Comparison of Mechanical Properties According to the Structural Materials of Lumber, GLT, CLT, and Ply-lam CLT

Seungmin Yang,[a] Gyuwoong Choi,[b] Junho Kim,[c] Hyunjae Lee,[c] and Seoggoo Kang [c,*]

The mechanical properties of materials such as lumber (L), glued laminated timber (GLT), cross-laminated timber (CLT), and Ply-lam CLT (P), which are laminated in cross layers, were compared. As a result, the modulus of elasticity (MOE) was 9.7 to 10.3 GPa, showing no significant difference between the materials. Modulus of rupture (MOR) of L and GLT showed higher strength than that of CLT and P. MOR of CLT and P was at the same level, and there was no difference in strength according to the plywood and lumber arranged alternately. Alternatively, there was a difference in the coefficient of variation of the materials, and CLT and P was 20.2% and 11.8%, respectively; therefore, uniform properties can be secured when using plywood. The compression strength showed the highest compression strength in the order of GLT, L, P, and CLT. P was failure by buckling+delamination, but other materials showed failure by only buckling. The adhesion of P passed the glulam standard (7.0 MPa), and the delamination ratio was very low at 0.41%. It can be used together with CLT. This study is expected to be used as basic data for establishing quality standards.

DOI: 10.15376/biores.18.4.6971-6985

Keywords: Lumber; Glued laminated timber; Cross-laminated timber; Ply-lam CLT; Bending properties; Compression strength; Failure mode; Block shear strength; Delamination rate

Contact information: a: Institute of Agricultural Science, Chungnam National University, P.O. 34134, 99 Daehak-ro, Yuseong-gu, Deajeon, Korea; b: Huin, co., Ltd, P.O. 58165, 26, lyangnonggong-gil, lyang-myeon, Hwasun-gun, Jeollanam-do, Korea; c: Department of Biobased materials, Chungnam National University, P.O. 3414, 99 Daehak-ro, Yuseong-gu, Deajeon, Korea;
** Corresponding author: lachesis@cnu.ac.kr*

INTRODUCTION

The world is declaring a goal of carbon neutrality and trying to reduce greenhouse gases to prevent global warming (Zhao *et al*. 2022). Among various materials, wood is an eco-friendly material that is attracting considerable attention as a carbon absorption and storage source that absorbs carbon dioxide and stores it as carbon (Kang *et al*. 2023; Vairo *et al*. 2023). Wood is easy to process and has been used for furniture, flooring, building materials, *etc*. (Martin *et al*. 2012). Among various uses, building materials in particular are rapidly developing with the advancement of wood processing technologies, and various engineering wood products are emerging.

Cross-laminated timber (CLT), which is arranged by crossing laminated boards such as plywood, was first patented in the 1920s (Frank and Robert 1920). The CLT patent was subsequently registered in France in 1985 (Dong *et al.* 2019), and use of CLT spread to across Europe in the 1990s (Song and Hong 2016; Yang *et al*. 2021). Developed CLT is a panel material and has become a means of realizing high-rise wooden buildings, and cases of high-rise wooden buildings are increasing (Li *et al.* 2019). CLT is applied to the structural members of walls and floors in buildings; therefore, the quality performance of CLT is essential (Brandner *et al.* 2016; Li *et al.* 2019). Accordingly, CLT standards are being established in various countries, starting with Europe in 2008, the United States in 2012, Japan in 2013, Canada in 2015, ISO in 2019, China in 2019, and Korea in 2021 (Kurzinski *et al.* 2022). Among the standards, the definition of CLT is different. The CLT standard (ANSI/APA PRG 320) of the US, a standard for performance-rated CLT, defines a prefabricated engineered wood product made of at least three orthogonal layers of graded sawn lumber or structural composite lumber (SCL) that are laminated by gluing with structural adhesives (ANSI/APA PRG 320). For SCLs, laminated veneer lumber, parallel strand lumber, and laminated stand lumber are suggested. CLT is defined as CLT products manufactured from soil-sawn timber or wood-based panels built up of at least three layers in which the grain of adjoining layers is at right angles to each other according to ISO 16696-1. However, it is specified that the wood-based panels must satisfy CLT requirements and pass the formaldehyde emission. ANSI/APA PRG 320 and ISO 16696-1 include various wood products in addition to lumber. Alternatively, Korean CLT standard (KS F 2081) defines it as engineered wood made by arranging layer materials in the length and width directions and bonding these layers to adjacent layers in three or more layers in the direction orthogonal to each other (KS F 2081). Although the wood industry differs from country to country, it is broadly defined to enable the development of CLT applied to the wood industry and wood products.

