and produce building products with the required uniformity and controlled properties (Stark *et al*. 2010). With appropriate adaptations and testing, it is believed that laminated bamboo lumber products have significant potential as a substitute for engineered wood products in modern building construction (Mahdavi *et al.* 2011).

Moso (*Phyllostachys pubescens* Mazel) bamboo is monopodial (intermittent stems from an interconnected, below-ground rhizome), commercially cultivated, and used in a diverse range of products in China, but rare in building structures. Almost 40% of all bamboo species grow in Latin America (Londoño 2004). Perhaps the best known genus is guadua. Of 38 known guadua species, *Guadua angustifolia* Kunth, a sympodial or “clumping” bamboo, is the main timber species cultivated and used in processing (Schroder 2014). Guadua has been a building staple as a mortar substrate in *bahareque* housing construction in countries such as Colombia for centuries. Other basic building products derived from guadua include *esterilla*, single or multilayer plywood-like panels made from flattened, thin-walled culms cut from the upper stem. Significant progress has been made in Colombia, especially in developing engineered, glue-laminated guadua bamboo (GLG), the mechanical properties of which are better than most conventional laminated wood or bamboo species (Correal *et al*. 2014), and equivalent to those of the highest quality structural tropical wood products in Colombia (Duran 2003; Voermans 2006; Lopez and Correal 2009; Correal and Ramirez 2010). It has excellent structural properties for dwellings in earthquake zones including a high shear and fastener tear resistance-to-weight ratio, high energy absorption capacity, and flexibility, increasing resistance to failure during earthquakes (Londoño *et al*. 2002; Correal and Varela 2012; Varela *et al.* 2013). Demand for guadua timber is increasing as consumers look for alternatives with similar appearance, density, and properties to tropical timber. *Guadua* stems can reach 20 cm in diameter (the largest recorded is 25 cm) and up to 30 m in height. Like moso, culms are harvested between 4 and 6 years of age.

Despite development of a range of solid, laminated products based on bamboo strips and slats, processing industries throughout China and Latin America are still small-scale, very labor-intensive, and often have low product recovery from the culm and low efficiency of adhesive use. Fifteen years ago, Dagilis (1999) wrote of the very limited efficiency and economic viability of Chinese bamboo plywood panel factories. Since then, the economic boom in China has increased competition for and costs of both labor and culm supplies, making existing bamboo processing enterprises increasingly economically marginal (Frith 2013). De Flander and Rovers (2009) noted that, despite a strong focus on novel whole-culm building systems (particularly in the West), research and development of the kinds of modern, standardized engineered composite building products from bamboo that would make processing more economically efficient and the building products more appealing to consumers in bamboo-using countries is lacking.

Conversion of bamboo culms to smaller, more uniform particles, wafers, or strands that are blended with resin and formed into a consistent, solid size and shape can overcome the problems associated with the irregularity of whole culms that precludes them from use in modern construction (Dagilis 1999). Aside from particleboard, the OSB process is one of the best opportunities for automation and mass production of bamboo-based building materials. The process technology has good adhesive efficiency and high biomass recovery into the product. Notwithstanding the removal of node plates, the conversion of culms to strands requires no removal of any inner or outer wall tissue, resulting in high tissue recovery and retention of the strongest, outer wall tissue. The potential for bamboo-based OSB is promising, and there has been considerable development in China regarding the production of strands and wafers from moso bamboo for use in structural, strand-based composites (Fu 2007a; Fu 2007b; Zhang *et al*. 2007; Grossenbacher 2012). The hollow geometry and tough nodes make efficiently converting culms to strands a problem in the OSB manufacturing process. Previous research (Lee *et al*. 1996; Sumardi *et al*. 2006; Fu 2007a, 2007b; Zhang *et al*. 2007; Barbu *et al*. 2009; Saad *et al.* 2010; Malanit *et al*. 2011; Ibrahim and Febrianto 2013) demonstrates that good quality OSB can be produced from (mostly) moso bamboo under controlled conditions with node removal. However there is virtually no published information specifically related to strand production and quality for any bamboo species. The objective of this work was to address this shortage of technical information related to bamboo strand production using flaker equipment designed for wood.

A comparison was made between two commercially important species of timber bamboo (moso and guadua) in terms of strand production and quality using a parameter-controlled disk flaker. Culm size and physical characteristics likely to impinge on strand size and quality were compared. The frequency distributions for strand width and thickness of moso, guadua, and factory-produced aspen (*Populus tremuloides* Michx.) OSB face strands are given. Because the only imported bamboo supplies available in Canada are seasoned, treated poles, a method was developed to re-saturate the tissue to the known moisture content of freshly-cut bamboo culms.

EXPERIMENTAL

Culms and Tissue Re-Saturation

For bulk strand production and OSB board fabrication, 20 poles of 5-inch diameter Chinese-grown moso culms in 8-ft lengths were purchased from Canada's Bamboo World, Chilliwack, BC, Canada. This supplier imports seasoned, fumigated (methyl bromide) bamboo poles from the Zhejiang Province of Southeastern China, harvested at 4 years of age. The average pole external diameter was 101.7 mm, and the average pole weight was 6.6 kg. Ten 19-ft-long guadua culms were acquired from Koolbamboo, Miami, FL, USA, who import seasoned, treated culms harvested between 4 and 6 years of age from Colombia and Panama. The guadua poles were treated *via* immersion for 8 h in a water-based mix of borax and boric acid at 37 °C providing protection against powder-post beetles and other insect pests (Holloway 2014). For shipping, each guadua pole was cut into three 6.5-ft-long poles labeled A to C from culm base to top. The average pole diameter was 103.7 mm and the average weight was 5.2 kg, equating to 156.9 kg total delivered weight at 13.3% MC (measured as per ASTM D4442-07).

