Building Tomorrow's Society
Bâtir la Société de Demain

Fredericton, Canada
June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

DEVELOPMENT OF LIGHTWEIGHT OVERLAID LAMINATED BAMBOO LUMBER FOR STRUCTURAL APPLICATIONS

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Abstract: The overlaid laminated bamboo lumber (OLBL) was developed for structural applications with an aim to substitute commonly-used building materials such as steel and concrete. The OLBL was, via a hot press, fabricated by cross-laminating bamboo layers, bamboo mats and phenolic impregnated adhesive papers. Since the weight of OLBL was governed by the high density bamboo layer, the panels made of OLBL had a relatively high density value of about 850 kg/m^3. In this study, a lightweight panel was developed by a proper arrangement of radial bamboo curtain. The major and minor directions of a panel were the parallel- and perpendicular-to-its length direction, respectively. It was found that 1) the density of an OLBL panel could be reduced by about 20%; 2) the failure occurred in the bamboo node(s); 3) there was a significant difference in modulus of elasticity and modulus of rupture between two panel directions; and 4) there was a good relationship between the density and strength in the minor direction.

1 INTRODUCTION

Formwork is an indispensable construction approach in buildings and bridges, which are usually made of steel, wood-based materials and bamboo-based materials (Smith and Hinze, 2009). The steel formwork is costly due to overweight. The wood-based formwork has the best performance, however the available resource is limited due to the restriction of deforestation (Hurd, 1998). Therefore, the bamboo-based formwork becomes an effective alternative material (Pallett, 1994). Bamboo, a fast growth plant of suitable characteristics for making formwork, is a superior resource to offset restricted supply of timber (Ni et al, 2016). The substantial density of bamboo is approximately 1.5 g/cm^3 similar to wood substance. The tensile strength of bamboo without node in the parallel-to-grain direction is twice as high as that of wood, and almost 3 times higher than that of common steel per unit weight. In order to meet the strength requirements of constructing buildings and bridges, the density of bamboo-based formwork is required up to 1.0g/cm^3. It is well known, however, that the density of the material used has a significant impact on the cost of the formwork made of. As for the concreting practice, the formwork material takes about 6.0% of the total cost, and the formwork labor associated with the installation and removal accounts for 46.7% of the total cost (Baxi, 2011). That is why the reduction of the formwork density has been increasingly drawing attention.

Due to the shape of bamboo materials, the bamboo-based formwork can be sorted into five categories, bamboo mat plywood, bamboo curtain plywood, bamboo particleboard, laminated bamboo lumber and laminated bamboo composite lumber (Jiang et al. 2002). To meet the surface properties of formwork, the overlaid laminated bamboo lumber (OLBL) is preferred. However, the absorption ability of bamboo-based formwork to concrete is less than one-seventh of that to steel formwork (Akmaluddin et al. 2015). Moreover, since the thermal conductivity coefficient of OLBL is quite small, it is suitable to be used in the region of a large day-night temperature fluctuation (Shah et al, 2016). OLBL is also easy of being processed into a variety of shapes.

On the other hand, although the manufacturing parameters, such as hot-pressing parameters and raw material characteristics, of making OLBL have been carried out by many researchers (Sharma et al, 2015; Yang et al. 2016; Mahdavi et al, 2011), the issue on the overweight of end products made of OLBL has not been fully resolved, calling for further research.

It is widely known that bamboo has poor surface properties, resulting in difficulties of adhesively bonding, and furthermore the quality of its final products. The previous studies by the first author's research team suggested that the cold plasma could be used to improve the surface activation of bamboo (Wu et al, 2017).

This study was aimed to reduce the density by optimizing the assembly of OLBL panels of satisfied mechanical properties for formwork application. OLBL used in this study was fabricated by bamboo mat, tangential bamboo curtain, radial bamboo curtain and phenolic impregnated adhesive paper.

2 MATERIALS AND METHODS

2.1 Specimen Preparation

Bamboo mat, tangential bamboo curtain and radial bamboo curtain were treated by oxygen-cold plasma at 60 W for 90 s. Considering the timeliness of processing, the post processing were done within three days. Modified bamboo mat and bamboo curtain were then dipped in phenol-formaldehyde resin adhesive for three minutes. After that, impregnated bamboo was dried to 12% moisture content in an oven. Finally, five-type layups were prepared, Table1 and Figure 1. It is noted that the major and minor directions of a panel were the parallel- and perpendicular-to-its length direction, respectively.

Table 1: Layups of OLBL specimens

Specimen ID	Layup	Layer orientation
9-A	P-M-T-R-R-R-T-M-P	//-//-//-⊥-//-⊥-//-//-//
9-B	P-M-T-R-RS-R-T-M-P	//-//-//-⊥-//-⊥-//-//-//
9-C	P-M-T-RS-R-RS-T-M-P	//-//-//-⊥-//-⊥-//-//-//
9-D	P-M-T-RS-RS-RS-T-M-P	//-//-//-⊥-//-⊥-//-//-//
9-E	P-M-T-RS'-RS'-RS'-T-M-P	//-//-//-⊥-//-⊥-//-//-//

Note: P stands for phenolic impregnated adhesive paper, M for bamboo mat, T for tangential bamboo curtain, R for radial bamboo curtain with 0 mm spacing, RS for radial bamboo curtain with 3 mm spacing, RS' for radial bamboo curtain with 5 mm spacing, // for parallel, and ⊥ for perpendicular to major strength direction.

The OLBL was manufactured by a so-called "cold-in and cold-out" hot-pressing method. The mat was put in the press at an initial temperature of 50°C, held at 138°C and 1.28 MPa for 16 min, and taken out after opening of the press. All the specimens were then conditioned at a relative humidity of 65±5% and a temperature of 20±3°C until reaching the constant weight.

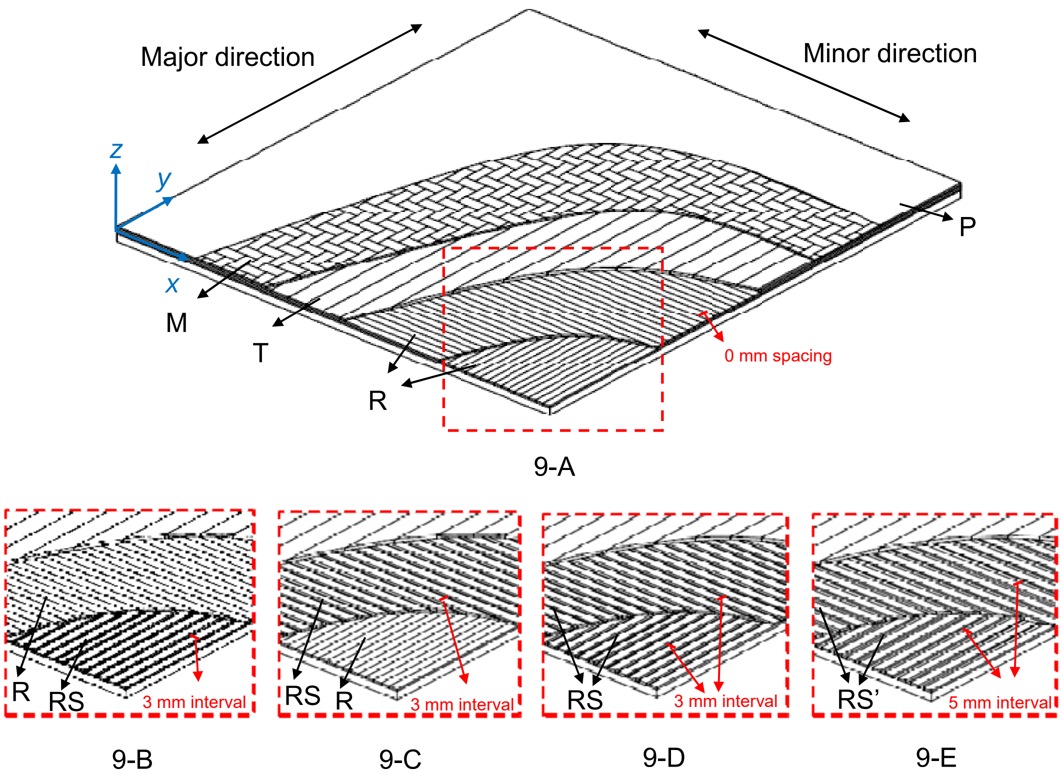

Figure1: A mirrored sketch of the five-type layups along the *x* axis

2.2 Testing Properties

The physics and mechanics properties of OLBL were tested based on JG/T 156-2004 *Plybamboo Form* (JG, 2004) and GB/T 17657-2013 *Test Methods of Evaluating the Properties of Wood-based Panels and Surface Decorated Wood-based Panels* (GB, 2013). The properties tested included density, moisture content, strength and elasticity. The testing methods used, properties tested and number of replicates of each test were given in Table 2. The length directions of small clear specimens were in the parallel- and perpendicular-to-the-length-direction of the OLBL panels, which were tested for the modulus of rupture (MOR) and modulus of elasticity (MOE). The random direction of small clear specimens was used for testing other properties.

3 RESULTS AND DISCUSSION

3.1 Density

Table 3 summarizes the density values of five groups of OLBL specimens. The density gradually decreases from group 9-A to 9-E, which was accredited to the increased porosity ranging from 0.0% to 19.0%. Compared with the traditional layup (9-A), the density values of groups 9-B, 9-C, 9-D and 9-E decreases by 8.75%, 15.00%, 21.25% and 27.50%, respectively. It can be also found that the coefficients of variance (COVs) of all five groups were relatively low, ranging from 6.25% to 14.15%.

Table 2: Methods for testing properties and specimen dimensions

Test method	Direction	*n*	Specimen size (mm) (Thickness × width × length)
Centre point bending	Major	8	12×75×250
	Minor	8	12×75×250
Centre point bending under the cyclic boil, freeze and dry treatment	Major	8	12×75×250
	Minor	8	12×75×250
Impact bending	Random	8	12×20×300
Bonding strength	Random	8	12×75×75

Table 3: Density of different layups

		9-A	9-B	9-C	9-D	9-E
Porosity (%)		0	5.0	9.0	13.0	19.0
Density	Average (g/cm^3)	0.80	0.73	0.68	0.63	0.58
	COVs (%)	8.79	13.78	6.25	12.66	14.15

3.2 MOE and MOR

The results of five types of OLBL panels studied are given in Figures 2 to 4, in which the MOE results in Figure 4 are from those specimens experiencing under the cyclic boil, freeze and dry treatments. It was found that the results largely met the standard requirements except the MOR and MOE of group 9-E. Generally speaking, MOR and MOE in the major or minor direction of a group of panels gradually decreased with decreasing density. The values of group 9-B was a slight larger than that of 9-C. This might be due to spaced arrangement of radial bamboo curtain, some of which were complemented one another during hot pressing. Accordingly, the thickness was smaller (11.5 mm on average) than others (from 11.9 mm to 12.5 mm). However, there existed an obvious difference in MOE and MOR between groups 9-D and 9-E. The MOR in both major and minor directions decreased markedly when the spacing reached up to 5mm. The MOR in the major direction was about 20% larger than that in the minor direction, and it was more than 30% larger than that under the cyclic boil, freeze and dry treatments. The difference in MOR between two directions had an increasing trend with decreasing density. It was also found that the density had a significant impact on MOR in the major direction than that in the minor direction. The reason was mainly due to on the radial bamboo curtain that controlled the performance of OLBL panels, in which two layer numbers were in the minor direction and one in the major direction, producing more porosity, and furthermore lower the density of the panels in their minor direction.

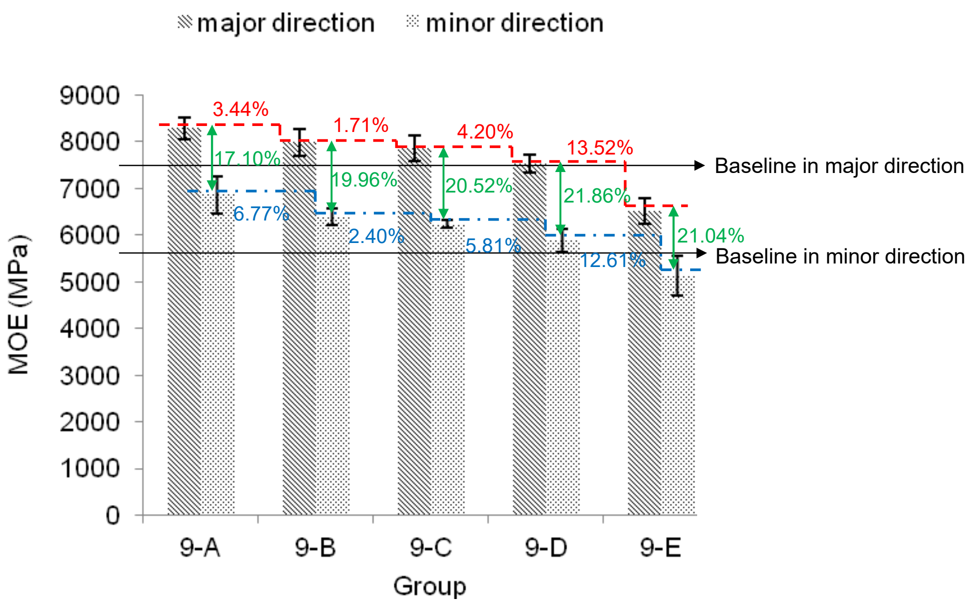

Figure 2: MOE in the major and minor directions (Error bars represent standard deviations. The baselines represent the required values stipulated in the Standard "*Plybamboo Form*".)

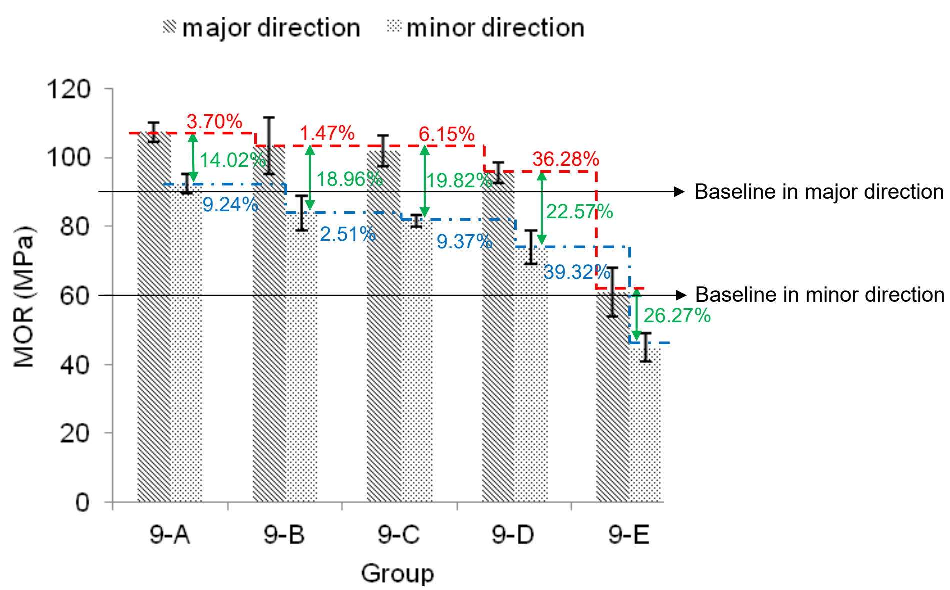

Figure 3: MOR in the major and minor directions (Error bars represent standard deviations. The baselines represent the required values stipulated in the Standard "*Plybamboo Form*".)

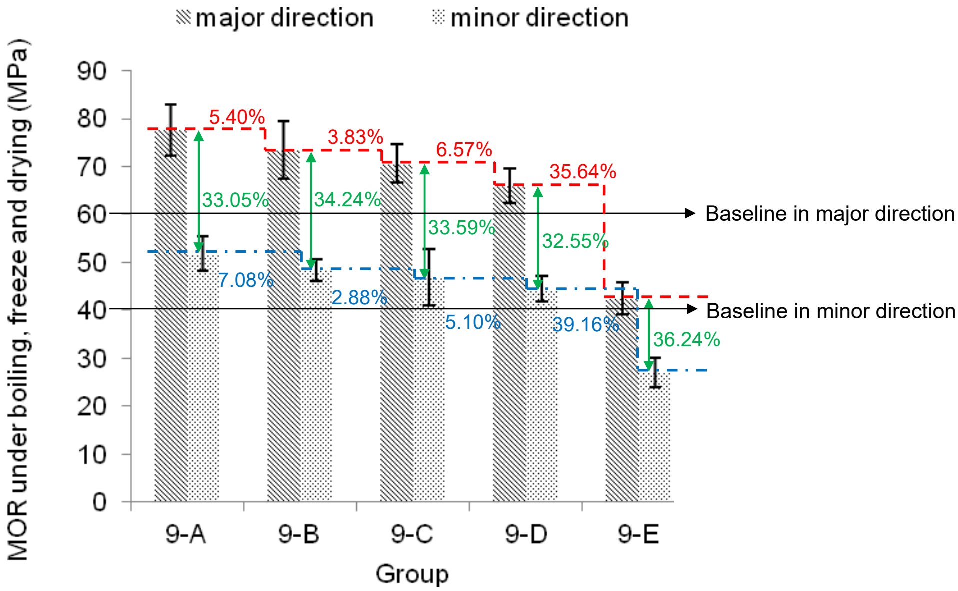

Figure 4: MOE in the major and minor directions of those panels tested under the cyclic boil, freeze and dry treatments (Error bars represent standard deviations. The baselines represent the required values stipulated in the Standard "*Plybamboo Form*".)

Figure 5 illustrates such a failure pattern, which was, during testing, observed in all the specimens tested. A specimen started cracking from the node at the tension side of a specimen, then the crack(s) propagated through the nearest node of bamboo curtain, and finally fractured in the form of splintering tension that was independent on the direction of panels. For those readers who are not familiar to bamboo, the bamboo node is one unique growth characteristic of bamboo in 'ring' shape. But the low density and irregular vascular bundle arrangement was the weakness region of strength properties.

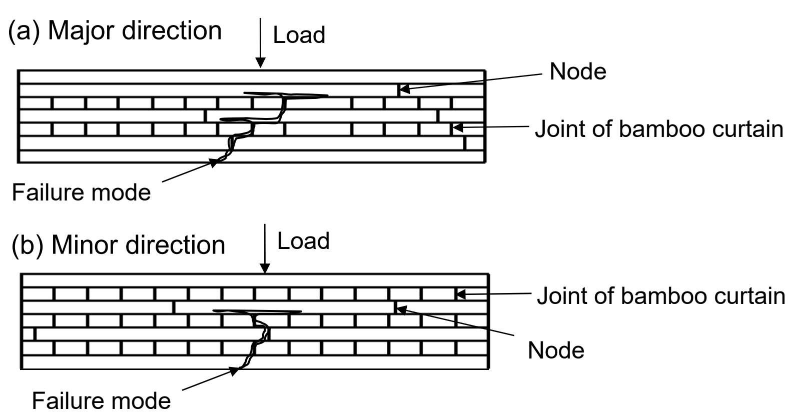

Figure 5: Failure modes of the specimens tested in the major (a) and minor (b) directions.

3.3 Impact Strength

Impact strength values of OLBL with different layups are showed in Figure 6. Impact strength of the specimens tested was smaller when the density became lower, which was decreased sharply in those specimens of 5 mm gaps. Considering the structure, the number of curtains in the major direction was more than that in the minor direction. Therefore, the impact strength was no doubt be larger in the major direction than in the minor direction. It was also discovered that the random samples had great variability (large standard deviation in Figure 6 such as group 9-E) of impact strength. However, the average impact strength in the major direction and minor direction was used as reference value in end use of formwork.

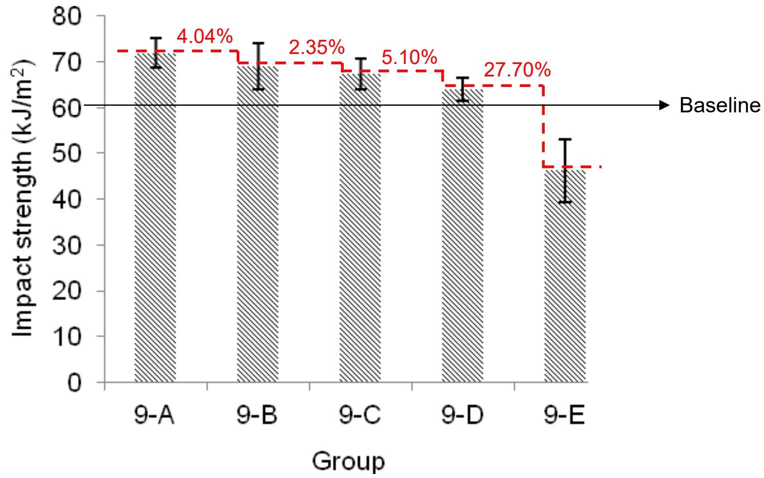

Figure 6: Impact strength (Error bars represent standard deviations. The baseline represents the required value stipulated in the Standard "*Plybamboo Form*".)

3.4 Bonding Strength

The bonding strength values of five groups are illustrated in Figure 7. The COV was higher in groups 9-B, 9-C, 9-D and 9-E related to specimens collection. This was due to the intervals in the radial bamboo curtain which resulted in heterogeneity during hot pressing. There was great compressibility in a closely overlap region with high bonding strength (Anuj et al, 2016). The effective pressure in the region of gaps would be reduced, which led to low bonding strength. In summary, it was found that the bonding strength of all the five groups conformed to the standard "*Plybamboo Form*" (2004) requirements.

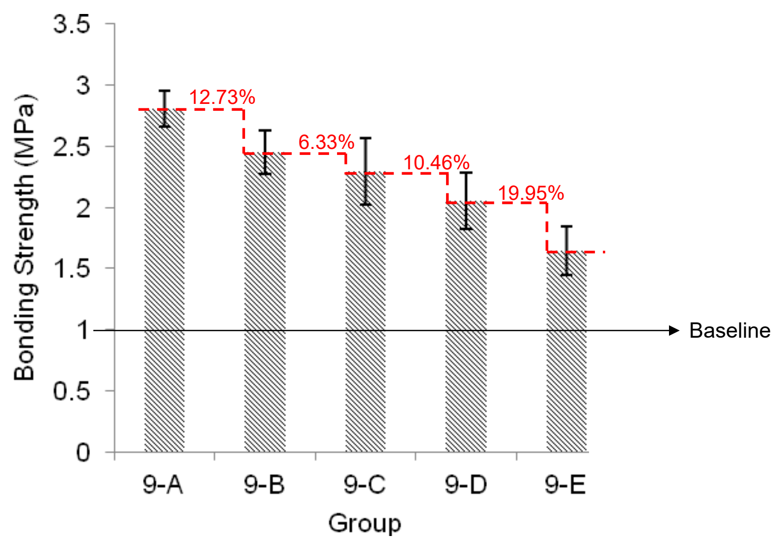

Figure 7: Bonding strength of OLBL specimens (Error bars represent standard deviations. The baseline represents the required value stipulated in the Standard "*Plybamboo Form*".)

4 CONCLUSIONS

The mechanical properties of OLBL decreased with decreasing the density, which including the MOE, MOR, impact strength and bonding strength. Group 9-D was found to be the optimal layup, the density of which was reduced by about 20% compared with traditional layup without reducing the MOE and MOR in both major and minor directions, MOR in both major and minor directions after treatments of boiling, freeze and drying, and impact strength in random direction. The failure of a OLBL specimen appeared in the bamboo node(s) first and then the bamboo joint(s).

The MOE, MOR, impact strength and bonding strength of OLBL could meet the required values stipulated in the Standard "*Plybamboo Form*". This suggests the lightweight OLBL developed in this study was feasible to be used as formwork in construction applications.

Acknowledgements

This study was supported by Fujian Major Special Projects (China) under its program "Research and Industrialization of Key Technology of Bamboo Energy Conservation Processing and Utilization for Higher Value" (Grant No.2014NZ0003-1), Natural Sciences and Engineering Research Council (CSERC) of Canada (Grant #: RGPIN 2017-03994), and New Brunswick Innovation Foundation under its Research Innovation Chair Program in Advanced Wood Products and Construction.

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