In Korea, solid wood is more expensive than concrete, and the wood-based materials industry (plywood, particle board, fiber board, *etc*.) has developed with the yield of raw materials, efficient use of resources, and low prices (Pang *et al*. 2023). Recently, to replace imported oriented strand board (OSB) used as sheathing panel in light-frame construction, research using plywood and particle board was conducted (Suh *et al.* 2012; Pang *et al.* 2023). To secure the price competitiveness of CLT made from conventional lumber, Ply-lam CLT, which contains laminated plywood on cross layer among wood-based materials, appeared in 2015 (Choi *et al.* 2015; Choi *et al.* 2018; Yang *et al.* 2021). Ply-lam CLT is a material with improved mechanical properties in comparison to CLT by replacing the cross-layer with structural plywood in the composition of CLT (Choi *et al.* 2018). Research on adhesion, bending properties, joints, wall composition, *etc*. continues, and products are being produced by establishing Ply-lam CLT manufacturing facilities (Pang *et al.* 2019; Choi *et al.* 2020, 2021; Chang *et al.* 2019, 2020, 2021; Pang *et al.* 2020). In addition, research collaboration is being conducted with the Miyazaki prefectural wood utilization research center in Japan (Fujimoto *et al.* 2021). However, Ply-lam CLT, a product that reflects the domestic wood industry, was omitted from CLT standards established in 2021.

Therefore, this study is intended to be used as basic data for the establishment of Korean industrial standards by comparing the mechanical properties of lumber, glued laminated timber (GLT), CLT, and ply-lam CLT, which are existing structural materials.

EXPERIMENTAL

Materials of Lumber and Adhesive

Japanese larch (*Larix kaempferi*; larch) is the most commonly used species in Korea for materials such as GLT and CLT (Kim *et al.* 2021). Larch was selected as a representative tree species for comparing structural materials for wooden construction.

Larch green lumber pieces were purchased from the Namwon Forest Cooperation (Namwon, Korea). The dimensions of the lumber were 65 (T) × 65 (W) × 2,700 (L) mm and 30 (T) × 122 (W) × 2,700 (L) mm. The green lumber pieces were dried using a kiln-dryer at Huin Co., Ltd. (Hwasun, Korea). The moisture content and oven-dry density of kiln-dried lumber were 13.9% (3.94%) and 0.6 g/cm^3 (10.69%), respectively. For lumber, only E10 (10 GPa) grade lumber was used through elastic modulus measurement and classification. In addition, the lumbers were surface planned and processed into 60 (T) × 60 (W) × 2,400 (L) mm and 20 (T) × 120 (W) × 2,400 (L) mm. Also, the plywood applied as the layer material for ply-lam CLT was larch structural 1st grade plywood manufactured by S company (Incheon, Korea). The dimensions of the plywood were 20 (T) × 1,220 (W) × 2,440 (L) mm, and the density and moisture content were 0.57 g/cm^3 (3.5%) and 8.0% (2.5%), respectively. Phenol-resorcinol-formaldehyde (PRF) resin (Oshika Corporation (Tokyo, Japan)) was used for adhesion among the layers of GLT, CLT, and ply-lam CLT. The curing agent for the PRF resin was paraformaldehyde, which was used by mixing the resin and curing agent at a weight ratio of 100:30.

