Influence of Layer Arrangement on Bonding and Bending Performances of Cross-laminated Timber Using Two Different Species

Keon-Ho Kim *

Cross-laminated timber (CLT) is a wood panel product that can be arranged in different ways. The advantage of utilizing CLT is the ability to use lamination even with low density materials or those that have defects, like knots. This study evaluated the bonding and bending performances of CLT utilizing domestic species in a shear wall or floor *via* a face bonding test of layers and a three-point bending test. The tests were carried out with three-layered CLT made up of Japanese larch and/or Korean red pine in various configurations. The layer arrangement for lamination was divided according to the species and grade of the wood. The out-of-plane and in-plane bending tests were conducted on the CLT according to the applicable direction in a wooden structure. The results of the bonding test showed that the block shear strength and delamination of all types of CLT met the BS EN 16351 (2015) standard requirements. The results of the bending test based on two wood species showed that the bending strength of the larch CLT was higher than that of the pine CLT in single species combinations. For mixed species combinations, the bending properties of CLT using larch as the major layer was higher than those using pine as the major layer. This demonstrated that the major layer had more influence on the bending properties of CLT and that Korean red pine was more suited for the minor layer of CLT.

Keywords: Cross-laminated timber; Bonding performance; Bending strength; Shear strength; Mixed species CLT

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INTRODUCTION

The number of wooden building permits using wood-based material has been increasing in Korea (MOLIT 2019). In addition to trends, such as increasing use of green building systems, wood use in urban settings has been on the rise.

The Korean Forest Service reported that the maturity of trees when harvested in forest policy would continue to decrease (Creation and Management of Forest Resources Act 2020). Forest policy in the 1960s was focused on reforestation and maintenance of the forest. Forest cover rapidly increased until the early 2000s (Fig. 1). Currently, the age at which the trees in private forests are harvested and sold is younger than before. In private forests, the harvest age is determined based on the goals of attaining the largest diameter of wood and increasing the utilization of domestic wood. The Korean red pine species has a lower density and more knots than the Japanese larch in air dried conditions, as reported by Chong and Park (2008), but it also has a wider distribution, and good supply across the country (Fig. 2). The proportion of the red pine was over the 70% of total growth stock by key tree species (Korea Forest Service 2019).

It is increasingly desirable to be able to construct wooden buildings that are massive and manhattanized. Cross-laminated timber (CLT) was introduced as a new type of engineered wood in the early 1990s in Germany and Austria (Mohammad *et al.* 2012). The CLT is a wood panel product that can be arranged in different ways to manufacture a variety of sizes and shapes.

The advantage of utilizing CLT is the ability to use lamination even with low density materials or those that have defects such as knots. However, the laminae of the glue-laminated timber for use as a beam or post are generally boards from which knots have been removed to improve the structural performance. Kramer *et al.* (2014) studied the bending and bonding properties of three layered CLT composed of hybrid poplar (*Pacific albus*) hardwood with low specific gravity. Results from the hybrid poplar CLT shear indicated that the CLT panels needed to be comprised of multi-species layers including low-density species such as hybrid poplar.

To ensure the durability of a wooden building, the bonding performance of materials and adhesives needs to be evaluated based on quality requirements of structural members. Kim and Jeon (2019) evaluated the bonding performance of the polyurethane (PUR) adhesive in mixed CLT using larch and yellow poplar based on block shear and delamination tests. It was mentioned that the delamination performance on mixed CLT was related the penetration of the adhesive.

In this study, the bonding performance of CLT using wood from mixed species was evaluated, and the bending performance of CLT using various load directions were tested. The in-plane and out-of-plane bendings that can occur within a building were applied. The bending properties were compared based on the arrangement and grades of different layers.