To evaluate the physical characteristics of the culm stock likely to affect strand dimensions and quality, the node frequency (number per unit length of culm), internode length, wall thickness, and basic density (ASTM D2935-14) of the wall and node tissue were measured. Since the strands are radially cut, the typical density profile from one edge of a strand to the other (*i.e.* from the inner to the outer culm wall) was measured using an X-ray density profiler for tissue taken from different heights in a sacrificial culm (moso only). A total of 12 culm disks measuring 50 mm high, were cut in order up the pole, and a 2-mm-thick sliver was cut using a small band saw from four equidistant points in the wall. From each sliver, a 10-mm-long section was cut and sanded smooth on both faces. A side-matched set of sacrificial slivers (4 per internode section) was also cut. These were used to derive the empirical oven dry basic density of the wall material for densitometer calibration, plotting average density with height. The dimensions of each sliver were measured with calipers, and slivers were placed in a QMS X-ray densitometer designed to measure the density along thin sections of radial tree cores. The mass absorption coefficient, μ, was determined from the average of 12 sacrificial density specimens. Average μ for these was 2.82. The X-ray densitometer took a reading of wall density at 0.04 mm increments from the inner to the outer wall.

For strand production each bamboo pole was divided into 130-mm-long sections. The number of sections per culm was 17 to 19, half of which were node-free. The other half was marked so as to contain embedded node tissue at or near their middle. Therefore some small sections of culm were cut and discarded. Each pole was then cut lengthwise into four quarters from which the protruding node diaphragms were removed. This was done with a hammer in the case of moso, but required a Dremel saw and sanding of the remaining thick portion until flush with the inner wall in the case of guadua. This allowed stacking of the pieces in the feed drawer of the disk flaker. The quarter lengths (minus node plates) were cross-cut into the pre-marked 130-mm sections, and the noded and internode sections were kept separate during re-saturation and stranding.

To re-saturate the bulk culm tissue prior to stranding, forty 130-mm-long culm pieces (representing 10 different moso and 10 different guadua stems) were randomly selected and divided into two batches of 20 pieces each. One batch was soaked in water at 20 °C for up to 4 d and the other was boiled for 6 h followed by steeping over-night in cold water. Each piece was weighed and its volume was determined using the Archimedian (volume displacement) method. Specimens were removed, drained, and weighed at intervals of 1, 3, 6, 24, 48, and 96 h before being oven-dried at 105 °C for 24 h to calculate their moisture content (MC). The bulk culm pieces of both species were re-saturated using the optimum boil-cold water soaking method as determined above. The conversion of poles to quarter rounds had been previously shown to maximize strand recovery from the culm per knife revolution (Semple and Smith 2014).

Stranding

To minimize fines generation and damage to the flaker knives, only bamboo tissue that had been saturated to its maximum capacity, based on the findings of the re-wetting experiments, were stranded. A 0.94-m-diameter laboratory Disc Flaker (6/36 Lab Flaker) built by Carmanah Design and Manufacturing, Ltd. (Vancouver, BC, Canada), was used, as shown in Fig. 1. The flaker is designed to simulate the flaking action of a full-size 37/118 disk flaker whose knife velocity at the blade mid-point is around 2585 m/min (Carmanah 2006). The disk was fitted with a single 15-mm-long, disposable, double-sided knife (Udderholm Sleipner heat-tempered cold-work tool; steel- HRc 58). The thickness of the strands and the amount of fines produced are mainly dependent on finely balanced interaction between the knife protrusion setting, the disk rotational speed, ω, and the feed rate, F, of the material into the machining blade (Kruse *et al*. 2000). The knife angular velocity at the mid-point of the blade length is a function of disk radius to blade mid-point and the disk rotation speed (RPM) as follows (Eq. 1),

$$V_k = 2\omega\pi r/12 \quad (1)$$

where V_k is the knife velocity in mm/min (the manufacturer's recommendation for the scaled-down, small-diameter disk is 1404.5 m/min); ω is the disc rotational speed in RPM; and r is the radius to the mid-length of the disk diameter where the knife starts (30.48 cm). Rearranging Eq. 1 as follows (Eq. 2),

$$\omega = 12V_k/2\pi \quad (2)$$

yields a recommended disk rotational speed of 734 RPM, which was used consistently throughout all bamboo stranding trials. To produce a particular strand target thickness at a fixed ω value, the material feed rate (F) in mm/s was calculated as follows (Eq. 3),

$$F = n_k t\omega/60 \quad (3)$$

where n_k is the number of knives per disc (1); t is the target thickness of the strands (0.65 mm), and ω is 734 RPM. F for the target thickness of 0.65 mm was 7.95 mm/s.

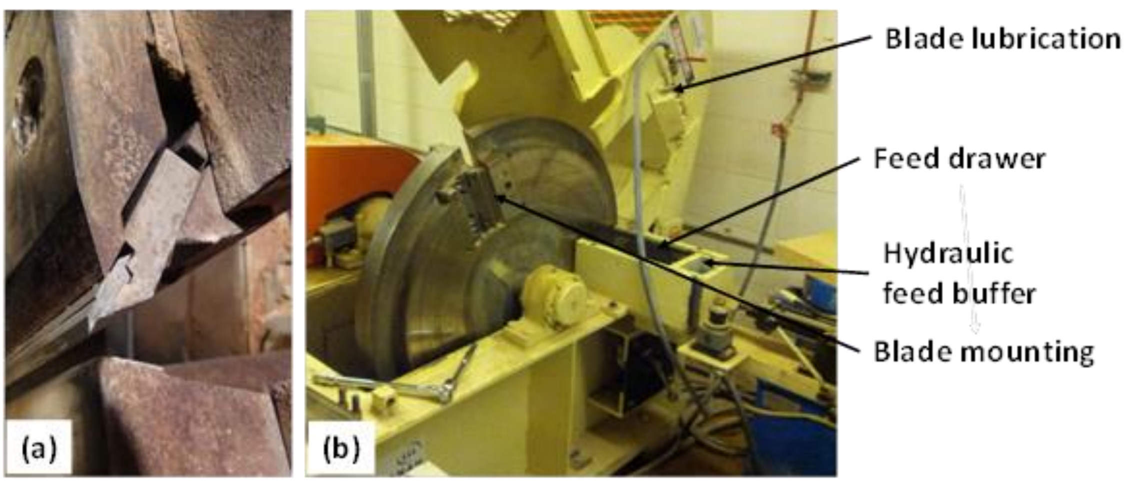

Fig. 1. CAE 6/36 Lab Flaker: (a) removable blade; (b) disk, blade mounting, and feed drawer

The most efficient quarter round arrangement in the feed drawer is shown in Fig. 2. A series of preliminary experiments regarding the tissue MC, knife protrusion, feed rate, and culm piece size and orientation (Semple *et al*. 2014) was carried out with moso to optimize the strand thickness, width, and surface quality. Optimal strand outcomes (average thickness, thickness distribution, and width distribution) and surface classification were obtained when fully-saturated culm pieces were quartered and stranded vertically at 734 RPM with a knife protrusion of 0.726 mm (to produce a nominal strand thickness 0.65 mm) and the corresponding feed rate of 7.95 mm/s. Vertical culm slicing resulted in more consistent strand thickness distribution with 85% of the strands falling within the thickness range of 0.25 to 0.75 mm. Strand recovery (number of strands per culm round) increased by over 50% if the culm rounds were converted to quarters and stacked as shown in Fig. 2 (Semple and Smith 2014). These stranding parameters were used to produce bulk strands from both moso and guadua for comparative purposes and subsequent OSB fabrication.

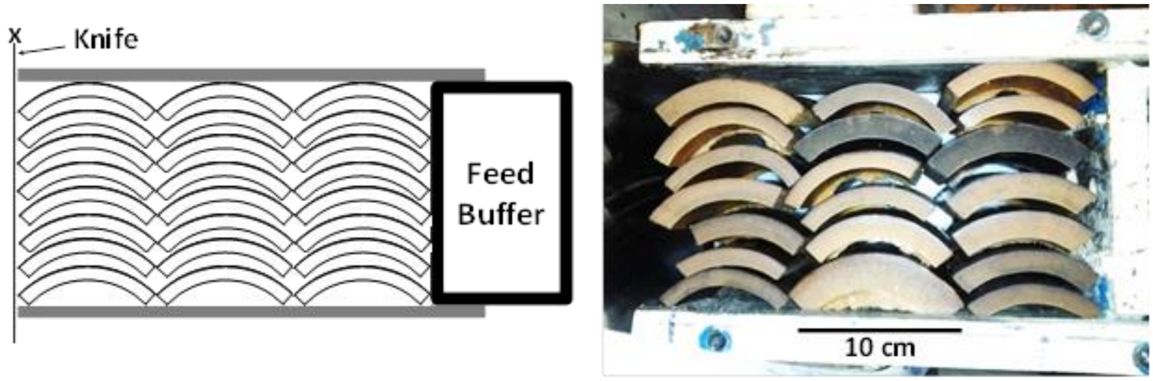

Fig. 2. Arrangement of quarter rounds in the feed drawer

The bulk strands were distributed into large wire baskets and dried to approximately 4% MC in a walk-in oven overnight at 85 °C. The dried strands were bagged and screened into three main fractions on a 56 cm x 117 cm vibrating sieve machine fitted with three square-opening screens of sizes 14.3-mm (collects complete strands), 7.8-mm (collects larger fines) and 3.2-mm (collects smaller fines), and dust (<3.2 mm screen). The strands, combined fines, and dust were bagged separately and weighed to determine their weight proportions out of the total weight of the bulk strands.

The full-sized strands retained on the 14.3-mm screen were sampled for representative strand thickness and width properties. Strand thickness and width at mid-length were tested for a randomly sampled batch of 250 strands each for the two bamboo species. Dimensions were measured using digital calipers and were compared with the same measurements made on 250 industrial aspen mill strands (face furnish) supplied by the Weyerhauser OSB mill in Edson, AB, Canada. Strands were randomly sampled in handfuls of approximately 50 strands each from the bulk strands. Only full-length (130-mm), intact strands (not fines or broken pieces) were assessed. Assessment of strand breakage problems, surface roughness and classification are covered in Part II (Semple *et al.* 2015c) of this series on stranding bamboo.

RESULTS AND DISCUSSION

Culms

A summary of the basic properties of the sampled moso and guadua poles is given in Table 1. Example inner-outer wall density profiles are shown in Fig. 3a to c, and a plot of average wall density with each successive internode shown in Fig. 3d. Typical moso and guadua node plates are shown in Fig. 3 and a comparison of the density of the internode *versus* the node tissue is shown in Fig. 4. The average basic density of moso was 447 kg/m^3 (internode) and 532 kg/m^3 (node plates), a 19% increase in the density of the node tissue. The average basic density of guadua was 526 kg/m^3 (internode) and 581 kg/m^3 (nodes), a 14% increase in the density of the nodes. Guadua poles had slightly greater average diameter and wall thickness (103.7 mm and 12 mm, respectively) than moso (101.7 mm and 10.9 mm, respectively). The frequency of nodes is less in guadua (3.3 nodes per meter of culm) than moso (3.8 per meter) and spaced further apart (average internode length of 30.7 cm compared with 24 cm for moso).