Manufactured Specimen of GLT, CLT, and Ply-lam CLT

The prepared lumber and plywood were manufactured with GLT, CLT, and ply-lam CLT through adhesion. GLT, CLT, and Ply-lam CLT were manufactured at the Huin Co., Ltd. (Hwasun, Korea), a GLT manufacturing company. The adhesive used at this time was PRF resin, and the amount of adhesive applied was 150 g/cm^2 based on the amount of single-sided application (Choi *et al.* 2021). After adhesive application and material lamination, cold pressing was performed at a pressure of 10 kgf/cm^2 for 24 h. After cold pressing, materials were used as test specimen through hardening process for 7 days. The oven-dry density, moisture content, and cross section of the prepared test specimen are shown in Table 1 and Fig. 1. The oven-dry density and moisture content of the prepared specimens were measured according to ASTM D2395 (2022).

Table 1. Basic Properties and Layer Composition of the Lumber, GLT, CLT, and Ply-lam CLT

		Lumber	GLT	CLT	Ply-lam CLT
Layer Composition	1-layer		L∥	L∥	L∥
	2-layer		L∥	L⊥	P∥
	3-layer		L∥	L∥	L∥
Thickness (mm)		58.0 (0.9%)	58.8 (0.8%)	58.7 (1.7%)	58.5 (1.2%)
Oven-dry density (g/cm^3)		0.6 (10.7%)	0.52 (16.5%)	0.52 (7.0%)	0.53 (5.1%)
Moisture content (%)		13.9 (3.9%)	10.5 (7.0%)	10.2 (9.1%)	10.4 (6.9%)
* L; larch lumber, ∥; parallel grain direction, ⊥; perpendicular grain direction					

Fig. 1. Representative photographs of tested lumber, GLT, CLT, and Ply-lam CLT

To compare the performance of structural materials for wooden construction, the bending properties and compression strength were tested. To analyze the material properties, the block shear strength, and the soaking delamination tests, which measure two different aspects of adhesive strengths, were performed.

Bending Properties Test

To compare the flexural performance of four types of specimens, a type A bending test (Four-point load) was performed in ASTM D198 (2015). The dimension of the test specimen was 60 (T) × 60 (W) × 1,200 (L) mm, and the span was tested at 18.3 times of the thickness. At this time, the number of repetitions of the bending test specimen was 10 times. The bending test was performed by installing the test specimen and LVDT (Fig. 2). LVDT was installed on the neutral axis of the center and two load points along the length direction, and the vertical strain between the center and two load points was measured. A 10-ton universal test machine was used, and the loading speed was set to reach the maximum load within 300 secs. The loading speed was 9 mm/min, which was applied equally to all materials. Also, the bending test was done 21 times for each material, and modulus of elasticity (MOE) and rupture (MOR) were calculated and compared. The MOE and MOR of flexural performance were calculated according to Eq. 1.

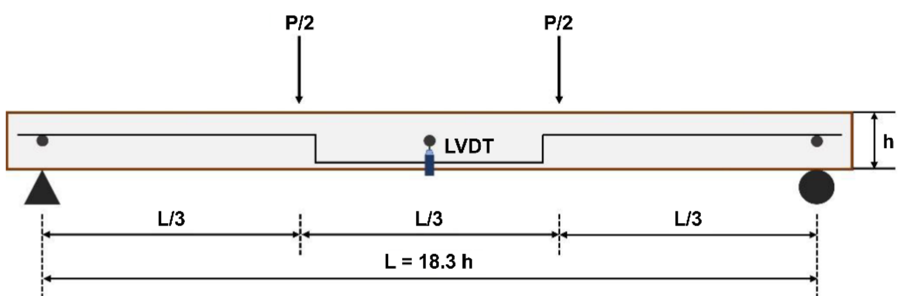

Fig. 2. Schematic of four-point bending test

$$MOE = \frac{23P_eL^3}{108bh^3\Delta_e} \tag{1}$$

$$MOR = \frac{P_mL}{bh^2} \tag{2}$$

where MOE is modulus of elasticity (GPa), MOR is modulus of rupture (MPa), P_e is proportional limit load (N), $\triangle_e$ is proportional limit displacement (mm), L is span (mm), b is width of specimen (mm), h is thickness of specimen (mm), and P_m is maximum load (N).

