THE EFFECT OF CULM AGE, HEIGHT, NODE, AND ADHESIVE ON THE PROPERTIES OF BAMBOO ORIENTED STRAND BOARDS

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Abstract. The effects of native character on the properties of strands board made from bamboo were evaluated, and the effect of mixing adhesive usage on durability property of the board was experientially researched. The strands of bamboo were classified under different bamboo age, height, and node or internode. The sorted strands were manually formed into strand mats and hot-pressed into strand boards using consistent parameters. Analysis of variance was used to analyze the significance of factors. The results of this study indicated that bamboo age was an insignificant factor for both MOR, MOE, and thickness swelling (TS), but significant for internal bond (IB) strength. The bamboo height and nodes in the core layer were a significant factor for parallel MOR, parallel MOE, and IB, whereas two factors had minimal effect on TS. Phenol-formaldehyde resin (PF)/emulsion polymer isocyanate adhesive (MDI) mixed-adhesive bonded board (type 6 PF/ MDI) had less TS and higher MOE retention than MDI only bonded board (type 6) when strand boards were subjected to boiling treatments. This proved that it was more durable, and could be considered as a potentially suitable raw material for moisture/heat–resistant panel for these specific applications.

Keywords: Culm age, height, node, bamboo OSB, property.

INTRODUCTION

Bamboo is abundantly available in many countries, and it is a very promising substitute material for wood because of its rapid growth rate, short rotation age, high tensile strength, and traditional use as a building material (Dixon et al 2017). The design and use of structural bamboo products allows more efficient use of this renewable resource. Bamboo-bundle laminated lumber, laminated bamboo lumber, and bamboo oriented strand board (OSB) are examples of such possibilities (Febrianto et al 2012). The OSB process represents one of the best opportunities for automation and mass production of bamboo-based building materials; the process technology has a high degree of adhesive efficiency and biomass recovery into product. *Dendrocalamus giganteus* Munro are a potential feedstock for bamboo OSBs. *Dendrocalamus giganteus* Munro most commonly grows in southeast Asian countries,

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including India, Sri Lanka, Myanmar, etc. It is among the bamboo species with a big potential to be used for OSB manufacturing because of its large culm diameter and thick culm wall (Liu et al 2012).

Currently, OSB is the most common structural panel. Despite considerable effort to improve the mechanical properties of OSBs, its application range is still more or less limited to the roof, wall, and floor sheeting because of moderate board stiffness and strength (Zhang et al 1998). Value-added products such as moisture-resistant panels for subflooring or longer sheathing panels could be developed from OSB panels engineered for these specific applications. Extending the application range of strand panels to the load-bearing sector requires considerable improvement of their mechanical properties.

Previous experimental investigations on the relations between strand and layer characteristics and effective properties of OSBs mostly focused on the influence of strand orientation, strand size, the vertical density profile, or the layer assembly on the board stiffness and strength (Ihak et al 2007; Alldritt et al 2013; Semple et al 2015; Sumardi et al 2015). Moreover, the effect of nodes in the bamboo strands have been researched, and the result showed that the presence of nodes significantly reduced the strength properties of OSBs, particularly those used in the surface layers (Semple et al 2015). Also, the effect of mechanical properties of individual strands on the wood and bamboo OSB strength have been reported in previous studies. Stürzenbecher et al (2010) found that the wood quality of the raw material naturally has a direct influence on the stiffness and strength properties of the finished boards. Beck (2009) concluded that the species had no significant effect on IB, but they did have a significant impact on bending properties. Generally, aspen panels had better bending properties than birch panels. Semple et al (2007) found that variation in solid wood density among the hybrid poplar clones led to variation in board-strength properties. Lower density wood from the fastest growing clone resulted in better mat compaction and higher bond strength. Febrianto et al (2015) investigated the effect of bamboo species on properties of bamboo OSB. The result showed that the physical and mechanical properties of OSBs from Betung and Andong strands were much superior to those of OSBs from Ampel strands. The qualities and species of strands, to a degree, affected the properties of boards. However, few have been conducted to evaluate the influence of bamboo height and age on its mechanical properties of OSBs made from bamboo.