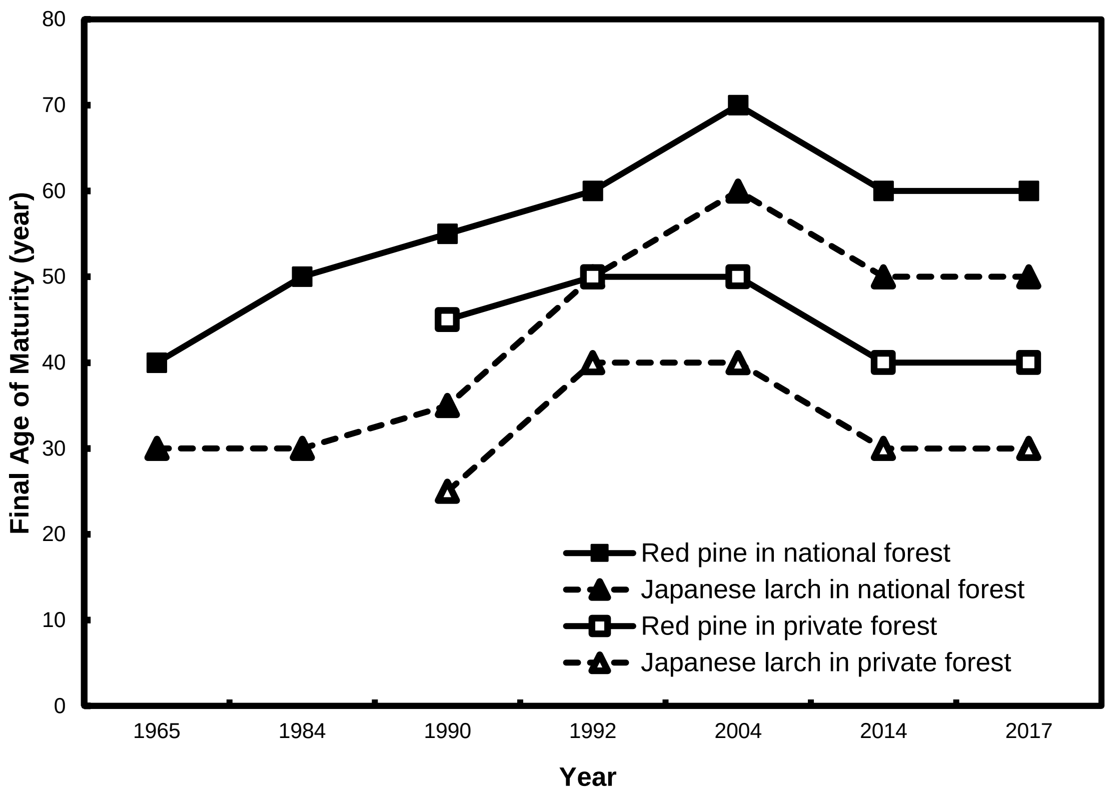


Fig. 1. Comparison of tree maturity in national forests and private forests

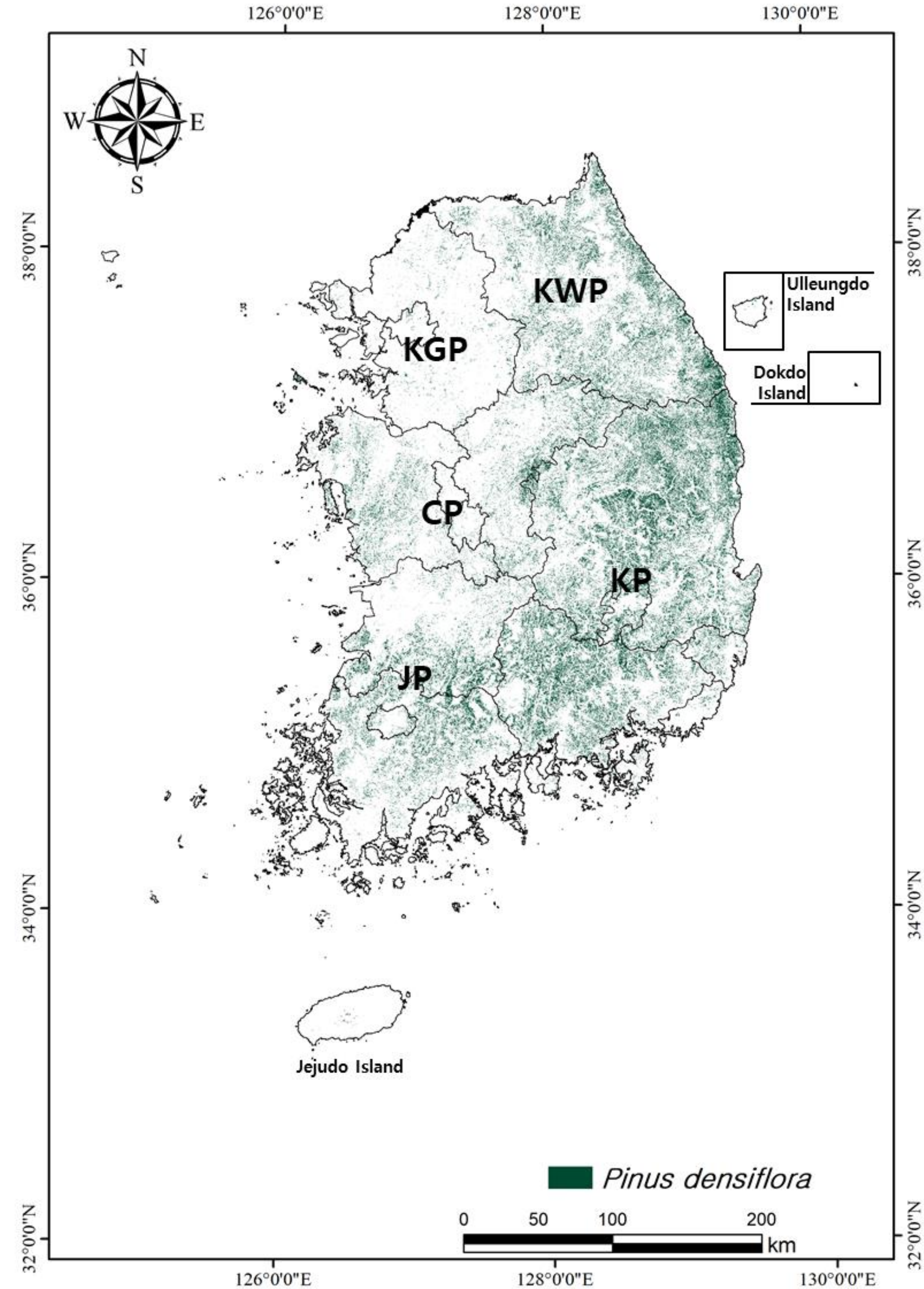


Fig. 2. Current distribution of red pine in Korea (Korea Forest Service 2014); * Abbreviations used: KWP - Kangwon Province; KGP - Kyunggi Province; CP - Chungchong Province; KP - Kyungsang Province; and JP - Jeolla Province