Compression Strength Test

To compare the compression strength of four types of materials under compressive load, a compression strength test was conducted according to ASTM D198 (2015). For the compression test, a 100 ton hydraulic tensile and compression strength tester (Fig. 3) was used, and the specimen size was 60 (T) × 60 (W) × 1,200 (L) mm. The compression strength was tested according to the presence or absence of blocking to confirm the difference according to the presence or absence of buckling. At this time, the repetition numbers were tested 10 times each. The loading rate was set so 2 mm/min so that compression failure could occur within 5 min, and the compression strength was calculated based on Eq. 2,

$$f_c = \frac{P_m}{A} \tag{3}$$

where f_c is compression strength (MPa), P_m is maximum load (N), and A is cross section area (m^2).

Fig. 3. Schematic of compression strength test

Adhesion Test

Block shear test was performed to compare the adhesive strength among layer materials, GLT, CLT, and Ply-lam CLT. It was performed according to KS F 2081 (2021). Specimen dimensions are shown in Fig. 4, and the number of repetitions was set to 10.

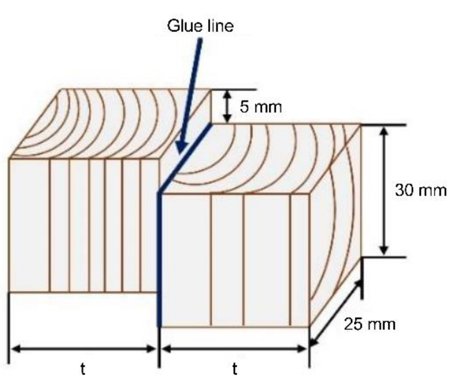

Fig. 4. Schematic of block shear strength test

For the block shear test, a 5 ton UTM (Tinius Olsen, U.K.) was used, and the load speed was set at 1 mm/min to reach the maximum load within 5 min. The block shear test was done 20 times for each material. The block shear strength was calculated according to Eq. 4.

$$\sigma = \frac{F_m}{bh} \quad (4)$$

where σ is block shear strength (MPa), F_m is maximum load (N), b is width of the shear area (mm), and h is length of the shear area (mm).

Adhesion strength between layer materials soaking delamination test was performed according to KS F 2081 (2021). The test specimen dimension was cut to 60 (T) × 60 (W) × 50 (L) mm, and in the case of ply-lam CLT in which plywood was laminated, all adhesive layers between veneers were measured. The test specimen is immersed in boiling water for 4 h and then cooled in cold water for 1 h. Thereafter, the test specimen was dried in an oven-dryer at 70 ± 3 °C for 24 h, the length of the delamination adhesive layer was measured, and the delamination ratio was calculated by Eq. 5,

$$p = \frac{l}{L} \quad (5)$$

where p is the delamination percentage of materials (%), l is the delamination length of glue line (mm), and L is the length of glue line (mm).

Statistical Analysis

For the comparison of properties according to the materials, SPSS 26 (IBM, V26.0.0, New York, USA) statistical program was used to verify the significance of the results of bending properties, shear strength, and block shear strength. One-way ANOVA was performed, and Duncan's multiple tests were performed to verify significance. According to the p value of the significance test result, $p < 0.05$ was marked as "*," $p < 0.01$ as "**," and $p < 0.001$ as "***."