According to previous studies, bamboo properties would have an effect on its utilization. Properties of bamboo such as anatomical, physical, and mechanical properties were reported to vary with age, height, and some other variable (presence of nodes and MC) (Sumardi et al 2015). It explained that the fiber amount and specific gravity increased from the bottom to the top of the culm, whereas its outer diameter and wall thickness gradually decrease with the height (Nordahlia et al 2012). Generally, the mechanical properties of *Dendrocalamus giganteus* culms increased with increasing age and increasing culm height (Zhang 1999; Wu 2008).

The experimental investigations presented in this article aim at identifying and quantifying such effects of bamboo age, height of bamboo, and strand nodes in the core layers on the physical and mechanical properties of OSBs prepared from *Dendrocalamus giganteus* bamboo strands to optimize this new type of OSBs and better exploit the mechanical potential of strand-based engineered wood products. In addition, the use of two kinds of adhesives brings about the exceptional chance to quantitatively compare the influence of different parameters on the durability property of strand boards. The advantage of MDI is the strong bond it forms with the wood strands, which results in a tough construction at the pressing stage. Phenol-formaldehyde (PF) resin was reported to be the most efficient in minimizing water absorption and thickness swelling (TS) under wet conditions, excellent heat and flame resistance, and electrical insulation (Chowdhury and Yadama 2011; Liu et al 2016). Exploring the MDI/PF copolymer system improves not only the physical and mechanical properties, but also excellent heat resistance of strand board.

MATERIALS AND METHODS

Materials

Bamboo (*Dendrocalamus giganteus*) were collected from Mangshi, Yunnan, China. The outer diameter of these culms ranged from 15-20 cm (bottom) to 7-11 cm (top), suitable for structural elements. The diameter at breast height was 15.7 cm, with an average culm wall thickness of 11-14 mm at this height. Three age groups (2, 4, and 6 yr) were chosen to represent the young and mature culms. Bamboo matures at 3 yr. At the age of 2 yr and and younger, they are considered young (Liese and Weiner 1997; Norul Hishamam 2006). The bamboo culms were cut 20 cm above the ground. Each culm was cut to a length of 20-30 m leaving out the top part with branches. The culms were later subdivided into three equal lengths of basal, middle, and top portions each. Emulsion polymer isocyanate adhesive and Phenol-formaldehyde resin obtained from commercial market (from Taier Corporation, Beijing, China) were used as adhesives.

Strand production. No attempt was made to remove the epidermis of the bamboo culms. The culms were crosscut into 140-150-mm long segments and then cut into thin pieces in the radial direction using a strand disc-flaker. Target strand dimensions were 150 mm long, 0.8 mm thick, and uncertainly wide. All strands were then dried in a 70°C rotary dryer to an MC of less than 5%. To determine the geometry of the strands, 30 strands from each group were randomly selected. A caliper with a precision of 0.01 mm was used to measure the length, width, and thickness of the strands.

Fabrication of OSB panels. The classified strands from each of the five strand types were formed into OSB panels. OSBs were produced with the dimensions of $700 \times 700 \times 12$ mm^3 and the target density of 0.8 g/cm^3. Commercial MDI adhesive was used to bond the strands to OSBs with a spreading rate of 6% based on the oven-dry mass of the strand. A rotary drum blender was used for mixing the strand and adhesive. The OSB layers were hand formed with the strands of each layer aligned parallel to one another but perpendicular to strands in adjacent layers indicated in Fig 1. Especially, one of the boards (type 6node) was fabricated matching set of board with noded strands in the core layer. Among them, type 6PF/MDI was mixed with PF and strands before adding MDI to strands, and PF was diluted with water to a solids content of 35%. The proportion of relative strand mass used for each layer was 20%. The board was hot pressed at 160, 25 kg/cm^2 pressure for 15 min. After that, the board was conditioned for 10 d in a room adjusted at 25-30% and 60-65% RH.

The produced boards differed in the bamboo ages, bamboo zones, bamboo age, height of bamboo, strand nodes in the core layers and applying adhesives, specific experiment design is presented in Table 1.