Table 1. Properties of Moso and Guadua Poles Used to Produce Strands

Property	Moso	Guadua	*N*
Internode Tissue Density* (kg/m^3)	446.8	533.1	40
Node Tissue Density* (kg/m^3)	531.8	601.6	20
Pole Diameter (mm)	101.7	103.7	20
Internode Length (cm)	23.98	30.67	20
Node Frequency (/m)	3.8	3.3	20
Wall Thickness (mm)	10.9	12.0	20
Node Thickness (mm)	2.77	7.38	20
Delivered MC (%)	11.69	13.27	40

*Oven-dry density

With increasing height the culm wall narrows and the proportion of higher density material in the culm wall increases (Fig. 3a-c), resulting in the increased average wall density with height (Fig. 3d). Note also that both the cortex and inner wall density are lower at the base (internode 1) than further up the stem. Average culm wall density in the sampled culm ranged between 600 kg/m^3 near the base to 680 kg/m^3 towards the top (over a distance of 240 cm); which was a bit higher than the density of most of the culms used to produce strands. The inner two thirds of the culm wall is mostly between 400 and 600 kg/m^3 in density, with a steep rise to over 1000 kg/m^3 at the outer cortex. At the top of the culm (internode 12), tissue density sharply increases again after the initial spike in density in the lining of the inner culm wall. Tissue density and strength is proportional to the volume fraction of fiber bundles (Obataya *et al.* 2007; Dixon and Gibson 2014).

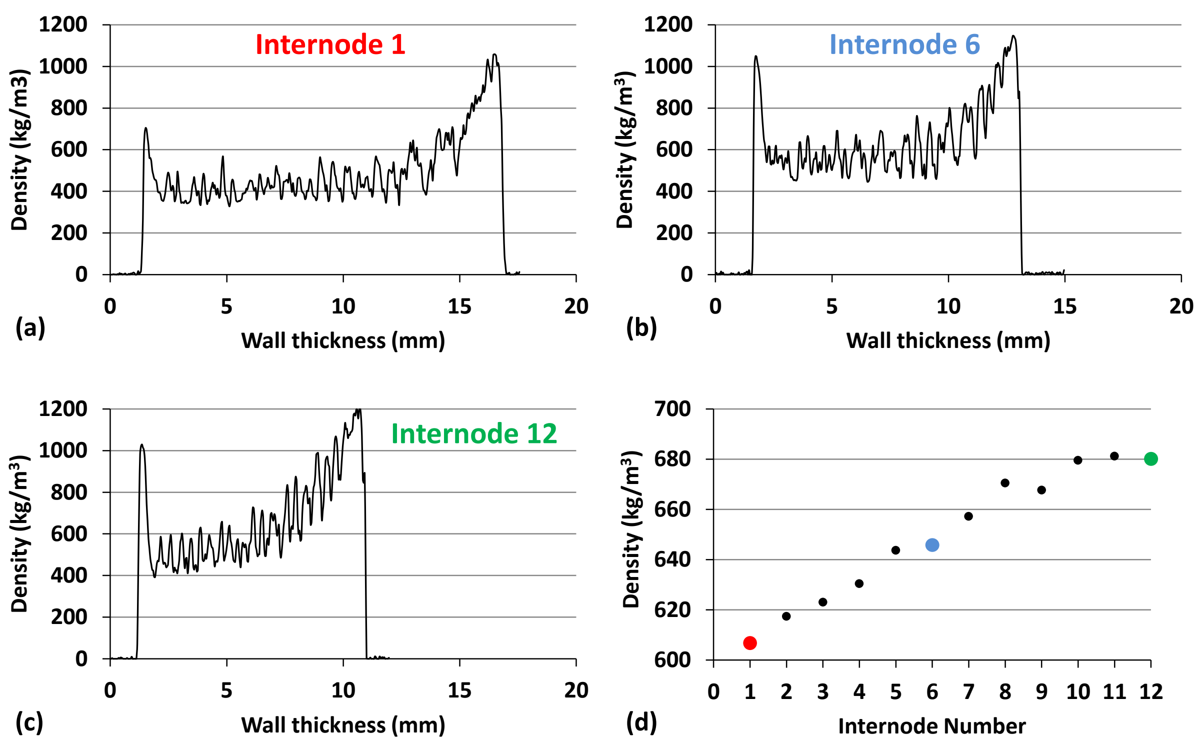

Fig. 3. (a) to (c) X-ray densitometry profiles from inner to outer culm wall of moso bamboo at internode 1, 6 and 12 up the culm stem; (d) plot of average wall density at successive internodes up the culm stem, *n* = 4.

Cost and time constraints restricted the detailed density assessments to moso; however research by Correal and Arbaláez (2010) have found a similar pattern of steady increase in density with height in the culm wall of guadua whereby the top merchantable culm (in the lower crown zone) is 21% greater in density than the bottom culm, and accordingly its flexural strength is 17% higher. The average wall density of bamboo culms increases because the same fiber bundles running all the way up the culm are confined to decreasing thickness and area of wall tissue, thereby increasing their contribution to total wall volume and weight (Leise and Weiner 1996).

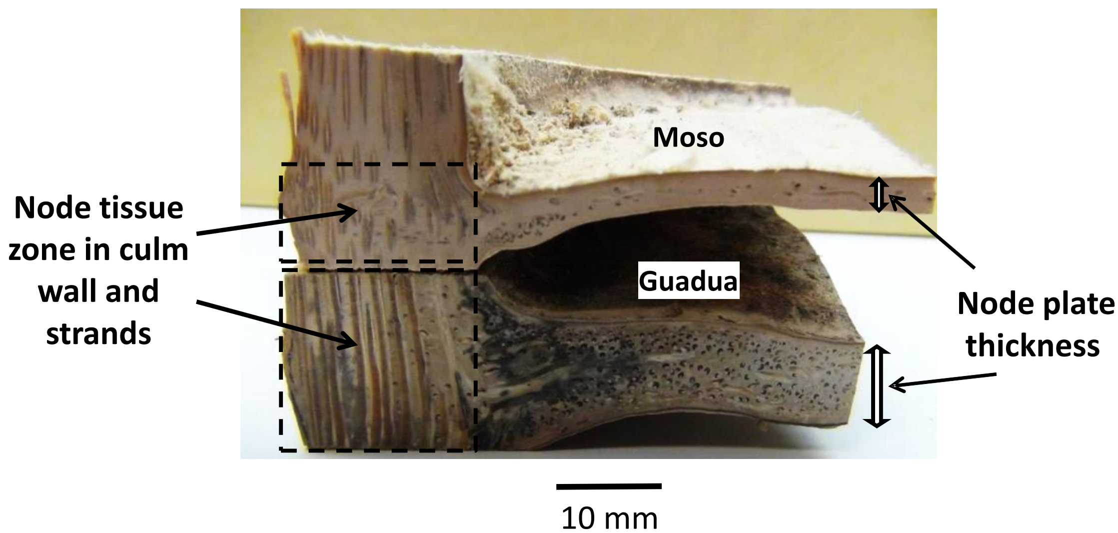

Fig. 4. Appearance of the node plates of moso and guadua; bottom 1 m portion of the culm

The average tissue moisture content of the culm pieces of moso and guadua subjected to either cold- or hot-water + cold-water treatment for increasing time intervals is shown in Fig. 5. With a starting MC of around 10% and after 6 h of soaking in cold water, the average tissue moisture content was 25.7% for moso and 26.4% for guadua. Boiling for the same duration resulted in 46% MC for moso and 55.7% for guadua, too low for stranding. After 24 h, the MC of cold water-soaked moso tissue was 38.6% and that of guadua was 38.4%, still far below the saturation level required for stranding. The MC of the pieces boiled and steeped in cold water for 18 h further was 128.1% for moso and 113.9% for guadua. After a further 3 days soaking (96 h from start), the cold water pieces reached 75.2% MC, while those boiled and steeped were 142.7% for moso. Guadua reached 60.7% MC after 96 h cold water soaking and 114.4% with the 6-h boil followed by cold water steeping for 96 h.

For comparison, fresh moso culm stock harvested and stranded by Lee *et al*. (1994) was 137% MC, indicating that the tissue was fully re-saturated by boil/steep for 6 h/24 h. The tissue water content was similar to that measured in green culm stock. It is possible that 6 h of boiling may not be necessary, and a useful follow-up study would be to measure the MC after boiling for 1 or 2 h followed by steeping. Note from Fig. 5 that the boil/steep moso continued to take up water between 24 and 96 h, but guadua gained no extra water during this time interval. This suggests that the guadua tissue, being considerably denser and containing less void space, reached its saturation point within 24 h. Attempts to convert moso to strands immediately after boiling produced very poor strands and many fines (Semple *et al*. 2014) due low moisture content.

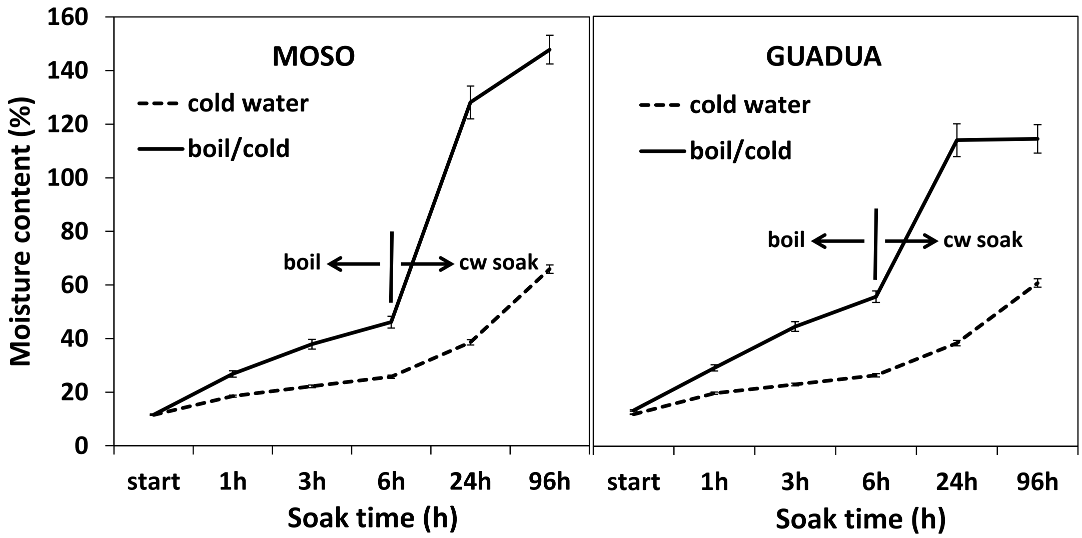

Fig. 5. Average MC of moso and guadua culm pieces after 0, 1, 3, 6, 24, and 96 h exposure to cold or boiling water, *n* = 20. Boil/cold pieces were boiled for 6 h followed by steeping in cold water for 24 or 96 h. Error bars represent the 95% confidence interval.

Strands

The comparative screen analysis for moso and guadua strands is shown in Table 2, and examples of bamboo screened fractions in Fig. 6. The total weight of the sieved fractions excludes the small portion of unstranded pieces or chips (approximately 5% of the total culm stock) left behind after each drawer load. The proportion of complete strands (remaining on top of the large 14.3-mm screen) was higher in moso (75.5% for internodes and 67.8% for noded pieces) than guadua (65.4% for internodes and 59.4% for noded pieces). The proportion of smaller material or 'fines' (see Figs. 6b and 5c) was higher for guadua (34.7% for internode and 40.6% for nodes), reflecting greater strand damage and fragmentation during slicing than in moso. Sampling of strands for thickness and width measurements revealed that the percentages of broken strands in the 250-strand sample of guadua (node) strands were 25.2% as compared to 7.6% for its internode strands. Many strands fractured at the site of node tissue in guadua strands, with its abrupt change in density and deviation of reinforcement fibers from the longitudinal direction resulting in greater tissue damage and rupturing during culm slicing.

Fig. 6. Appearance of moso bamboo: (a) strands (>14.3-mm); (b) large fines (7.8-mm to 14.3-mm); and (c) small fines (3.18-mm to 7.8-mm)

Table 2. Screen Analysis of Moso and Guadua Strands

	Moso Internodes	Moso Nodes	Guadua Internodes	Guadua Nodes
		Mass (kg)		
Strands	41.66	34.18	40.89	29.58
Fines	8.62	12.38	17.06	15.88
Residue (dust)	4.96	3.88	4.62	4.32
Total	55.24	50.44	62.57	49.78
		Mass Proportions (%)		
Strands	75.4	67.8	65.4	59.4
Fines	15.6	24.5	27.3	31.9
Residue (dust)	9.0	7.7	7.4	8.7
Total	100	100	100	100

The proportion of fines resulting from screening the stranded moso was 24.6% for internodes and 32.2% for noded pieces. These figures were slightly higher than the typical fines contents produced at a typical OSB mill processing mixed hardwoods (oaks, sweet gum, and others), between 15 and 25% (De Vallance *et al*. 2012). As a comparison, the size classification for sampled aspen OSB face furnish indicated that they yielded 73% strands and 27% fines. The aspen face furnish had already undergone a cursory screening process to remove much of the fines and boiler dust. Therefore, the size classification of the moso bamboo strands was not very different from that of industrial OSB strands produced from wood logs.

The average and COV for sampled strand thickness and width for aspen, moso, and guadua strands are given in Table 3. The average strand thickness was 0.67 mm for aspen, 0.65 mm for moso, and 0.75 mm for guadua, and the average strand width was 18.1 mm for aspen, 12.9 mm for moso, and 15.0 mm for guadua. The greater average thickness of guadua strands was due to the higher proportion of excessively thick strands (>0.75 mm) in the mix, almost 40% of all strands. This is despite adjustment of the flaker settings to produce strands with an average thickness of 0.65 mm, which worked well for moso.

Table 3. Average Strand Thickness and Width with COV for aspen, moso, and guadua

	Strand Thickness		Strand Width	
	Average (mm)	COV (%)	Average (mm)	COV (%)
aspen	0.67	35.7	18.1	50.3
moso	0.65	37.7	12.9	30.7
guadua	0.75	31.3	15.0	27.3

COV: Coefficient of Variation. *n* = 250.

The percentage of strands falling into each thickness and width class for moso, guadua, and industrial aspen strands are given in Table 4, and the frequency distributions for thickness and width of aspen, moso, and guadua are shown in Fig. 7. Note that the frequency of moso and guadua strands in the optimum 0.5- to 0.75-mm thickness class were very similar at 53% of the total strands. However, over a quarter of the guadua strands were in the 0.75- to 1-mm thickness class, and another 13% >1 mm thick; whereas only 18% of moso strands were 0.75 to 1 mm in thickness. Moso yielded a greater proportion of thinner strands 0.25- to 0.5-mm-thick (21.4%) than did guadua

(7.2%). A large proportion of the guadua bulk strands (65%) were not sliced cleanly by the flaker knife, especially the thicker strands, but rather ‘splintered’ apart leaving raised ridges along the edges of fiber bundles. The fiber bundles in guadua tissue were also 2 to 3 times the size of those in moso, and with much larger zones of very dense sclerenchyma tissue that likely accounted for the knife dulling and greater difficulty slicing the tissue cleanly (Semple *et al.* 2015c).

The shape of the strand thickness distribution for moso was closer to that of aspen strands. The distribution of strand width for guadua was closer to that of the aspen, with a greater proportion of strands in the 15- to 20-mm width class (27.6%) than moso (12.4%). 32% of aspen strands were greater than 20 mm in width. Wood flaking knives are profiled at the back of the blade with an angled protrusion, termed the ‘counter knife angle’, which places bending stresses on the veneer as it is sliced away from the main body of the material and forcing it to break into a series of narrow strands (Maietta *et al*. 2011). Depending on the type and density of wood being processed, the counter knife angle is set to produce a desired width distribution of strands for OSB. Harder, denser woods generally require a higher angle to exert greater stress on the substrate. Due to the finite thickness of the bamboo culm wall, the proportion of strands above 20 mm was limited to 5.2% for moso and 8% for guadua. From Table 1, the average culm wall thickness for stranded moso poles was 10.9 mm, with a range of 8 to 15 mm, and for guadua the average wall thickness was 12 mm with a range of 8.5 mm to 16.7 mm. The greater average wall thickness for guadua resulted in a greater portion of strands in the upper width classes (15 to 20 mm and 20 to 25 mm).

Table 4. Percentage of Strands in Each Thickness and Width Category

Thickness Class	moso	guadua	aspen	Width Class	moso	guadua	aspen
<0.25	0.4	0.4	2.4	<5	0.0	0.0	2.0
0.25 to 0.5	21.4	7.2	23.0	5 to 10	15.9	2.0	15.6
0.5 to 0.75	53.2	53.2	44.0	10 to 15	66.5	62.4	23.2
0.75 to 1.0	17.9	26.4	19.4	15 to 20	12.4	27.6	23.2
1.0 to 1.25	6.0	10.0	9.5	20 to 25	2.4	6.4	14.8
1.25 to 1.5	0.4	1.2	1.2	25 to 30	1.6	0.4	10.4
1.5 to 1.75	0.8	1.6	0.4	30 to 35	1.2	0.8	4.0
Nominal thickness = 0.65 mm				35 to 40	0.0	0.0	3.2
				40 to 45	0.0	0.4	2.0
				45 to 50	0.0	0.0	1.2
				50 to 55	0.0	0.0	0.0
				55 to 60	0.0	0.0	0.4

The most detailed information available on experimental stranding of bamboo is from Barbu *et al.* (2009) and Malanit *et al.* (2011), who used a CAE 6/36 laboratory disk flaker similar to the one used in the present study to produce 140-mm-long strands for OSB and OSL prototype fabricating. The bamboo was *Dendrocalamus asper* Backer, commonly planted in Thailand. They converted the culms to internode-only sections in the form of 140-mm-long half rounds and used stranding parameters as follows: counter knife angle, 60°; knife projection, 0.736 mm; scoring knife distance, 140 mm; and horizontal culm orientation (*i.e.*, slicing perpendicular to the grain direction). Their average strand dimensions were 0.7 mm thickness, 140 mm length, and 12.5 to 20 mm width. Their strands were screened through a 12.5-mm screen to remove fines. The disk

RPM, feed rate, and fines fraction were not specified. There is no known guadua OSB production operation in Latin America. The only previous work found on converting guadua to strands was an attempt by Dagilis (1991) to produce thin, wafer-based panels. Wafer quality was poor and precluded the fabrication of waferboards (the precursor to OSB). Here, after upgrading the knives to hardened steel blades, it was possible to produce a sufficient quantity of guadua strands for experimental OSB manufacturing, although it is possible that strander operating parameters (such as knife velocity and feed rate) that suited moso may have been sub-optimal for guadua.

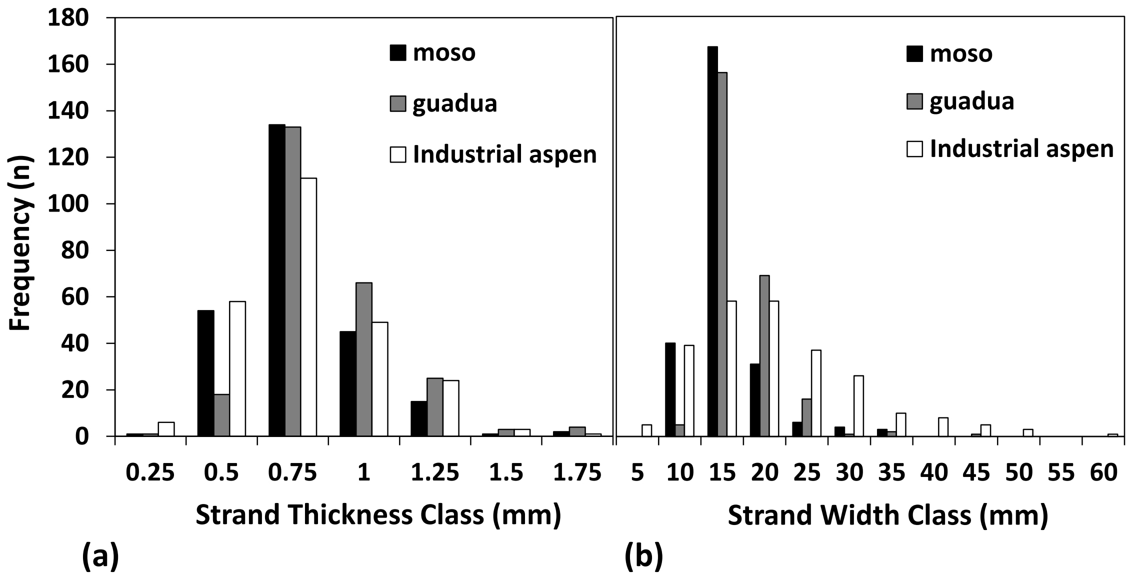

Fig. 7. Frequency distributions for (a) strand thickness and (b) strand widths for moso and guadua bamboo and industrial aspen mill strands. n = 250

Commercial bamboo OSB production in China is still hindered by the inefficient process of reducing culms to strands using machinery designed and built to be suited to wood. One company, Yunnan Yung Lifa Forest Co., Ltd., has spent several years adapting OSB process technology to bamboo and has recently begun trial production of commercial quality-bamboo OSB in their pilot plant (Wood Based Panels International 2012b; Grossenbacher 2012). This was in response to a growing market for tough, durable flooring to replace the tropical timber plywood used in shipping containers. Bamboo has been shown to produce a harder, tougher, and more water- and wear-resistant panel than any conventional wood-based panel (Wood Based Panels International 2012a, 2012b). The Yunnan Yung Lifa enterprise uses small disk standers to convert culms to strands. While most other aspects of the automated OSB process have been successfully extended to bamboo, the stranding process remains a bottleneck. Culms are laboriously cross-cut into small rounds of internode-only tissue which are stacked inside one another, where possible, prior to stranding (Grossenbacher 2012; Boeck 2013). Presumably, during the course of product development, the effects of nodes on strand quality and product properties became apparent.

Removing the node tissue from the culm wall is uneconomic, requiring intensive manual handling of small pieces and wastes much of the culm stock that is expensive to procure. While a high proportion of node tissue in OSB face strands has a significant negative impact on OSB strength properties (Semple *et al.* 2015a,b), subsequent research (unpublished) shows that for both moso and guadua bamboo, evenly mixing noded strands with internode strands produces panels of acceptable quality. 11.1-mm-thick, 750 kg/m^3 density OSB made from mixed face strands of either moso or guadua are similar in bending strength (64 to 65 MPa) and meet recommended minimum properties for Grade 2 commodity OSB. Mixed guadua face strands produces OSB with superior stiffness (10.5 GPa) to the same product made from moso (8 GPa), meaning that with the development of more appropriate strand production technology guadua has good potential for use in strand-based composites. For comparison, the properties of a 3-layer cross laminated strip sheathing panels of solid guadua (9 mm in thickness and 720 kg/m^3 in density) are 64 MPa in MOR, and 14 GPa in MOE (Varela *et al.* 2013).

While a purpose-designed culm splitter exists for moso, which passes culms through a multi-blade splitting wheel fitted with a nose cone that removes the nodes plates at the same time, the machine may not be sufficiently robust for guadua with its much thicker and tougher node plates. Guadua may require a more specialized corer to grind out the thick, tough node plates prior to conversion of culms to strands. Node plate-free, quartered culm lengths can then be stacked securely and sliced into strands which can be achieved using an industrial-scale disk or ring flaker (Fu 2007b) with scoring knives to produce strands of the desired length. Geometric modelling of culm slicing (Semple and Smith 2014) had almost 40% increase in the number of strands produced per culm round if they are split into quarters, stacked, and sliced through the radial direction rather than sliced as whole rounds. This also ensures that the waxy outer cortex is confined to one narrow edge of every strand where it cannot interfere with resin bonds between strand surfaces. Slicing perpendicular-to-grain represents a departure from the experimental approach here of slicing the tissue longitudinally, but it appears to be the only viable configuration for converting long flitches to strands using industrial-scale wood flakers, avoiding the need to cross-cut culms into very short pieces.

The hard, siliceous outer cortex of both guadua and moso bamboo culms creates potential challenges for knife maintenance as they dull quickly, and therefore close attention will need to be given to knife metallurgy and sharpness. Knives that are capable of slicing guadua tissue cleanly through its large, dense fiber bundles to a consistent target thickness without splintering will be necessary. A wedge-shaped blade without a profiled counter knife angle would also better suit bamboo, for reasons which are elaborated on in Part II (Semple *et al.* 2015c). Based on the findings of density profiling of the culm wall and the fact there is a greater frequency of nodes near the base of the culm it would make sense to partition culms into upper and lower portions, process these separately into strands and use the stronger material from the upper portions for the face layers of composites, where strength is required, and that from the lower, less dense regions in the core where furnish geometry and strength are not as critical to product quality.

CONCLUSIONS

1. Guadua has a higher density than moso bamboo, with much thicker node plates and larger zone of node tissue in the culm wall. These features plus the more heterogeneous culm wall tissue (very large, dense fiber bundles surrounded by very low density, soft parenchyma tissue) created significant challenges for slicing smooth,

good-quality strands with the desired thickness distribution using flaker equipment designed for wood.

2. Culm wall density measurement (across and with height) of moso showed tissue density increases with height in culm by almost 15%, and each radially cut strand has a thin zone of very dense tissue along one edge (inner wall lining) followed by low density tissue (400 kg/m^3) which grades upwards density to above 1000 kg/m^3 at the outer cortex.
3. Tissue re-saturation for stranding requires up to 6 h of boiling followed by at least 18 h further steeping in cold water. Being denser, the saturation moisture content (MC) of guadua is lower (114%) than that of moso (128%).
4. The proportion of complete internode strands (>14.3 mm) was higher for moso (75%) than guadua (65%). Stranding culm wall tissue with nodes in it reduced the proportions of large strands to 68% for moso and 59% for guadua. Fracture of noded strands was more problematic in guadua, with up to a quarter of the bulk strands breaking into shorter pieces at the node tissue.
5. The average strand thickness and coefficient of variation (0.65 mm and 37.7% COV) for moso was very close to those of industrial aspen strands (0.67 mm and 35.7% COV). The average moso strand width was around 13 mm as compared to 18 mm for sampled industrial aspen strands. In contrast, guadua strands produced under the same stranding conditions were an average of 0.75 mm in thickness with 31.3% COV; and 15.0 mm in width with 27.3% COV.
6. Sub-optimal slicing of guadua is likely from an interacting combination of greater heterogeneity in tissue structure and density between nodes, internodes, sclerenchyma and parenchyma cell types, larger and tougher sclerenchyma tissue, blade dulling, and possibly a blade profile and machine operation parameters that were unsuitable for guadua. Further attention is required on redesigning and adapting wood flaking equipment to better suit the production of good-quality strands from bamboo culms, in particular, guadua.
7. Follow-up research (Part II) evaluates the surface characteristics and roughness indices of the strands and how this may affect the blending of strands with liquid resin droplets during OSB manufacture. The effects of the large differences in strand quality between moso and guadua on the performance of the materials in OSB are also evaluated.

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