RESULTS AND DISCUSSION

Bending Properties

Load and displacement according to materials are shown in Table 2 and Fig. 5. GLT reduced the load and displacement by 17% and 32% compared to that of lumber, respectively. The load and displacement of CLT decreased by 35% and 44% compared to that of lumber and decreased by 22.5% and 17.2% compared to that of GLT, respectively. Ply-lam CLT reduced load and displacement by 28% and 42% compared to that of lumber and decreased load and displacement by 13.6% and 14.9% compared to that of GLT, respectively. Alternatively, the load and displacement of ply-lam CLT increased by 10% and 2.8%, respectively, compared to that of CLT. GLT, CLT, and ply-lam CLT exhibited a reduced maximum load in comparison to that of lumber, but the deflection of materials will be improved owing to a decrease in displacement. In addition, the proportions of lumber and veneer arranged in an orthogonal layer material among the CLT and Ply-lam CLT composition were 30% and 14%, respectively. The ratio of orthogonal layers showed similar results to the load reduction ratio of GLT. It has been reported that MOE in the direction perpendicular to the lumber fiber direction is 1/30 of MOE in the fiber direction, showing an inversely proportional relationship in which the maximum load decreases as the composition ratio of the cross-layer increases (Dong *et al.* 2021). Therefore, the result that the maximum load decreased as the ratio of layer materials arranged in an intersection increased was consistent with previous studies (Dong *et al*. 2021).

Table 2. Load-displacement Result in the Proportional Limit Range

	Lumber	GLT	CLT	Ply-lam CLT
Load (kN)	11.97 (14.1%)	9.96 (19.3%)	7.72 (20.3)%	8.61 (11.9%)
Displacement (mm)	13.99 (7.4%)	9.49 (24.9%)	7.86 (23%)	8.08 (17.5%)

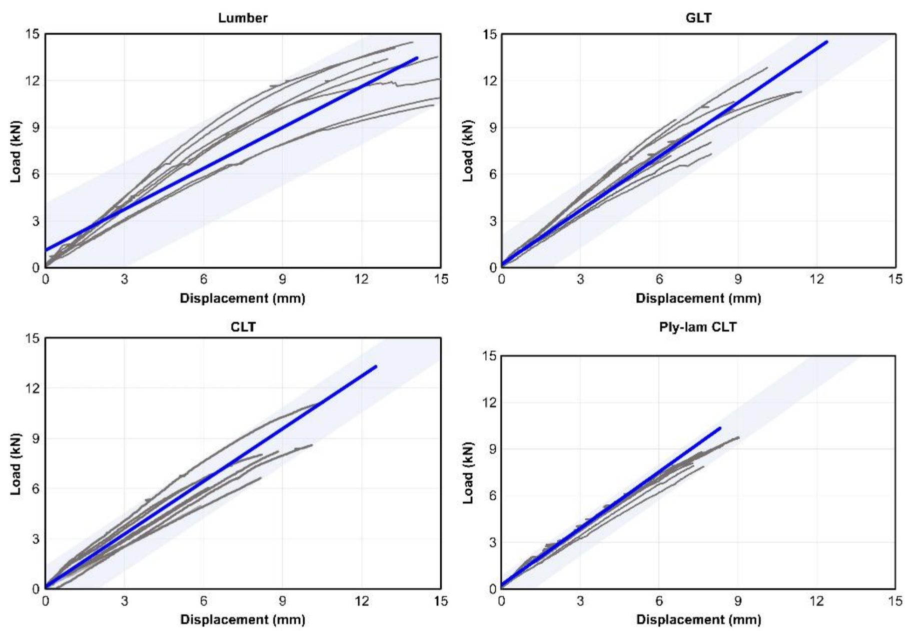

Fig. 5. Load-displacement curve in the proportional limit range

The flexural performance results are shown in Figs. 6 and 7. Although the layer composition was different depending on the lumber and plywood, MOE did not show a considerable difference and was at the same level ($F = -0.376$, $p = 0.711$; lumber 10.3 GPa (14.8%); GLT 10.2 GPa (7.4%); CLT 9.7 GPa (14.7%); ply-lam CLT 10.1 GPa (7.3%)). The MOE coefficient of variation (COV) of ply-lam CLT and GLT were 7.3% and 7.4%, respectively, and more uniform properties can be secured than that of lumber and GLT.

MOR ($F^{***} = 13.152$, $p = 0.000$) showed high results in the order of lumber > GLT > Ply-lam CLT ≒ CLT. CLT and ply-lam CLT, which showed an equivalent level, were subjected to an independent t-test, and as a result ($t = -1.056$, $p=0.305$), no significant difference in MOR according to the materials composition of CLT and Ply-lam CLT could be confirmed. MOR showed differences depending on the composition of the materials, and Byeon *et al.* (2018) reported that MOR is affected by the strength of materials used for the core and bottom layers. Unlike UOE, MOR showed a difference because the strength was different depending on plywood, lumber, and arrangement direction among the composition materials.

MOR of lumber was 60.7 MPa (13.1), the highest among materials, followed by GLT 50.2 MPa (19.3%), ply-lam CLT 42.7 MPa (11.8%), and CLT 39.4 MPa (20.2%). COV according to the materials was the lowest in ply-lam CLT, and uniform product quality can be secured. MOR of GLT, CLT, and ply-lam CLT decreased by 17.3%, 35.2%, and 29.7%, respectively, compared to that of lumber.

Also, MOR of CLT and ply-lam CLT decreased by 21.6% and 15.0% compared to GLT, respectively. CLT and ply-lam CLT, as a panel material, showed lower MOR than lumber and GLT, which are beam materials. When comparing load-displacement, the cross-layer ratio and load reduction ratio showed similar results, and MOR also showed similar results in the layer ratio and reduction in MOR.

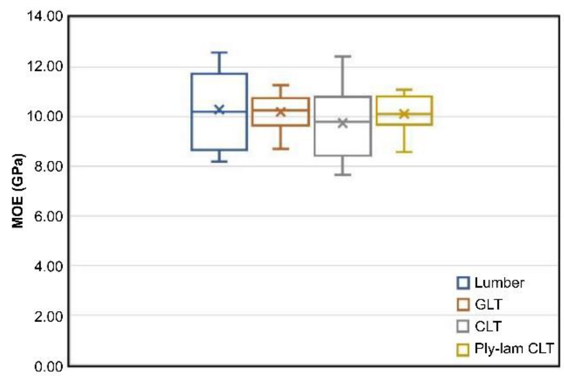

Fig. 6. Modulus of elasticity of materials

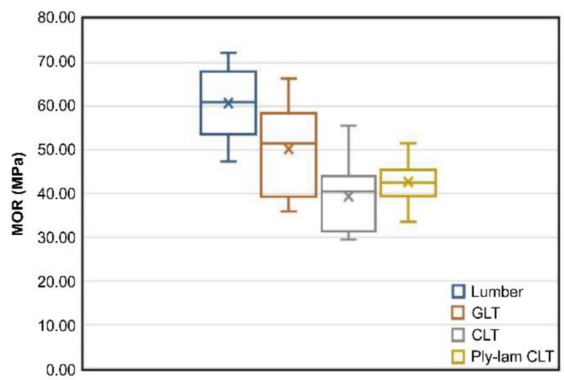

Fig. 7. Modulus of rupture of materials

The results of the bending test are shown in Fig. 8. Lumber and GLT showed a tensile failure type owing to the concentration of tensile force at the lower part of the specimen by the applied bending load. In the CLT, the initial failure was caused by tensile force owing to the layers arranged in an intersection, but as the load was transferred to the layers arranged in a perpendicular layer, it exhibited a rolling shear failure type. Rolling shear failure is a representative failure type of CLT that is destroyed along the annual rings and adjacent areas of the early and late wood of lumber (Wang *et al.* 2017). Rolling shear failure is an important characteristic that appears when out-of-plane loads such as short-span bending and concentrated loads are applied (Zhou *et al.* 2014).

Alternatively, in the case of ply-lam CLT, the failure type was a tensile+rolling shear failure. Rolling shear failure of ply-lam CLT occurred in the plywood layer owing to the lower rolling shear strength of the plywood than the longitudinal shear strength of the plywood (Pang *et al.* 2019; Soti *et al.* 2021). CLT showed rolling shear failure in all specimens, but ply-lam CLT showed 50% tensile failure and 50% tensile+rolling shear failure. Therefore, rolling shear failure and excessive deflection can be prevented by reducing the thickness of CLT cross-layer, but additional research on the mechanical properties of CLT according to the layer thickness and number of layers is required.

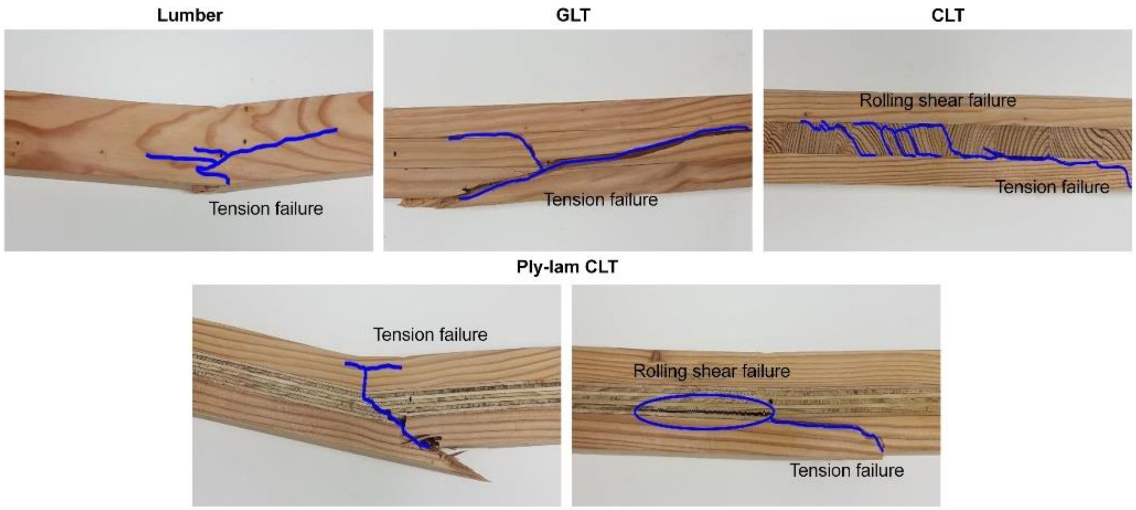

Fig. 8. Failure mode in bending tests according to materials

Compression Strength

The compression strength results according to the type of materials and whether the blocking was installed is shown in Table 3. The compression strength (F*** = 22.788) of the specimen without blocking showed the result of lumber ≒ GLT ≒ ply-lam CLT > CLT. A one-way ANOVA was conducted to confirm the significance of the compression strength of lumber, GLT, and ply-lam CLT, and the result was equivalent ($F = 2.138$, $p = 0.169$). Buckling was generated when a compression load was applied, and the internal moment was changed, so that there was no difference in the compressive strength of lumber, GLT, and ply-lam CLT (Fig. 9). As for the failure type, lumber, GLT, and CLT showed buckling failure owing to compression load, but ply-lam CLT showed a buckling + delamination type. Rajendra *et al.* (2021), which was the same as the failure type shown in the compression test of the mass plywood panel, which is decided to be caused by the veneers arranged perpendicular on the plywood.

To compare the compression strength according to the materials, the compression strength was tested by installing a blocking. As a result (F*** = 22.788), high strength was shown in the order of GLT > lumber > ply-lam CLT > CLT. This is consistent with the results of MOR, and the higher the ratio of the cross-arranged plywood, the lower the compression strength. The initial failure occurred in the outermost layer, but the load was transferred to the inner layer; therefore, lumber and GLT showed compression failure. Alternatively, CLT and ply-lam CLT showed compression failure at the boundary between the early and late wood in cross-section, as the compression load was transferred to the lumber and veneer arranged alternately on the inner layer. