Properties of Cross-laminated Oriented Bamboo Scrimber Board (CL-OBSB)

Min-Jay Chung,[a] and Sheng-Yang Wang [b,c,d,*]

Physical and mechanical properties were evaluated for cross-laminated oriented bamboo scrimber board (CL-OBSB). Results of non-destructive testing revealed a linear relationship of parallel grain content with ultrasonic-wave velocity, dynamic modulus of elasticity ($DMOE_u$), tap-tone velocity, and $DMOE_t$ values. In terms of the ratio of parallel grain, CL-OBSB $_{80\%(//)}$ possessed the highest modulus of elasticity and modulus of rupture values along with the greatest strength. The high grain content compressed in a parallel direction contributed to superior strength performance. Regarding the perpendicular compressive ($C_\perp$) strength, because both the CL-OBSB $_{40\%(//)}$ configuration and CL-OBSB have a mid-layer consisting of 60% parallel grain, CL-OBSB $_{40\%(//)}$ holds the largest $C_\perp$ value. Furthermore, the shear bond strength (S) showed that the $S_{//}$ value was 1.03 times that of the $S_\perp$ value with a wood failure frequency of 97%. After the dimensional stability test, the water absorption and volumetric swelling of the four CL-OBSB types ranged between 15.3% and 17.7% and 9.5% to 10.6%, respectively. In conclusion, the orthogonal configuration of CL-OBSBs can improve balance expansion and contraction in different directions, thus increasing its dimensional stability.

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Keywords: Cross-laminated oriented bamboo scrimber board (CL-OBSB); Mechanical properties; Dimensional stability

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INTRODUCTION

In the past two decades, reputed as natural and sustainable, timber has become popular and a preferred constructing material for offices, multi-residential buildings, and schools. Another reason for such a return is the development of cross-laminated timber (CLT), a quasi-rigid composite, and plate-like engineered timber. Compared with other composite panels or boards for construction, CLT has broader applications. In addition to flooring, CLT is also used as the structural material for load-bearing and shear walls (Brandner *et al*. 2016). Furthermore, the basic structure of CLT is the same as that of plywood, sandwich, or three-layer solid wood panels. Composed usually of an odd number of layers, from three to seven, of laminated boards laid successively at an angle of 90°, CLT has an orthogonal laminar structure that can withstand in- and out-of-plane loadings (Vessby *et al*. 2009). The CLT has transverse layers bonded together, thus minimizing the risk of swelling and shrinking, which in turn contributes to more excellent dimensional stability (Gsell *et al*. 2007). Moreover, the thickness of CLT enables it to be used as a stand-alone structural element of good strength and stiffness. Other advantageous features of CLT include its large dimensions, ease of handling, and versatile applications (Schickhofer *et al*. 2016).

In addition to the application and development of CLT materials, many countries have also developed methods for applying bamboo as structural materials (Abdul Khalil *et al*. 2012). Bamboo is a “green” natural fiber material that many advanced countries have highly emphasized in recent years. In particular, it has the advantages of rapid growth, a short renewal period, and excellent strength properties. Therefore, bamboo is a renewable and sustainable wood material and an alternative raw material for engineering and wood construction. Moreover, many studies have indicated that oriented bamboo scrimber board (OBSB) has an ideal surface texture, high hardness, excellent mechanical properties, and good longitudinal compressive strength (Wang 1989; Yu and Yu 2013; Sharma *et al*. 2015a, 2015b; Yu *et al*. 2015; Chung and Wang 2018a,b). It can be seen that OBSB is also widely used for flooring, railings, furniture, and as structural materials.

Non-destructive testing (NDT) has been widely applied to examine a tree’s health conditions and to determine the quality of wood composites. In particular, ultrasonic velocity testing has been commonly used in testing the physical properties of wood materials (Mishiro 1996; Yang *et al*. 2008) and laminated bamboo boards (Lin *et al*. 2006; Lee *et al*. 2012). However, up to now, only Chung and Wang (2018a,b) have used the NDT method to evaluate the quality of OBSB. Their studies found that ultrasonic velocity (V_u) and tap-tone velocity (V_t) has a good correlation between wood density, dynamic modulus of elasticity (DMOE), modulus of elasticity (MOE), and modulus of rupture (MOR). Thus, the structural properties of CL-OBSB have not been evaluated using NDT. Given the above, three-year makino bamboo culms were processed into OBSBs, further bonded into three-layer CL-OBSB with different parallel grain content. The NDT properties (V_u and V_t tests), mechanical properties, compressive strength, gluing properties, and dimensional stabilities of these CL-OBSBs were examined in this study. The results of this study can contribute to a better understanding of the various properties of CL-OBSB made from unpeeled makino bamboo-based boards and provide helpful information for the CL-OBSB products used for flooring, railings, furniture, and as structural materials.

EXPERIMENTAL

Materials

Three-year-old makino bamboo culms (*Phyllostachys makinoi*) were collected from the Experimental Forest of National Taiwan University in Nan-Tou County, Taiwan, in September 2018. The harvested makino bamboo culms, unpeeled/with the epidermis, were processed into 2-cm strips. All samples were pre-treated with an alkaline solution containing 4% potassium hydroxide (KOH) at 100 °C for 30 min, rinsed with water, and then oven-dried at 80 °C. For steam-heating treatment (SHT), makino bamboo strips were placed in a steam-heating furnace at 120 °C for 6 h.

This study used a water-soluble binding agent, phenol-formaldehyde resin (PF) (purchased from Wood Glue Industrial Co., Ltd., Tainan, Taiwan), with a solid content of 58.1% and a spreading rate of 200 g/m^2. The weight of bamboo strips and adhesive content used were calculated according to the manufacturing specifications of National Standards of the Republic of China (CNS) 2215 (2017) particleboard. The specifications were as follows: Density at 900 kg/m^3 (SI unit), binding agent at 10 wt% of raw material, and bamboo strips of 45 cm × 45 cm in size; with a thickness of 12 mm when placed into a metal frame with board orientations as illustrated in Fig. 1. The glued bamboo strips then underwent heat compression at 140 °C under 14,710,000 N/m^2 (SI unit) for 12 min, followed by cold compression for 20 min into an OBSB. The number of repeat specimens was 9 (n=9). Three OBSBs were then arranged in alternating orientations (Fig. 1) and thermally compressed into a three-layer CL-OBSB. Before analyzing various physical and chemical properties, the CL-OBSB was acclimatized in a controlled environment with a temperature of 20 °C and a relative humidity (RH) at 65% for 2 weeks. Table 1 shows the compositions and codes of the four CL-OBSB samples analyzed in this study.

Table 1. Four CL-OBSB Samples of Different Compositions and Their Codes

No.	Composition (strip orientation shows //:⊥://)	Parallel Grain Content (%)	Code
1	1:3:1	40	CL-OBSB $_{40\% (//)}$
2	1:2:1	50	CL-OBSB $_{50\% (//)}$
3	1:1:1	67	CL-OBSB $_{67\% (//)}$
4	2:1:2	80	CL-OBSB $_{80\% (//)}$

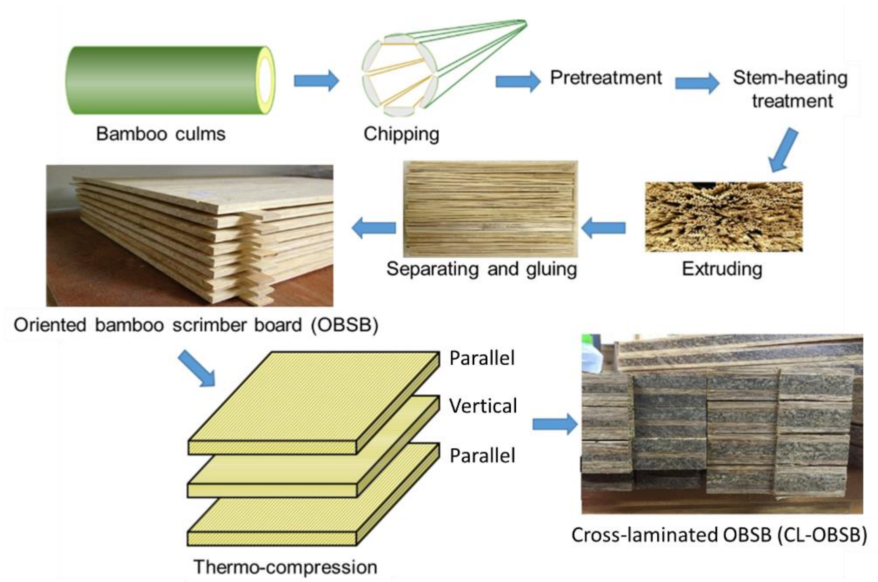

Fig. 1. The manufacturing process of CL-OBSB

Methods

Non-destructive testing (NDT)

Both ultrasonic-wave velocity (V_u) and dynamic modulus of elasticity (DMOE) were measured using a portable ultrasonic non-destructive testing device (Sylvatest Duo, Saint Sulpice, Switzerland) at a frequency of 22 kHz. Specimens were placed between the transmitting and receiving transducers, and the travel time of the ultrasonic wave (transmission time) was recorded. Moreover, the tap-tone velocity (V_t) was measured using a tap-tone analyzer (Multi-purpose FFT analyzer CF-5220, Ono Sokki, Yokohama, Japan). Specimen size was 450 × 50 × 12 mm^3 (length × width × thickness), and each specimen was supported by a piece of foam that was placed at the center and hit on one end with a hard-rubber hammer. The tap tone transmitted from the hit end was received by the microphone placed at the other end. The instantaneously generated sound waveform was decomposed into a spectrum using the fast Fourier transform (FFT) as an accurate measurement of the natural vibration frequency. Then, its sound velocity (V_t) and dynamic elastic modulus ($DMOE_t$) could be calculated.

Mechanical strength

According to the American Society Testing and Materials (ASTM) standard D-1037 (2006), the mechanical strength of CL-OBSB specimens was examined using the static bending test conducted with a universal-type testing machine (Shimadzu UH-10A, Tokyo, Japan) according to the center-loading method for specimens. A concentrated bending load was applied at the center with a span 15 times the thickness of the specimen. Both MOE and MOR were calculated from load-deflection curves.

Compressive and gluing strength

According to the standard of CNS 453 (2013), the compressive strengths of CL-OBSB specimens were examined using the static compression test performed with a universal-type testing machine (Shimadzu UH-10A, Tokyo, Japan) according to the center-loading method for specimens. Specimen size was 30 mm × 30 mm × 60 mm (length × width × height), and loading was applied at 5 mm/min. Both the loads parallel to the direction of the grain ($C_{//}$) and perpendicular to the direction of the grain ($C_{\perp}$) were measured separately. Further, gluing strength, according to CNS 11031 (2014), shear bond strength (S) of specimens with panel texture parallel and perpendicular to the load direction was examined with load applied at a speed of 2 mm/min.

Delamination test

According to CNS 11031 (2014), there are two types of delamination tests; both are conducted in cycles. For the cyclic-dipping test, specimens were immersed in water at room temperature (10 to 25 °C) for 24 h, and then dried in an oven of 70 ± 3 °C for 24 h. For the cyclic-boiling test, specimens were immersed in boiling water at 100 °C for 4 h, then placed in water at room temperature (10 to 25 °C) for 1 h, and finally oven-dried at 70 ± 3 °C for 24 h. The delaminated portion of the glued layer was measured, and the delamination ratio was calculated.

Dimensional stability

The CL-OBSB specimens were tested according to ASTM D1037 (2006) to determine water absorption (WA), thickness swelling (TS), and volumetric swelling (VS). Initial thickness in the middle of the test specimen was first measured with a micrometer. Then, all test specimens were placed in parallel 30 mm under water and soaked for 2 h and 24 h before the thickness was measured again.

Statistical analysis

Data are presented as the mean of nine replicates with standard deviation (SD, presented in parentheses). Differences between experimental specimens were examined using Tukey's test and analysis of variance (ANOVA) with $p < 0.05$ indicating a statistically significant difference. All analyses were performed using the software Statistical Analysis System 8.0 (SAS Institute Inc., Cary, NC, USA).

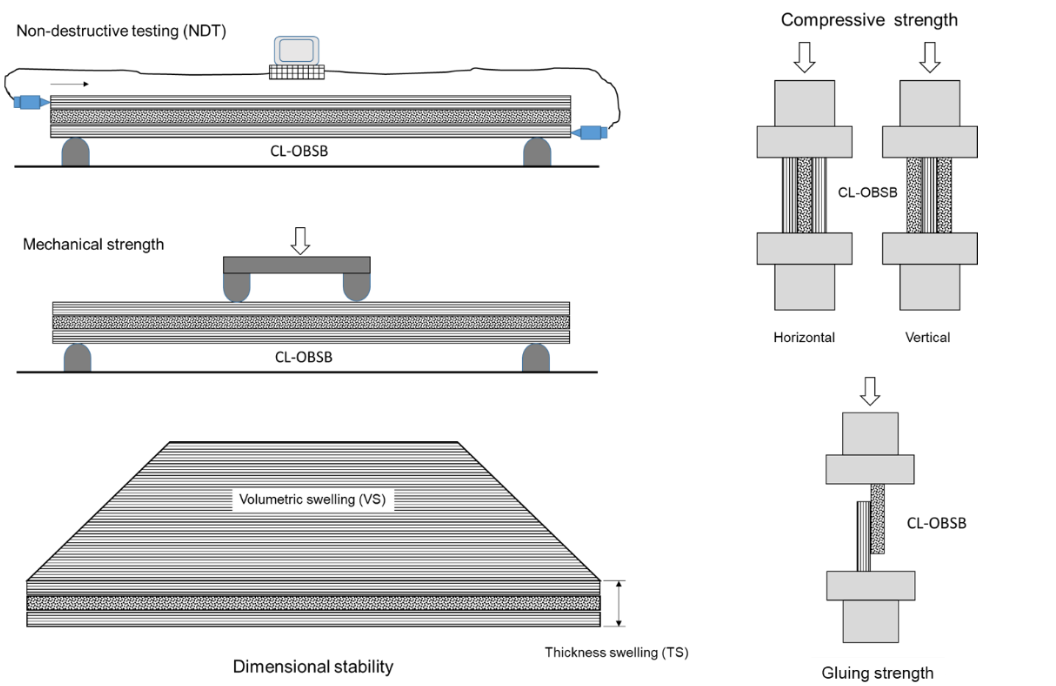

Fig. 2. Determination of various properties

RESULTS AND DISCUSSION

Non-destructive Testing

Measurements of $V_{u(//)}$ at various contents of parallel grain in horizontal orientation were conducted as shown in Table 2, were in the order of CL-OBSB $_{40\% (//)}$ < CL-OBSB $_{50\% (//)}$ < CL-OBSB $_{67\% (//)}$ < CL-OBSB $_{80\% (//)}$, indicating a positive correlation between $V_{u(//)}$ and parallel grain content. In other words, a higher parallel grain content resulted in a higher $V_{u(//)}$ value. The same trend and relationship were observed for DMOE$_u$. This result indicates that in CL-OBSBs, when the top and bottom boards have a parallel grain, it corresponds to the analysis made by Lee *et al*. (2012) of the configurations of parallel configured boards made of moso bamboo in China. Chung and Wang (2018b) stated that when heat-treated *P. makinoi* bamboo is manufactured into OBSBs, its correlational ratio is 100% while the $V_{u(//)}$ is 5780 m/s, which is higher than that of CL-OBSB $_{80\% (//)}$. In addition, Lin *et al.* (2006) employed NDT to evaluate the DMOE and MOE of moso bamboo laminates and showed they have a strong relationship with each other. For measurements of $V_{u(//)}$ at different contents of parallel grain in vertical orientation, the ultrasonic speeds $V_{u(\perp)}$ for CL-OBSB $_{40\% (//)}$, CL-OBSB $_{50\% (//)}$, CL-OBSB $_{67\% (//)}$, and CL-OBSB $_{80\% (//)}$ perpendicular boards were as follows: 3784, 3764, 3234, and 2781 m/s, which indicates parallel board configurations have a higher $V_{u(//)}$ compared to the $V_{u(\perp)}$ value.

Moreover, the DMOE$_{u (//)}$ of CL-OBSB $_{40\% (//)}$, CL-OBSB $_{50\% (//)}$, CL-OBSB $_{67\% (//)}$, and CL-OBSB $_{80\% (//)}$ made from OBSBs and parallel orientation bamboo boards were 23.45, 25.91, 26.44, and 26.94 GPa, respectively, which indicates that CL-OBSBs have higher DMOE$_{u(//)}$ values compared to the DMOE$_{u(\perp)}$ values of parallel orientated bamboo boards that correspond to 14.19, 14.68, 10.66, and 7.81 GPa, respectively. Lee *et al*. (2012) stated that laminates made from moso bamboo from China have a DMOE$_{u(//)}$ of 10.4 GPa. The finding mentioned above indicates that the DMOE$_{u(//)}$ of CL-OBSBs are usually higher than those of laminates. It indicates that the density of CL-OBSBs increases during the process of steam compression. When Wang *et al*. (2008) utilized ultrasonic waves of NDT to measure pine boards from Taiwan Cedar (*Taiwania cryptomerioides*), Japan Cedar (*Cryptomeria japonica*), and Southern Pine (*Pinus* spp.) along with other coniferous timbers, it was seen that the density of each board configuration directly influences the transmission rate.

In contrast, the relationship between the ultrasonic speed (V_t) and $DMOE_{t(//)}$ of CL-OBSB $_{40\% (//)}$, CL-OBSB $_{50\% (//)}$, CL-OBSB $_{67\% (//)}$, and CL-OBSB $_{80\% (//)}$ are shown in Table 2. The $V_{t(//)}$ values of CL-OBSB $_{40\% (//)}$, CL-OBSB $_{50\% (//)}$, CL-OBSB $_{67\% (//)}$, and CL-OBSB $_{80\% (//)}$ were accordingly 3763, 3902, 4375, and 4752 m/s, which shows the fastest transmission rate in CL-OBSB $_{80\% (//)}$ followed by CL-OBSB $_{50\% (//)}$, and CL-OBSB $_{67\% (//)}$; this indicates a strong correlation between board ratios and transmission speed. The $DMOE_{t(//)}$ values of the parallel grain boards were as follows: CL-OBSB $_{40\% (//)}$ (14.36 GPa), CL-OBSB $_{50\% (//)}$ (15.49 GPa), CL-OBSB $_{67\% (//)}$ (20.62 GPa), and CL-OBSB $_{80\% (//)}$ (22.81 GPa); these results correspond to the transmission speeds for $V_{t(//)}$ whereby CL-OBSB $_{80\% (//)}$ showed the greatest resistance to strain while CL-OBSB $_{40\% (//)}$ showed the least. This showed a common pattern between sound velocity (V_t) and dynamic modulus of elasticity ($DMOE_t$), ultrasonic velocity (V_u) and dynamic modulus of elasticity ($DMOE_u$).

Conversely, observing the sound velocity $V_{t(\perp)}$ of boards with a perpendicular grain, the $V_{t(\perp)}$ values were as follows: CL-OBSB $_{40\% (//)}$ (3870 m/s), CL-OBSB $_{50\% (//)}$ (3687 m/s), CL-OBSB $_{67\% (//)}$ (3128 m/s), and CL-OBSB $_{80\% (//)}$ (2580 m/s). Of the $V_{t(\perp)}$ values, CL-OBSB $_{80\% (//)}$ showed the lowest velocity; this is due to CL-OBSB $_{80\% (//)}$ being 80% composed of material that is perpendicular in grain. Additionally, when comparing both types of boards, the $DMOE_{u(//)}$ was larger than $DMOE_{t(\perp)}$. From this, it can be seen that the $DMOE_{u(//)}$ values usually exceeded the $DMOE_{t(//)}$ values. The above analysis results align with the findings of Lee and Yang (2010), where they used NDT to test the bending resistance of 2 m × 6 m and 2 m × 8 m pine laminate; the results showed that the $DMOE_u$ value (17.9%) was larger than the $DMOE_t$ value (13.4%). Similarly, according to the analysis of Wang *et al*. (2008), the utilization of ultrasonic vibration for testing of 2 × 4 timber boards made from various local Taiwanese timbers such as Japanese cedar, Taiwan cedar, and Southern pine along with imported Douglas fir (*Pseudotsuga menziesii*) showed the following correlation: $DMOE_u > DMOE_t > MOE$, thus aligning with the tested boards.

Strength Properties

As shown in Table 2, the average density variation between the four different CL-OBSBs equated to 0.02^a to 0.04^a, which the Tukey's test indicates was an insignificant difference because $p > 0.05$. This also indicates no significant difference between the four different types of CL-OBSBs with a mean difference in density at 1.0 g/cm^3. As shown in Table 2, the $MOE_{(//)}$ values between CL-OBSB $_{40\% (//)}$, CL-OBSB $_{50\% (//)}$, CL-OBSB $_{67\% (//)}$, and CL-OBSB $_{80\% (//)}$ OBSBs and the four different parallel grain CL-OBSBs were as follows: 16.27, 16.66, 18.76, and 22.15 GPa, respectively. According to Tukey's test, CL-OBSB $_{40\% (//)}$, OBSB $_{50\% (//)}$ and CL-OBSB $_{67\% (//)}$ showed an insignificant difference. From the following pattern: CL-OBSB $_{80\% (//)}$ > CL-OBSB $_{67\% (//)}$ ≧ CL-OBSB $_{50\% (//)}$ ≧ CL-OBSB $_{40\% (//)}$, it can be seen that there were similarities between the changes in parallel V_u, $DMOE_u$, V_t, and $DMOE_t$ values across the four CL-OBSBs. Lee *et al*. (2012) stated that parallel-grained structural boards made of China-origin moso bamboo hold a $MOE_{(//)}$ of 9.1 GPa, showing that CL-OBSBs are made of parallel grain OBSBs, a higher MOE value can be obtained than for structural laminate bamboo boards.

As indicated in Table 2, the MOE(┴) of the four different CL-OBSBs were CL-OBSB 40% (//) (5.01 GPa), CL-OBSB 50% (//) (4.01 GPa), CL-OBSB 67% (//) (1.60 GPa), and CL-OBSB 80% (//) (0.81 GPa). Thus, CL-OBSB 67% (//) and CL-OBSB 80% (//) had a MOE value that is lower than those of the China-origin moso bamboo structural boards that hold a MOE(┴) value of 2.6 GPa (Lee *et al*. 2012). In a study conducted by Wang *et al*. (2008), Taiwanese cedar held a MOE value of 9.1 GPa, while Japanese cedar held a MOE value of 9.4 GPa. This shows that parallel grain CL-OBSBs made from timbers from Taiwan hold a higher MOE value, which indicates that the strength from perpendicular grain boards comes largely from the type of adhesive used.

Table 2. Non-destructive and Strength Properties of Different CL-OBSB Combination Styles

Samples	Board Type	ρ (g/cm^3)	V_t (m/s)	V_u (m/s)	DMOE$_t$ (GPa)	DMOE$_u$ (GPa)	MOE (GPa)	MOR (MPa)	Shear Strength (MPa)
H (//)	CL-OBSB 40% (//)	0.99 (0.03) a	3763 (43)	4834 (42)a	14.36 (0.08)	23.45 (1.48)	16.27 (0.38)b	62.01 (2.49) d	7.41 (1.39) *
	CL-OBSB 50% (//)	0.99 (0.03) a	3902 (54)	5059 (35)a	15.49 (0.43)	25.91 (0.46)	16.66 (0.28)b	65.60 (3.65) d	
	CL-OBSB 67% (//)	1.03 (0.04) a	4375 (55)	5079 (49)a	20.62 (1.21)	26.44 (1.44)	18.76 (0.90)b	90.12 (2.78) b	
	CL-OBSB 80% (//)	1.01 (0.04) a	4752 (43)	5165 (31) a	22.81 (0.53)	26.94 (0.50)	22.15 (0.30)a	98.87 (4.72) a	
V (┴)	CL-OBSB 40% (//)	1.00 (0.02) a	3870 (51)	3784 (49)b	15.39 (0.25)	14.19 (0.64)	5.01 (0.34)d	77.05 (7.13) c	7.22 (1.29) *
	CL-OBSB 50% (//)	1.01 (0.02) a	3687 (54)	3764 (59)b	14.13 (0.27)	14.68 (0.59)	4.01 (0.19)d	68.13 (2.93) d	
	CL-OBSB 67% (//)	1.02 (0.02) a	3128 (55)	3234 (44)b	9.98 (0.65)	10.66 (0.38)	1.60 (0.14)e	41.05 (2.42) e	
	CL-OBSB 80% (//)	1.01 (0.02) a	2580 (35)	2781 (42)c	6.72 (0.16)	7.81 (0.24)	0.81 (0.01)f	27.37 (2.00) f	

H: Horizontal to surface bamboo strips direction
V: Vertical to surface bamboo strips direction
Values in parentheses are the standard deviations.
Different letters *, a, b, c, d, e and f in a given column indicate significant differences at the 0.05 level according to the Tukey's test and ANOVA.
ρ, Density; V_t, tap tone velocity; V_u, ultrasonic-wave velocity; DMOE, dynamic modulus of elasticity calculated from V.
MOE, modulus of elasticity; MOR, modulus of rupture

Additionally, Table 2 shows the four different CL-OBSBs, and their MOR(//) values were correspondingly 62.01, 65.60, 90.12, and 98.87 MPa. Tukey's Test shows that CL-OBSB 40% (//) and CL-OBSB 50% (//) did not show a significant difference, while CL-OBSB 67% (//) and CL-OBSB 80% (//) showed a significant difference ($p < 0.05$), which indicates the following relationship: CL-OBSB $_{80\% (//)}$ > CL-OBSB $_{67\% (//)}$ > CL-OBSB $_{50\% (//)}$ ≧ CL-OBSB $_{40\% (//)}$. Because CL-OBSB $_{80\% (//)}$ CL-OBSB contains 80% parallel grain OBSBs, it holds the largest MOR value. Following CL-OBSB $_{80\% (//)}$ is CL-OBSB $_{50\% (//)}$ with only 50% parallel grain and CL-OBSB $_{40\% (//)}$ with 40% parallel grain, which is the reason for their descent in MOR value compared to CL-OBSB $_{80\% (//)}$. Chung and Wang (2018b) stated that of the eight types of heat-treated makino bamboo OBSBs (code: T*Pm*E-H), those holding a parallel grain orientation achieved the highest strength properties with a MOR at 196.5 MPa. Comparatively, a perpendicular grain OBSB only had a MOR of 5.22 MPa.

The four samples of perpendicular grain CL-OBSBs were tested, the MOR$_{(\perp)}$ values of CL-OBSB $_{40\% (//)}$, CL-OBSB $_{50\% (//)}$, CL-OBSB $_{67\% (//)}$, and CL-OBSB $_{80\% (//)}$obtained were 77.05, 68.13, 41.05, and 27.37 MPa, respectively. It can be seen that CL-OBSB $_{40\% (//)}$ held the highest MOR$_{(\perp)}$ value, yet conversely, in this instance, CL-OBSB $_{80\% (//)}$ had the smallest MOR $_{(\perp)}$ value. Because in both parallel and perpendicular CL-OBSBs, the CL-OBSB $_{50\% (//)}$ with 50% parallel grain OBSB in both, the difference in MOR value differed minutely with a MOR$_{(//)}$ value of 65.60 MPa and a MOR$_{(\perp)}$ value of 68.13 MPa. This was shown by Tukey's test, which showed no significant difference ($p > 0.05$) between the MOR values of CL-OBSB $_{50\% (//)}$ across both types of parallel-grain and perpendicular-grain CL-OBSBs. Thus, the MOR values of CL-OBSBs were largely impacted by their grain direction and proportion of OBSBs. A study conducted by Lee *et al.* (2012) showed that under particular constraints, the difference in MOR $_{(//)}$ value could be minimized between CL-OBSBs and structural laminates made of moso bamboo. If the CL-OBSB consists of at least 80% parallel-grain OBSBs, the CL-OBSB $_{80\% (//)}$ configuration has a MOR $_{(//)}$ value of 98.87 MPa, while moso bamboo structural laminates hold a MOR $_{(//)}$ value of 95.60 MPa. Conversely, the MOR $_{(\perp)}$ value of CL-OBSB $_{80\% (//)}$ was 27.37 MPa, while Lee *et al.* (2012) found the MOR $_{(\perp)}$ value of moso bamboo structural laminates to be 15.80 MPa. The higher MOR$_{(\perp)}$ value of CL-OBSB $_{80\% (//)}$ compared to the structural laminate indicates that the strength of CL-OBSBs relies heavily on the strength of the perpendicularly-oriented OBSBs. Park *et al*. (2003) studied static bending strength performances of cross-laminated woods made with five species and indicated an extremely high positive correlation between the MOR and the measured MOE parallel to the grain of the face laminae of CL-OBSB.

Compressive Strength

When considering the application of CL-OBSBs as structural construction materials, bending strength and compressive strength are the two factors that need to be noted when assessing the mechanical properties. As depicted in Fig. 3, the compressive strength values ($C_{//}$) of CL-OBSB $_{40\% (//)}$, CL-OBSB $_{50\% (//)}$, CL-OBSB $_{67\% (//)}$, and CL-OBSB $_{80\% (//)}$ were 41.34, 60.89, 75.66, and 103.17 MPa, respectively. According to Tukey's test, there were significant differences across the four types of CL-OBSBs ($p < 0.05$) and the following correlation was shown: CL-OBSB $_{80\% (//)}$ > CL-OBSB $_{67\% (//)}$ > CL-OBSB $_{0\% (//)}$ > CL-OBSB $_{40\% (//)}$. For the same reason that of all the boards CL-OBSB $_{80\% (//)}$ held the highest MOR$_{(//)}$ value in terms of bending strength, it also had the highest proportion of parallel-grain OBSB at 80%. This high content of parallel-grain OBSB in CL-OBSB $_{80\% (//)}$ is also the reason it had the highest ($C_{//}$) value, while CL-OBSB $_{50\% (//)}$ was only composed of 50% parallel-grain board, thus reducing its relative compressive strength. Lin *et al.* (2015) examined the mechanical properties of tri-layered CLTs composed of Japanese cedar and showed that the compressive strengths were between 27.4 and 44.8 MPa, with an average of 35.6 MPa. In addition to showing that CL-OBSBs made from bamboo has a higher compressive strength than CLTs made of Japanese cedar, it also shows the species of lamina also directly affects the strength of tri-layered CLT.

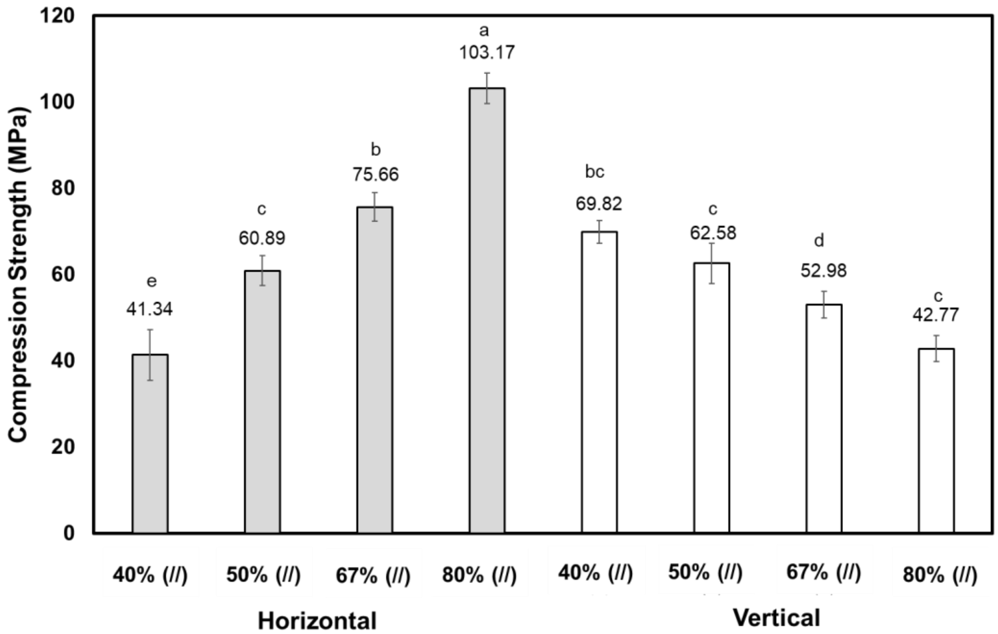

Fig. 3. Compression strengths of different CL-OBSB combination styles (H: Horizontal to bamboo strips direction; V: Vertical to bamboo strips direction; Results are mean ± SD, n = 9; Different letters a, b, c, d, and e in a given column indicate significant differences at the 0.05 level by Tukey's test and ANOVA)

Conversely, in terms of compressive strength across the four board types in the ($C⊥$) range, their proportion of parallel-grain OBSB content was as follows: CL-OBSB $_{40\%\ (//)}$ (60%), CL-OBSB $_{50\%\ (//)}$ (50%), CL-OBSB $_{67\%\ (//)}$ (33%), and CL-OBSB $_{80\%\ (//)}$ (20%), and they held the following compressive strength (C⊥) values: 69.82, 62.58, 52.98, and 42.77 MPa, respectively. Tukey's test showed that CL-OBSB $_{40\%\ (//)}$ and CL-OBSB $_{50\%\ (//)}$ did not have any significant differences, while CL-OBSB $_{67\%\ (//)}$ and CL-OBSB $_{80\%\ (//)}$ had a significant difference ($p < 0.05$), which shows the following relationship: CL-OBSB $_{40\%\ (//)}$ ≧ CL-OBSB $_{50\%\ (//)}$ > CL-OBSB $_{67\%\ (//)}$ > CL-OBSB $_{80\%\ (//)}$. This relationship is attributed to the fact that the CL-OBSB contained 60% parallel-grain OBSB, enabling the highest $C⊥$ value. Meanwhile, CL-OBSB $_{80\%\ (//)}$ only contained 20% parallel-grain OBSB, thus causing a diminution in $C⊥$ strength. Lin *et al.* (2015) investigated the transverse compressive strength of Japanese cedar CLTs and found that the compressive strength of Japanese cedar CLTs ranged between 14.2 and 19.7 MPa, averaging 17.3 MPa. These results show that even when testing for transverse compressive strength, CL-OBSBs had a higher $C⊥$ value than Japanese cedar CLTs. Part of the reason is due to the adhesion process of these boards. The CL-OBSBs require an adhesive that contains urea-formaldehyde (UF) at 10% per weight. The CL-OBSBs had a density of 0.9 g/cm^3 and a bond adhesive spread of 250 g/cm^2, which are both higher than the values of Japanese cedar CLTs, which had a density of 504 kg/cm^3 and a bond adhesive spread of 200 g/cm^2. Thus, it is evident that the grain direction and configuration of the CL-OBSBs had a significant impact on their bending and compressive strengths; in particular, the ratio between the OBSB grain direction and the direction of the force showed the most obvious impact.

Gluing Performance

Lin *et al.* (2015) analyzed the parallel and perpendicular shear bond strengths (S) of the gluing performance in tri-layered CL-OBSB s made of Japanese cedar (*Cryptomeria japonica*). The results showed that the parallel shear bond strength value was 3.9 MPa while the perpendicular shear bond strength had a value of 2.2 MPa. The parallel shear bond strength value was 1.8 times larger than the perpendicular shear bond strength. Damage to the test material occurred most frequently on boards with perpendicular-grain due to the weakness of the timbers' annual rings, causing a decline in adhesive performance. This indicates that the orientations of the layers within CL-OBSBs had a direct impact on the bonding properties.

Table 2 shows the adhesive performance of each board. The shear strength of parallel-grain boards was 7.41 MPa, while perpendicular-grain boards have a shear strength of 7.22 MPa; thus, the $S_{//}$ value was 1.03 times that of the $S_{\perp}$ value. It can be seen that the bonding strength of the two CL-OBSB varieties was higher than that of the Japanese cedar CLTs, which had a wood failure frequency of 97%. Furthermore, for these two varieties, $p > 0.05$, showing that there was no significant difference between the two CL-OBSB types: parallel-grain and vertical-grain. It indicates that when phenol-formaldehyde (PF) adhesives are used to bond OBSBs into CL-OBSBs, higher strength can be obtained while lowering adhesive anisotropy's incongruence. Because the adhesive required for bonding OBSB layers into CL-OBSBs has a significant impact on structural stability, it is necessary to comply with specifications that surpass the required structural strength.

Table 3 shows the adhesive performance results of each CL-OBSB configuration after cold water immersion and boiling tests. The first cycle of cold-water immersion and boiling tests of the four CL-OBSBs showed an average detachment rate of 0%. After the second cycle of water immersion and boiling tests, the four boards showed the following detachment percentages: CL-OBSB $_{40\%\,(//)}$ (3.2%), CL-OBSB $_{50\%\,(//)}$ (2.3%), CL-OBSB $_{67\%\,(//)}$ (2.5%), and CL-OBSB $_{80\%\,(//)}$ (2.5%), which indicates no significant difference according to Tukey's test ($p > 0.05$). It shows that the application of PF adhesive as the bonding agent for making CL-OBSBs resulted in outstanding adhesive performance.

Table 3. Gluing Performances of Different CL-OBSB Combination Styles after Cold Water and Boil Peel Tests

Types	1st Cycle (%)		2nd Cycle (%)	
	A	B	A	B
CL-OBSB $_{40\%\,(//)}$	0	0	0	3.2 ^{a}
CL-OBSB $_{50\%\,(//)}$	0	0	0	2.3 ^{a}
CL-OBSB $_{67\%\,(//)}$	0	0	0	2.5 ^{a}
CL-OBSB $_{80\%\,(//)}$	0	0	0	2.5 ^{a}

A: Soaking delaminating test
B: Boiling delaminating test
(Results are mean ± SD, *n* = 9; Different letters in a given column indicate significant differences at the 0.05 level by Tukey's test and ANOVA)

Dimensional Stability

Lee *et al.* (1996) studied the physical and mechanical properties of OSBs made of moso bamboo. Their study showed that the quantity of bonding agents used did not affect the dimensional stabilities of WA%, TA%, and *S*%. Regarding the production of reconstituted bamboo, Yu *et al*. (2015) studied the nature of the material and its application. They found that WA% impacts the strength of the board structure and the integrity of the fiber interface, resulting in subsequent alterations to its dimensional stability and physical properties. The results of their study for WA%, TA%, and *S*% on CL-OBSBs are shown in Table 4. The WA% are as follows: CL-OBSB $_{40\%\ (//)}$ (15.3%), CL-OBSB $_{50\%\ (//)}$ (15.7%), CL-OBSB $_{67\%\ (//)}$ (17.0%), and CL-OBSB $_{80\%\ (//)}$ (17.7%), which shows that CL-OBSBs hold a WA% range of 15.3% to 17.7%, yet when the four OBSBs undergo steam heat treatment (SHT), the steam-treated makino bamboo (T*Pm*E-H) holds a WA% of 43.1%. However, when T*Pm*E-H is made into OBSBs, the WA% is reduced to 15.7%. This shows that when T*Pm*E-H covers any adhesives, the WA% has a higher value; however, when T*Pm*E-H is processed into OBSBs, its WA% is similar to CL-OBSBs. The water absorption percentages showed no significant differences across the four different configurations ($p < 0.05$).

Table 4. Thickness Swelling Coefficient and Volumetric Swelling Coefficient of Four Types of CL-OBSB

Types	Combination Type	TS (%)	*S* (%)	WA (%)
CL-OBSB $_{40\%\ (//)}$	1:3:1	7.29 (0.83)^{b}	9.57 (0.84)	15.31 (2.14) ^{a}
CL-OBSB $_{50\%\ (//)}$	1:2:1	7.98 (0.95)^{b}	9.48 (0.68)	15.71 (2.14) ^{a}
CL-OBSB $_{67\%\ (//)}$	1:1:1	8.24 (1.73)^{b}	10.57 (0.95)	16.96 (2.14) ^{a}
CL-OBSB $_{80\%\ (//)}$	2:1:2	8.17 (1.21)^{b}	10.63 (1.66)	17.72 (2.14) ^{a}
Results are mean ± SD, *n* = 9; different letters a, b, c, d, and e in a given column indicate significant differences at the 0.05 level by Tukey's test and ANOVA.				

Kojima and Suzuki (2011) stated that the internal bond (IB) strength of reconstituted timber boards and their adhesive strength are directly proportional to each other; conversely, the TS% value and adhesive strength show an inverse relation. Thus, the IB value and TS% can be used as a basis for evaluating the strength and durability of reconstituted timber boards. Aside from evaluating the condition and WA% of CL-OBSBs immersed in water, Table 4 shows the variations across TS% and *S*% of the four different configurations. The four CL-OBSB configurations were in a TS% range between 7.29 and 8.24%, while the *S*% ranged between 9.5% and 10.6%. However, when bamboo had undergone SHT, the TS% and *S*% changed as indicated in the results of OBSBs made from T*Pm*E-H; the TS% averages were around 8.0%, while the *S*% increased to 12.57%. This showed that the TS% of OBSBs made from T*Pm*E-H and CL-OBSBs had no significant difference, while the *S*% of CL-OBSBs showed a smaller value than the *S*% of OBSBs made of T*Pm*E-H.

Because the ratio between the chord direction and radial direction of moso bamboo is not large, it is speculated that the bamboo structure lacks horizontal cells because bamboo predominantly holds vertical fiber structures. Thus, this absence of horizontal fiber structure results in a lack of transverse tissue traction, which causes a strong contrast between the impacts on chord and radial directions. Because the *S*% is a sum of the chord, radial, and length changes of the test material, the *S*% value would have an average higher than the TS% value. Gülzow *et al.* (2011) stated that orthogonal configurations effectively bring balance to the shrinkage and expansion properties of wood in various directions, which aids in improving dimensional stability. When Lee and Yang (2010) tested material strength, they found that the material anisotropy can be affected by variation in tree species and, subsequently their microstructure characteristics and wood strength. However, an orthogonal configuration can assist the parallel grain and perpendicular grain of Japanese cedar timber flooring, thus decreasing the extent of its linear expansion and variability.

CONCLUSIONS

1. Of the four parallel-grain cross-laminated oriented bamboo scrimber boards (CL-OBSBs) tested, CL-OBSB$_{80\%\ (//)}$ showed the highest ultrasonic velocity $V_{u\ (//)}$, modulus of elasticity MOE $_{(//)}$, and modulus of rupture MOR $_{(//)}$ values followed by CL-OBSB $_{67\%\ (//)}$. It is because the CL-OBSB $_{80\%\ (//)}$ is composed of 80% parallel-grain OBSB. Inversely, in concerning perpendicular-grain CL-OBSBs, CL-OBSB $_{40\%\ (//)}$ holds the largest MOR $_{(\perp)}$ value while CL-OBSB $_{80\%\ (//)}$ holds the smallest MOR $_{(\perp)}$.
2. The compressive strength ($C_{//}$) of the CL-OBSBs also showed, due to the 80% parallel-grain OBSB composition, that the CL-OBSB $_{80\%\ (//)}$ had the highest $C_{//}$ value; The parallel-grain OBSB composition of only 50% is the main reason for the decline in $C_{//}$ in CL-OBSB $_{50\%\ (//)}$. The shear bond strength of $S_{//}$ was 1.03 times that of $S_{\perp}$, and it also had a 97% wood failure percentage.
3. After a dimensional stability test, the results showed that the WA% of the four CL-OBSB types ranged between 15.3% and 17.7%, and TS% and S% were measured at 7.9% and 12.6%, respectively.

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