Methods

Determination of physical and mechanical properties. Before testing, the boards were conditioned in a room at an RH of 65% and a temperature of 25°C. The board parameters measured were air-dry density, TS, MOR, MOE, and internal bond (IB) in accordance with Chinese National Standard GB17657-2013 and CSA O437.0-2011. Sample size and quantity are shown in Table 2. With its initial 2-h and 24-h submersion period, it provides information on the

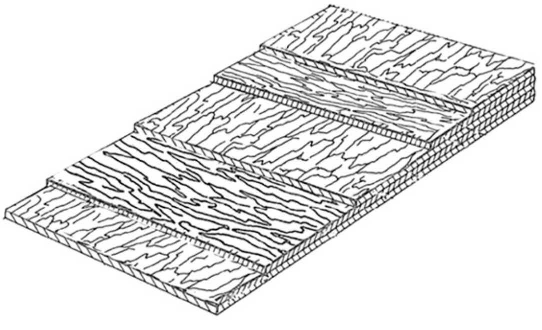

Figure 1. Strand alignment pattern.

Table 1. Specification for board manufacture.

Experiment design	Board type	Adhesives	Age/yr	Height of bamboo	Surface/core strands	Replicates
Various age of bamboo	2	MDI	2	Middle	Internode/Internode	3
	4	MDI	4	Middle		3
	6	MDI	6	Middle		3
Various parts of bamboo pole	6top	MDI	6	Top	Internode/Internode	3
	6bottom	MDI	6	Bottom		3
With node	6node	MDI	6	Middle	Internode/ node	3
Various type of adhesive	6MDI/PF	MDI and PF	6	Middle	Internode/internode	3

PF, phenol-formaldehyde.

short-term and long-term (2 h + 22 h) TS performance.

Determination of durability property. At the present time, most of the information concerning durability of materials is collected from so-called "short-term accelerated aging tests" to expose specimens to selected conditions, followed by determination of the rate of loss of important mechanical properties (Kajita et al 1991; Fu et al 2014). In this article, the durability of OSBs was evaluated by measuring thickness changes and MOE retention after these accelerated aging tests under the standard of GB17657-2013. The bending test was performed using an Instron 5582 (Instron Corporation, Norwood, MA) mechanical testing machine to investigate the effects of aging time on the change of MOE at two kinds of boards (type 6 and 6PF/MDI in Table 1) with two different adhesives. The test times were 0, 2, 6, 12, 18, 22, and 24 h after immersing the boards in 100°C water for 24 h totally. Also, MOR of both boards after the last boiling process was tested to estimate the change of strength.

Data analysis. The effects of clone on board properties were analyzed by covariate analysis of variance (ANOVA) models to account for the underlying effect of board specimen age, height, node, and adhesive on most properties. The effects of board type on physical and mechanical properties were assessed using single-factor ANOVA, using a 5% probability level. All statistical calculations were performed on IBM SPSS Statistics Version 21 (IBM Corporation, Armonk, NY).

RESULTS AND DISCUSSION

Strand Geometry/Dimensions and Shape Factors for Strand Types

Strand geometry was a key parameter affecting both bamboo board properties and the manufacturing process (Nishimura et al 2004). It had a definite relationship with the compression ratio and influenced the density of the composite board. Table 3 summarizes the mean values of the lengths, widths, thicknesses, density, and aspect ratio. The lengths and thicknesses of strands from various ages of bamboo was approximately the same on account of the same parameter for technical design. Nonetheless, it was also indicated that the width of the strand in various parts of the same bamboo pole was obviously decreased as bamboo height increased. This mainly depended on the culm wall thickness, which significantly

Table 2. Sample size and quantity.

Property	Unit	Size of test specimen (mm)	Number of specimens per board
Density	g/cm^3	50×50	3
TS (2 h and 24 h)	%	50	6
MOR	MPa	$75 \times (50 + 20t)$	$6\|6\perp$
MOE	GPa	$75 \times (50 + 20t)$	$6\|6\perp$
IB	MPa	50×50	6

TS, thickness swelling; IB, internal bond; $\|$, parallel to the surface strands direction; $\perp$, perpendicular to the surface strands direction; "t" is the nominal thickness in millimeters.