EXPERIMENTAL

Materials and Manufacturing of CLT

The species studied were Japanese larch (*Larix kaempferi*) and Korean red pine (*Pinus densiflora*) harvested in Gapyueng province and cut by the National Forestry Cooperative Federation. The laminates used for the CLT manufacturing were 30 mm (thickness) and 140 mm (width), and the lengths of the laminates for the minor and major layers were 1200 mm and 2300 mm, respectively. The laminae were sorted by the mechanical stress rated machine in National Forestry Cooperative Federation. The MOE distribution of 650 larch laminae by MSR is shown in Fig. 3. The E12 grade means the MOE range is 12 GPa or higher, but lower than 13 GPa. The average MOE (COV: coefficient of variation) of larch lamina was 13.13 (0.13) GPa. The 72.8 % of total larch lumbers was categorized in higher E12 grades. The average MOE (COV) of 80 red pine laminae was 12.56 (0.18) GPa. Table 1 shows the mechanical properties of each species (Chong and Park 2008). The CLT consisted of three layers composed of top and bottom 'major layers' and a middle 'minor layer.' Based on the direction of the grain of the outmost layer, the major and minor layers were placed parallel and perpendicular, respectively, to the major strength direction of the plane as per ANSI/APA PRG 320 (2018). Table 2 shows the six different combinations of CLT based on species and grades evaluated in this study. The L and P types were composed of larch and red pine, respectively. The M type using the different species was classified as ML and MP according to the species of major layer. The structural adhesive used was phenol-resorcinol-formaldehyde resin and glued over 250 g/m^2 under 1.0 MPa using clamping equipment (Kyung Min Industrial Co., Ltd., Seoul, Korea). The lamination of the layers of the different CLT combinations were classified into two grades based on the modulus of elasticity (MOE). The MOE of the laminates was measured with a machine stress rating (MSR). The Grades were assigned based on MSR rating of the laminations, whereby MOEs $\geq$ 12 GPa were grouped in Grade I and boards with MOE < 12 GPA were assigned to grade II. No further knot area ratio or fiber inclination criterions are reported in this paper. In total six different combinations of throughout 3-layer CLT were manufactured. One generic group of CLT combinations comprises homogeneous CLT, whereby all 3 layers (the two outer layers and the inner cross-layer) consist of the same species and the same grade. The homogeneous CLTs comprise:

- Larch CLT made of either Grade I (termed LA) or Grade II (termed LB)
- Pine CLT made of either Grade I (termed PA) or Grade II (termed PB)

The second generic CLT group comprises mixed or inhomogeneous built-up CLT whereby the outer layers and the inner layer belong to different species and different grades. Hereby the outer layers are throughout made of grade I laminations and the inner layer consists of Grade II laminations, so:

- Larch Grade I outside and pine Grade II inside, termed ML
- Pine Grade I outside and larch grade II inside, termed MP

Table 1. Wood Properties by Species for Manufacturing CLT (Chong and Park 2008)

Scientific name	Specific gravity		Compressive strength	Tensile strength	Bending strength	Shear strength	
	Air dried wood	Oven dried wood				Radial	Tangential
	(kgf/cm^2)						
Pinus densiflora	0.47	0.44	430	885	747	97	104
Larix kaempferi	0.61	0.56	532	584	986	113	110

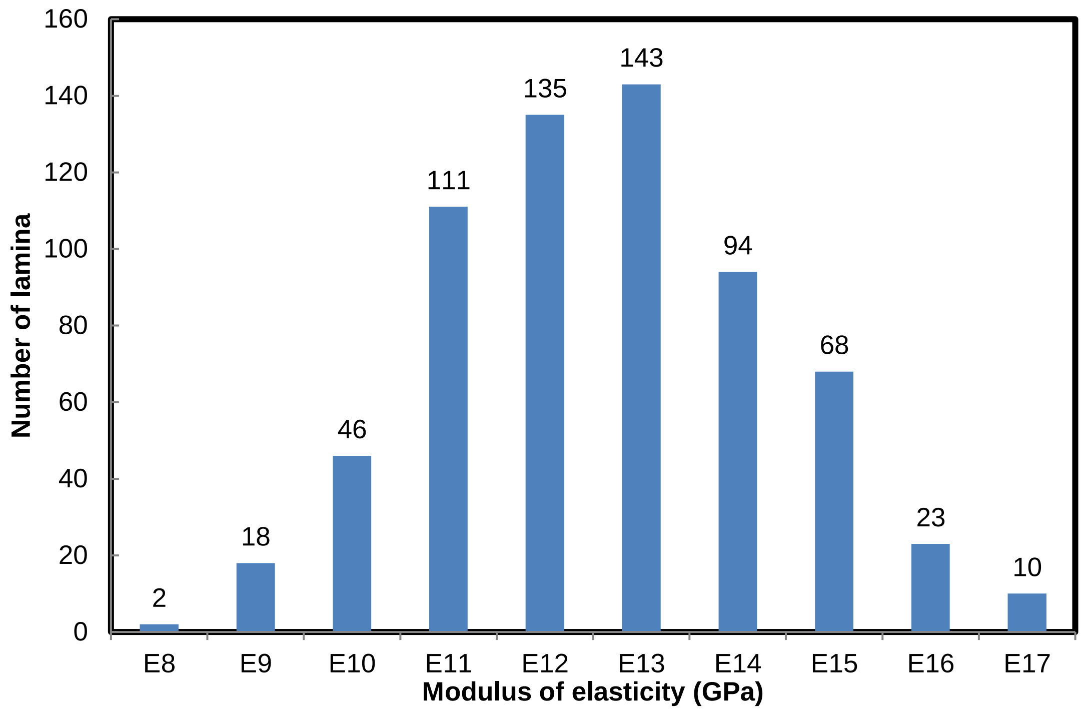


Fig. 3. MOE distribution of larch laminae by MSR

Table 2. Layer Arrangements of CLT

Type of CLT	Larch CLT		Red pine CLT		Mixed CLT	
	LA	LB	PA	PB	ML	MP
Major Axis Layer	Japanese larch (Grade I)	Japanese larch (Grade II)	Korean red pine (Grade I)	Korean red pine (Grade II)	Japanese larch (Grade I)	Korean red pine (Grade I)
Minor Axis Layer	Japanese larch (Grade II)	Japanese larch (Grade II)	Korean red pine (Grade II)	Korean red pine (Grade II)	Korean red pine (Grade II)	Japanese larch (Grade II)

Methods

Bonding performance test

To verify the face bonding properties of the various layers with adhesives, tests of the block shear strength and wood failure were conducted. For the block shear test, 10 specimens were prepared for each of the six types (Fig. 4a). The shear loading speed of

INSTRON5585(USA) was 1.0 mm/min. After the test, the wood failure rate was measured based on ASTM D5266-99 (2005). The delamination test by soaking in boiling water was conducted according to the Japanese Agricultural Standard JAS 3079 (2019). The test specimens used were 140 mm wide and 140 mm long. The specimens were soaked in boiling water for 4 h and then in cold water for an additional 1 h. The soaking procedure was followed by one day of storage in a drying chamber at 70 ± 3 °C. The delamination rate of the bond lines was measured except for splits caused by knots or over drying. The overall delamination rate was calculated by Eq.1:

$$Delamination\ (\%) = \frac{The\ sum\ of\ delaminated\ length\ on\ 4\ surfaces}{The\ sum\ of\ bonding\ line\ length\ on\ 4\ surface} \times 100 \qquad (1)$$

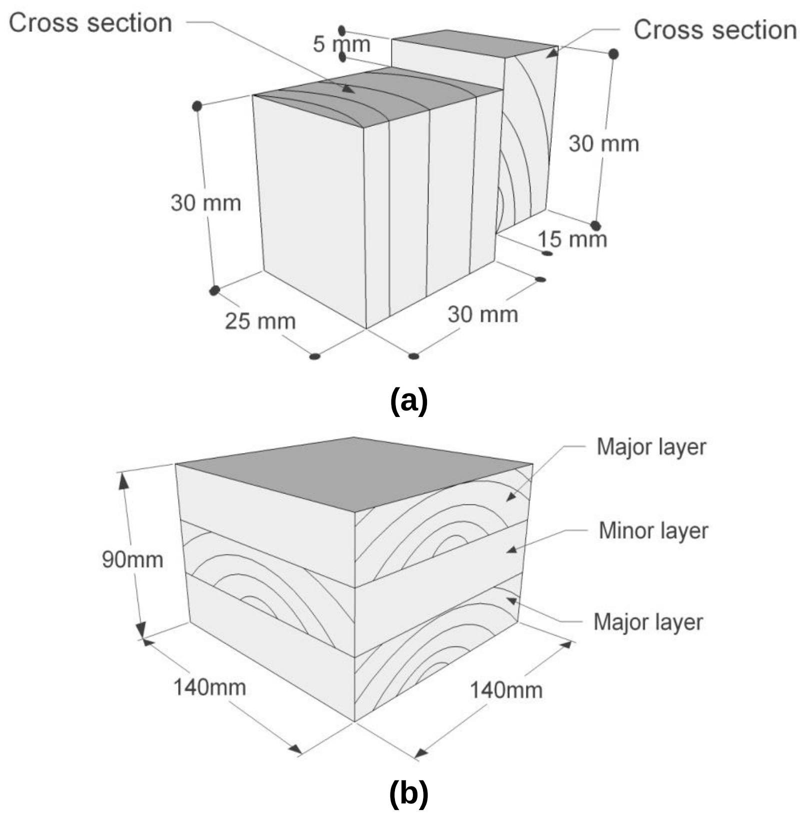


Fig. 4. Schematics of bonding test specimens: (a): Block shear and (b): Soaking delamination

Bending test

To evaluate the bending performance of the CLT combinations under transverse loads, a 3-point bending test was performed. The size of the bending specimens was 90 mm thick, 280 mm wide, and 2300 mm long. The loading directions were applied to bending tests in-plane (I-type) and out-of-plane (O-type). The O-type test was used for specimens that would be used as a roof or floor material. When designing a high-rise building, it is important to account for the dead load, *i.e.*, weight of the roof, snow, *etc*. The I-type test was used for specimens that would be used as the opening of a building, *i.e.*, windows, door, *etc*. The span length was 2100 mm and the loading rate was 10 mm/min. The load and deflection were measured using an INSTRON 5585 (Instron, Norwood, MA, USA) machine. To effectively test the stability of the specimens, the bearing plate was set at the loading point. For the O-type test, the stopper was installed to restrain the deflection by the eccentric loading. The modulus of rupture (MOR) and the MOE were calculated as follows,

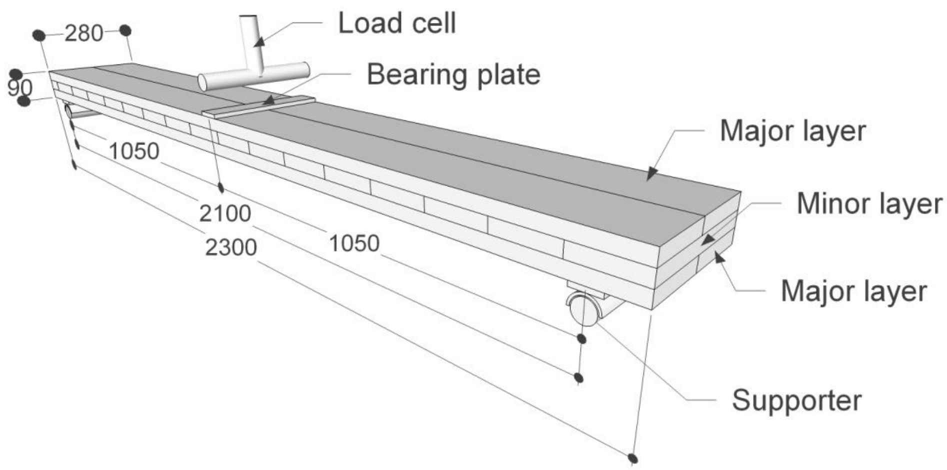
$$\text{MOR (MPa)} = \frac{3P_{max}L}{2bh^2} \tag{2}$$

where $P_{\max}$ denotes maximum load (N), L describes the span length (mm), b is the width (mm), and h is the depth (mm) of specimens. Equation 3 is as follows,

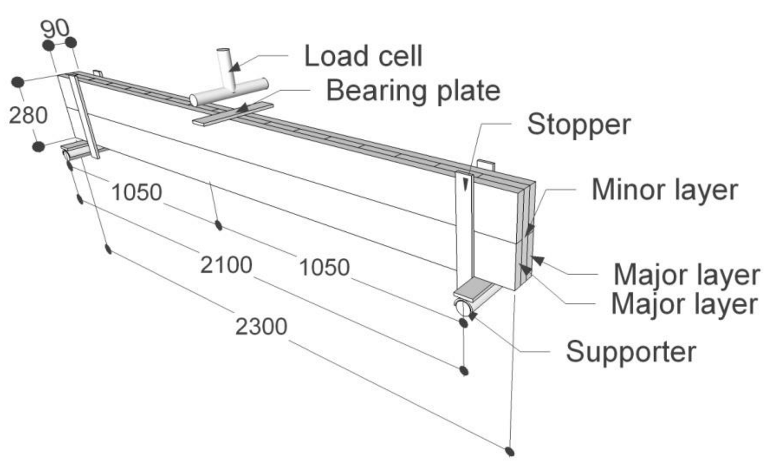
$$\text{MOE(GPa)} = \frac{PL^3}{48\delta I} = \frac{L^3}{48I} \times a \tag{3}$$

where P stands for proportional load (kN), L is the span length (mm), δ is the deflection at mid-span (mm), I denotes the moment of inertia (mm^4), and a represents the stiffness (P/δ).

For the O-type test, different MOE ratios were applied according to the direction of the grain in the inner and outer layers. The moment of inertia of outer layers was calculated by 30 times larger than inner layers as per ANSI/APA PRG-320 (2018).



(a)



(b)

Fig. 5. Schematics for bending test based on the loading direction: (a): O-type, (b): I-type, and unit: mm

RESULTS AND DISCUSSION

Bonding Properties of CLT Using Mixed Species of Wood

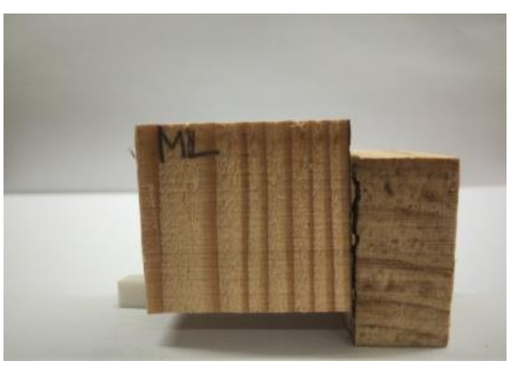
To evaluate the bonding strength properties of CLT based on wood species, the block shear strength and delamination tests were compared. The requirements for bonding properties of CLT in the European standard BS EN 16351 (2015) include a certain level of block shear strength of the face bonding layers and water soaking delamination of the CLT specimens. The shear properties of the wood are also different depending on the direction of the grain (longitudinal > radial > transverse). A good result for the bonding performance of the adhesives used with glulam or CLT was achieved when the lamination fails, not the bonding line.

Table 3 shows the bonding properties of the CLT using single and mixed species. These results show values that surpass the minimum requirement of 1.5 N/mm^2 for shear strength per BS EN 16351 (2015). Kim *et al.* (2013) reported that the face bonding strength of CLT was 1/3 the strength of parallel grain specimens of glulam tested by KS F 3021 (2018). Green *et al.* (Wood Handbook 2010) mentioned that the rolling shear strength of sawn wood has an average of 18% to 28% the shear values of parallel grain. For the block shear strength of CLT using different species, the value of the MP type was higher than that of the ML type.

Table 3. Comparison of Block Shear Properties by CLT Type

Type	LA	LB	PA	PB	ML	MP
Ave. Shear Strength (MPa)	3.15 (0.17)*	3.52 (0.14)	4.70 (0.14)	3.10 (0.14)	2.68 (0.25)	3.83 (0.13)
Ave. Wood Failure (%)	95.1	94.3	91.0	99.8	99.5	96.0
WSD (%)	3.13 (1.10)	4.22 (0.88)	4.88 (0.77)	2.58 (0.48)	3.56 (0.87)	4.88 (0.90)
BSD (%)	5.42 (1.28)	7.58 (1.08)	6.96 (0.93)	6.49 (0.96)	0.43 (2.24)	2.62 (0.81)

* The value in parenthesis is coefficient of variation; WSD: Water soaking delamination; BSD: Boiling water soaking delamination

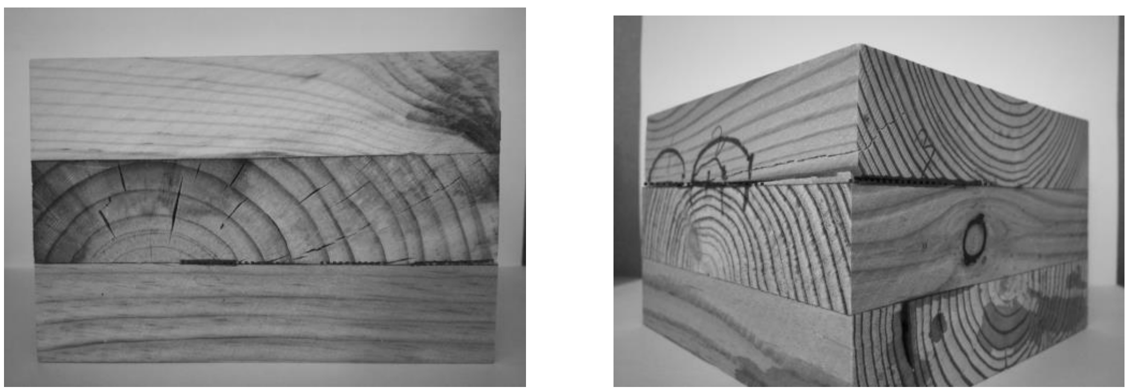


(a)

(b)

Fig. 6. Failure of block shear test between major and minor axial laminates: (a): ML-type, (b): MP-type

The block shear failure of specimens occurred mainly due to the rolling shear (Fig. 6). The difference in shear strength properties is considered to be related to the direction to the grain layers of the CLT. The results of the water and boiling water soaking delamination tests are shown in Table 3. The requirement for delamination of JAS standard 3079 (2019) is less than 10%. The phenol resorcinol formaldehyde resin had high durability in the service conditions. All specimens across wood species combinations were found to meet the EN standard requirements. Remarkably, the boiling water soaking delamination test of the CLT with mixed species had better results than the single species CLT. The delamination of the CLT occurred mainly at the edge of the specimens (Fig. 7). A bonding test on CLT using different adhesives is to be conducted for future studies.



(a) (b)

Fig. 7. Typical delamination seen in CLT specimens: (a): side view, (b): isometric view

Comparison of Bending Properties of Various Wood Species Combinations

Figure 8 shows the comparison of bending MOR based on the wood species of the specimen. For the CLT specimens made using the single species of larch, the MOR of the O-type tested LA specimens was 1.54 times higher than the LB (Fig. 9.).

The MOR of the pine CLT was similar to the larch CLT, and the PA type revealed higher MOR than the PB type. For the CLT using mixed species, the ML showed a higher strength rate than that of the MB. This means that the bending properties were mainly influenced by the strength of the major layer and therefore the minor layer can be made with a low-density wood species.

In the I-type tests, the MOR according to species showed the same tendency as the O-type tests but with a lower value. Kim *et al.* (2004) reported that knots located in the tensile part of the lumber are the weakest points. In the CLT composed of one species, the LA and PA within the I-type test was approximately 15% to 20% higher than the LB and PB samples. Compared to the PA and ML within the O-type test, the MOR of the CLT using the larch for the major layer was 1.87 times higher than the CLT with the red pine major layer.

The bonding strength of ML using minor red pine layer was similar to LA using larch layers. The arrangement of the mixed CLT was an efficient way to use the red pine as the minor axial laminate as opposed to the larch. Through using the low-density species as part of the structural framework, it can serve as a high-value addition to the wood product.

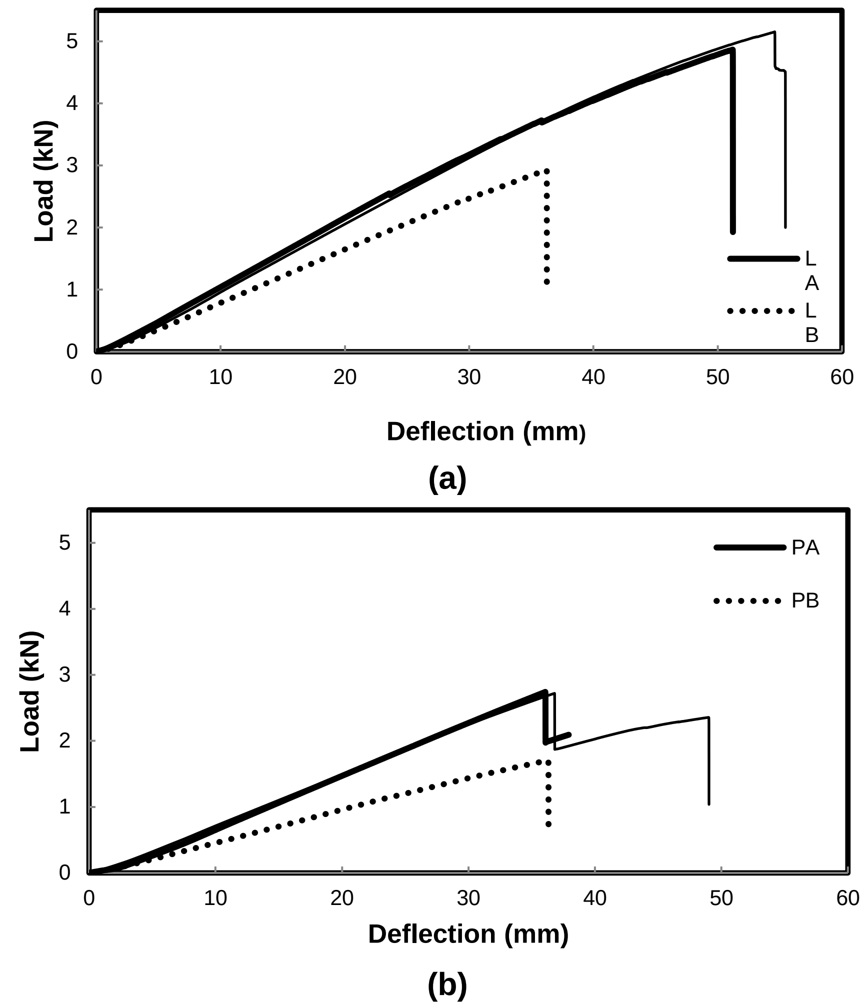


Fig. 8. Typical load-deflection curves of Larch CLT(LA and LB), Pine CLT(PA and PB) and mixed CLT(ML and MP)

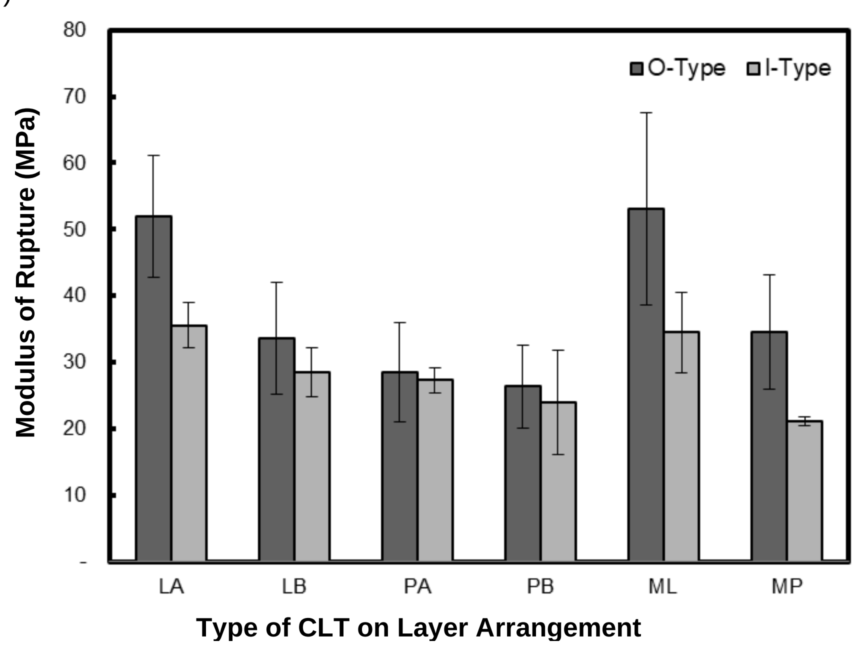


Fig. 9. Comparison of bending MOR by arrangements of CLT layers

The MOE of the CLT by O- or I-type tests is expressed in Fig. 10. The MOE of LA and LB within O-type tests reflected the grade of the bottom laminate and was 11.5 GPa and 9.7 GPa, respectively. The ratio of the MOE of LB to LA within the I-type test was 0.84, while for CLT composed of Korean red pine the ratio of PB to PA was 0.78. The MOE of I types by arrangement showed similar tendencies in the O-type test but were lower than the O types.

The CLT specimens were considered to be not long enough to conduct the bending test without shear stress occurring. For specimens with the same grade as the major layer, the MOE of LA was similar to that of ML. This result showed that the MOE of the outermost layer or that of the major layer was one of the most important factors in determining the bending properties of the CLT. This reinforces results from other studies, such as Byeon *et al.* (2018), who reported the bending MOR was influenced by the strength of the materials used in the core and bottom layers.

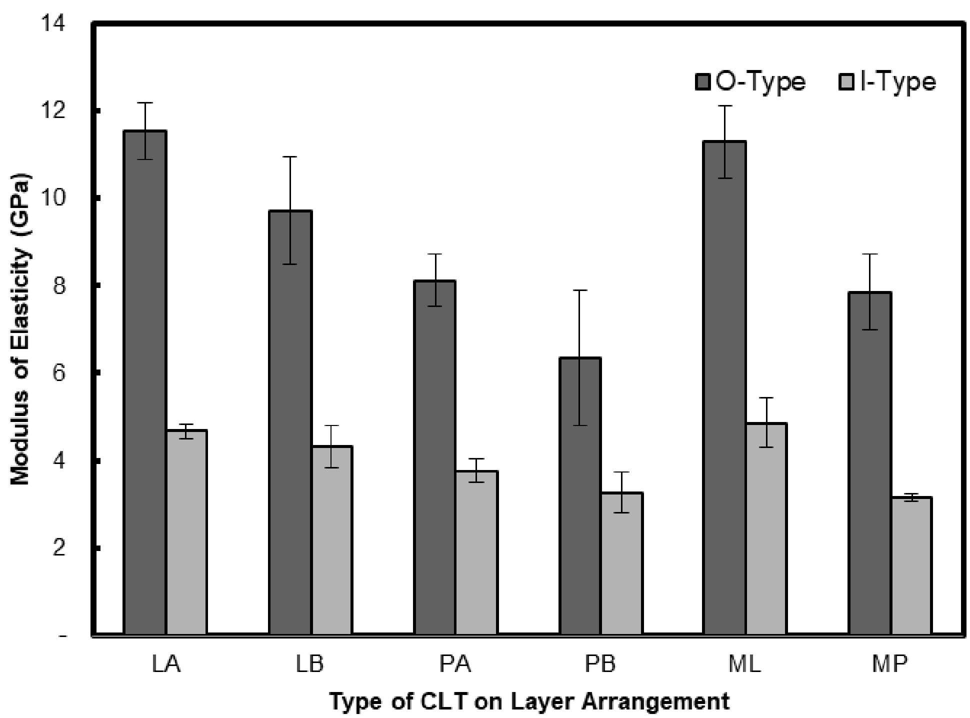


Fig. 10. Comparison of bending MOE by arrangement of CLT

Bending Failure Mode

The typical failure shown in the bending tests was similar across different arrangements of layers. The failure of specimens usually occurred at the knots and the splitting failure originated from the tensile part of the major layer and spread to the minor layer.

Figure 11 shows the failure mode of CLT types on the ultimate load. The failures of CLT occurred by tensile failure of the bottom layer and the minor layer failed across the annual ring as a rolling shear failure. This reinforces results from other studies, such as Blass and Gorlacher (2000), who reported that the direction of the cracks across the annual ring was related to the rolling shear force in the minor layer.

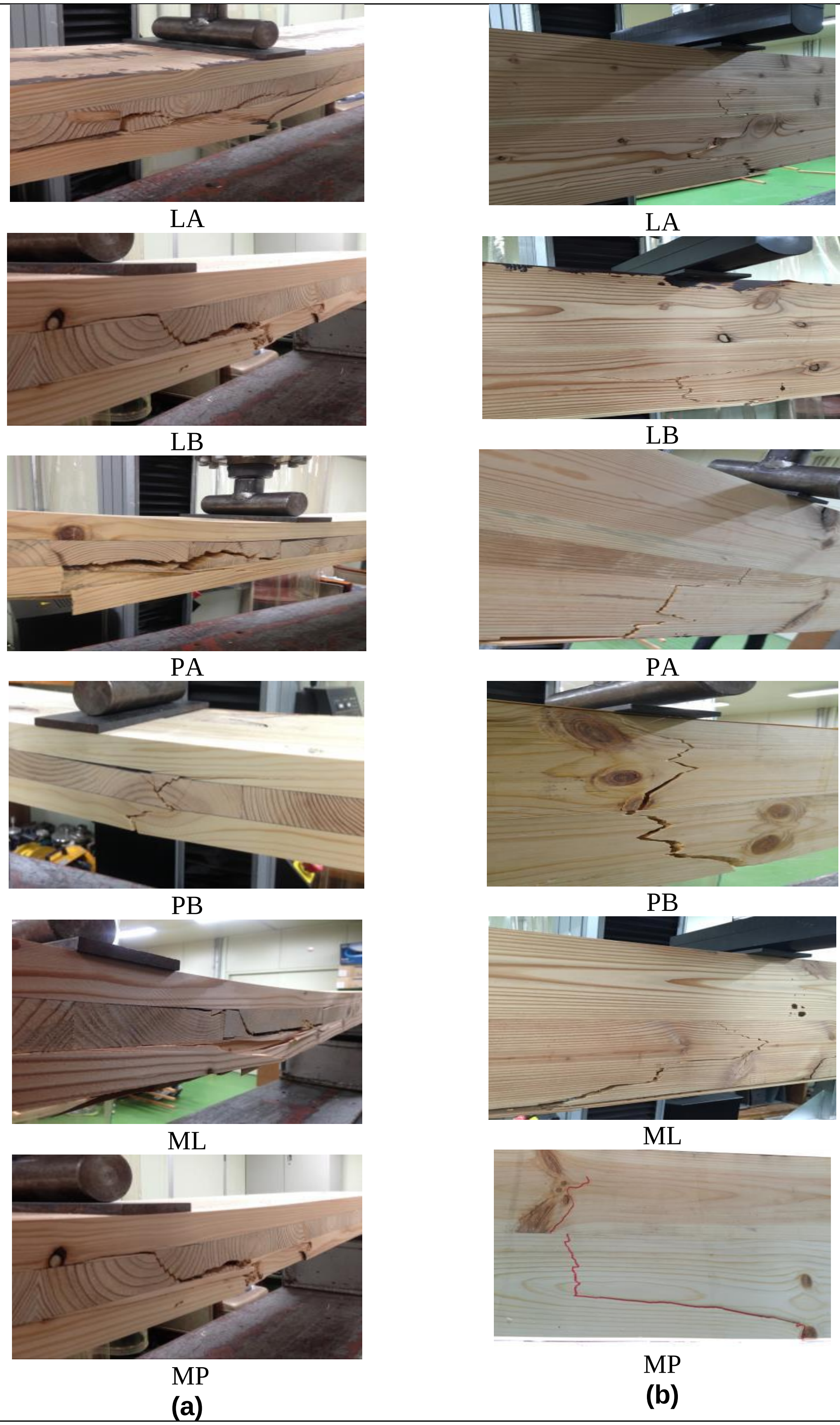


Fig. 11. Typical bending failures by loading direction (a: O-type, and b: I-type)

CONCLUSIONS

To evaluate the mechanical properties of cross-laminated timber (CLT) using two domestic wood species, bonding and bending tests were conducted. The following three conclusions were drawn:

1. The block shear strength was found to meet the requirement of BS EN 16351 (2015). The wood failure percentage of mixed CLT in the block shear test was more than 90% met the JAS 3079 (2019). Mainly, the failures were due to rolling shear because the direction of the grain was perpendicular to the load. In the boiling water soaking test, the mixed CLT prepared using phenol resorcinol formaldehyde resin was found to have sufficient durability.
2. The modulus of elasticity (MOE) of the laminate at the major layer was shown to affect the bending properties of the CLT. The bending strength of mixed larch CLTs using red pine as minor layer was similar to the larch CLT. In out of plane bending test, the bending tension and the rolling shear failure occurred. It is necessary to study the efficiency of minor layer using species with high rolling shear resistance in mixed CLT.
3. For the minor axial laminate of larch CLT, it is recommended to use red pine as the lower density and lower graded species. As a part of the structural framework, low density wood can add high value in products with high longevity.

ACKNOWLEDGEMENTS

This study was supported by a research fellowship program through the National Institute of Forest Science (NIFoS), Korea.

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Article submitted: January 28, 2020; Peer review completed: April 18, 2020; Revised version received and accepted: May 18, 2020; Published: May 21, 2020.
DOI: 10.15376/biores.15.3.5328-5341