Table 3. Dimensions and shape factors of strands.

	Parameter				
Board type	Length (mm)	Width (mm)	Thickness (mm)	Density (g·cm^{-3})	Aspect ratio
2	142.15 (1.59)	16.95 (8.98)	0.76 (0.34)	0.49 (0.10)	10.14 (4.16)
4	139.82 (7.70)	16.82 (6.69)	0.69 (0.28)	0.50 (0.11)	9.61 (3.91)
6	142.49 (2.05)	16.41 (8.14)	0.68 (0.23)	0.46 (0.10)	8.68 (0.25)
6top	141.35 (4.23)	10.37 (3.61)	0.75 (0.28)	0.61 (0.13)	14.83 (4.03)
6down	137.49 (16.58)	21.96 (8.25)	0.75 (0.27)	0.47 (0.11)	7.08 (7.15)

Values in parentheses are standard deviation.

decreased from the bottom to the top part. Also, air-dry density significantly increased from the bottom to the top of the culm. The mean aspect ratio was 10.14, 9.61, 8.68, 14.83, and 7.08 for board types 2, 4, 6, 6top, and 6bottom, respectively. According to Febrianto et al (2015), a strand aspect ratio of more than 7 was enough to produce an OSB with excellent poperies.

Effects of Bamboo Age on Density, TS, MOR, MOE and IB

As shown in Table 4, specimens of various bamboo ages show similar values of air-dry density, TS, MOR, MOE, and IB, parallel and perpendicular to the surface strand direction. The similar TS performance possibly resulted from no substantial distinctions of air-dry density among three different culms as shown in Table 3. The TS (24 h) of three kinds of boards made without wax were lower than the maximum 15% TS required by CSA O437.0 for industrial OSB products. Similar results appeared in previous research for bamboo OSB (Semple et al 2015; Sumardi et al 2015). It suggested that natural hydrophobic substances such as silica in the bamboo strands likely contributed to the much greater dimensional stability of the bamboo OSB.

In addition, no significant difference in MOR and MOE illustrated that late-stage technical processing technology had great influence on the bending performance of boards (Zhang et al 1998). Because the elastic modulus and strength in bending was crucially affected by the strand orientation and the degree of compaction in the outer layers, thin parallel surface layers as in boards may be sufficient to obtain a higher elastic modulus in bending in the strand orientation direction of these layers (Stürzenbecher et al 2010). Although the ANOVA test showed that there was no significant difference between the three ages, the MOR values in parallel to the grain direction of OSB tend to increase with increasing age. Moreover, Table 4 shows that the IB of boards made of 6-yr-old culm is higher than 2- and 4-yr-old culms. The difference observed for MOR and IB with age was possibly because of the relationship of these properties

Table 4. Average values for measured physical and mechanical properties oriented strand board.

	Physical and mechanical properties							
		Thickness swelling (%)		MOR (MPa)		MOE (MPa)		
Board type	Density (g·cm^{-3})	2 h	24 h	∥	⊥	∥	⊥	Internal bond (MPa)
2	0.85a	4.84%a	9.23%a	98.95a,b	36.82a	12.41a	2.58a	1.63b
4	0.83a	6.60%a	11.90%a	105.44a,b	43.02a	12.08a	3.06a	1.75b
6	0.85a	3.82%a	7.58%a	118.30a	46.02a	12.05a	3.02a	2.24a
6top	0.85a	6.71%a	11.54%a	79.5b,c	33.5a	10.73a	2.78a	1.89a,b
6bottom	0.78a	4.91%a	9.79%a	65.25d	40.51a	7.672b	2.48a	1.13c
6node	0.85a	5.89%a	11.80%a	80.98c,d	42.85a	11.06a	3.28a	1.02c
6MDI/PF	0.83a	2.89%b	4.89%b	124.55a	51.50a	13.27a	3.35a	2.37a

p: 0.05. Homogeneity group: Same letters in each column indicate that there is no significant difference between the samples according to Duncan's multiple range test with typical anatomical features and fiber morphology of such species (Febrianto et al 2015). For example, fiber length has been reported to influence the physical and mechanical properties of the material and was often associated with its toughness, workability, and durability (Nordahlia et al 2012). The older the culm was, the longer fiber length of the strands were, which may ultimately manifest as high mechanical performance of some OSBs.

Effects of Bamboo Height on Density, TS, MOR and MOE

The mean values of density, TS, MOR, MOE, and IB of OSBs prepared from various heights of bamboo are presented in Table 4. It is clear that type 6 had the best parallel MOR and IB. Although Nishimura et al (2004) have reached the conclusions that long slender strands of wood produce panels that are significantly stiffer (MOE) and stronger (MOR) than wide strands which were not suitable for OSBs used in different positions of bamboo for strands. The reason for this poor performance of 6bottom and 6up is mainly due to the structural differences. For type 6up, with bamboo epidermis increasing on top, the adhesive was possibly incapable of deeper penetration; it will not provide sufficient bonding strength and will affect the bond strength of bamboo OSBs (Sumardi et al 2015). Moreover, narrow strands have more space to rotate in the course of paving, resulting in a greater degree of disorientation and more void space. The type 6bottom had the lowest parallel MOR, MOE, and IB which may be attributed to the effect of the microscopic structure of strands. The tissue of the bamboo culm consists of fiber-like structural features known as vascular bundles and parenchyma cells. In strands originating from the bottom internodes of bamboo, it is composed of more parenchyma cells with lower specific gravity which might inhibit surface attachment of the glue to the bamboo cells. And decreasing the volume fraction of fiber leads to impaired mechanical properties because bamboo fiber has better mechanical properties than the parenchyma cells and vessels (Yu 2014).

According to the comparative analysis of properties in Table 4, OSBs prepared in different heights showed similar values of air-dry density, TS, and perpendicular MOR and MOE. The difference of strand microstructure and strand width went over without obvious variation of dimensional stability and perpendicular bending properties. Also, similar perpendicular MOR and MOE suggested that once the strong overriding effect of surface strand orientation in the loading direction was removed, the composition of the core significantly affected perpendicular MOR and MOE.

Effects of Bamboo Nodes on Density, TS, MOR, and MOE

The presence of nodes on the strands has a pronounced effect on the mechanical properties of bamboo OSBs by the comparison of test results of type 6 and 6node, respectively, throughout certain test types and both testing directions in Table 4. The presence of nodes on the strands in the core layer significantly reduced the parallel MOR (80.93 MPa) and IB (1.02 MPa). Boards with nodes exhibited lower strength and internal bonding values because node tissue was weaker and could decrease the consolidation and strength properties of laminated composites made from bamboo (Shao et al 2010). The result of this article for parallel MOR and IB values was not in agreement with that of Semple et al (2015) that the node strand effect on parallel MOR and IB was very minimal and not statistically significant. The different results generated by various studies may be because of the different raw materials used of various node strand characteristics (Cheng et al 2007). In addition, it showed that nodes in bamboo strands (type 6node) had no effect on TS, and perpendicular MOR and MOE which was consistent with Semple et al (2015). Although nodes were present in the core layers, the average TS, MOR, MOE, and IB for board type 6node exceeded the values required for industrial OSB products by CSA O437.0 (2011) (grade O-2).

Effects of Adhesives on Physical and Mechanical Properties and Durability of OSBs

Results of physical, mechanical, and durability tests on board type 6 and type 6PF/MDI used in this study are shown in Table 4 and Fig 2. A mixture of PF and MDI resulted in lower TS of specimens after immersion in cold and hot water. Blending the strands with PF first gave rise to better adhesion between the strands and the adhesive restricted water absorption of the specimen to some extent. Moreover, the values of parallel MOR and MOE of type 6PF/MDI were greater, but it was not statistically significant between the two kinds of boards. Before boiling treatment, both boards had similar TS, MOR, and MOE which showed that the application of extra PF hardly improved the mechanical performance of the bamboo OSBs.

In this article, the durability of boards was evaluated by measuring thickness changes and MOE retention after these accelerated aging tests. The results of TS and MOE retention at the end of each cycle of the different accelerated aging tests are summarized in Fig 2. TS values of both boards increased gradually during successive cycles, with the values for 6PF/MDI-board being less than those for the 6-board. The value of parallel and perpendicular MOE retention in this test is relatively high, and after the first cycle amounts to about 50% of the original strength for both boards. Much of the decrease in MOE retention occurred in the first cycle, and the rate of decrease became less in subsequent cycles. Concerning MOE retention, remarkable differences were found between 6PF/MDI- and 6-boards in cycles; MOE retention of the 6PF/MDI-board was remarkably higher that of the 6-board.

It was clear from this Figure that the adhesives used in producing the boards exerted a noticeable effect on TS and MOE retention. The results also showed clearly that PF/MDI-boards were more durable than the 6-board. It was also reported in previous studies that phenolic resin and isocyanates mixed boards were not especially susceptible to steam or boil treatments (Kajita et al 1991). It may be because phenolic resin penetrated into the lumens of thin-walled cells such as vessels and parenchyma cells through the cracks caused by de-fibering during the immers process, thus forming glue nails in the cell cavity. These glue nails fix the intensively distributed parenchymal cells tightly. These glue nails link fiber and fiber, fiber and parenchyma cells, and parenchyma cells and parenchyma cells; such links enhance the interfacial properties of the intercellular layer, improve the stress transfer among fibers, and develop the dimensional stability and load-carrying property of OSB effectively (Yu 2014).

CONCLUSIONS

All the properties of OSBs discussed in this study were not affected by age except IB which was higher in board type 6 because of the microscopic structure. In terms of culm height, it affected most of the properties in the boards because of the

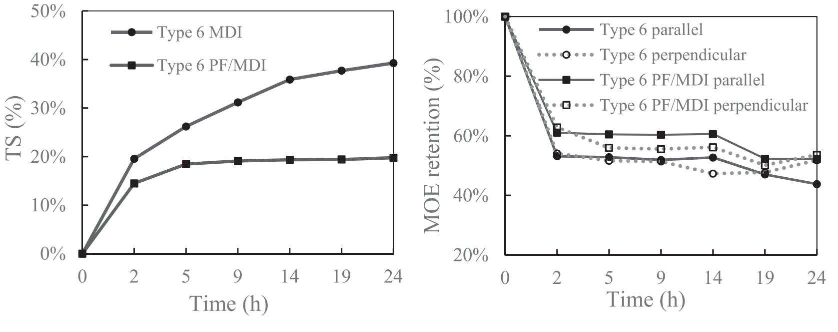

Figure 2. Thickness swelling (TS) and MOE retention of both boards in the successive boiling tests. PF, phenol-formaldehyde.

different geometry and microstructure of strands. Board type 6 possessed preferable physical and mechanical properties compared with those of board type 6up and 6down. The presence of nodes on the strands in the core layer significantly reduced the parallel MOR and IB, but the average MOR, MOE, and IB for board type 6node still far exceeded the values required for industrial OSB products by CSA O437.0.

In all the tested specimens in this study, the TS (24 h) of boards made without wax were lower than the maximum 15% TS required by CSA O437.0 for industrial OSB products. This suggested that bamboo OSBs (*Dendrocalamus giganteus*) with five-layer assembly structure enhanced the structural integrity of composites and offered superior dimensional stability. Moreover, the board made from the 6-yr-old middle culm was provided with superior stiffness and strength which could extend the range of application from sheetings to load-bearing constructional elements. Because most properties of OSBs in the study were not influenced by age, there was no need to fabricate boards by age.

Phenol/isocyanate mixed bonded boards (type 6PF/MDI) had less TS and higher MOE retention than isocyanate only bonded boards (type 6) when strands boards were subjected to boil treatments. This proved that it could be considered as a potentially suitable raw material for moisture/heat-resistant panel for these specific applications.

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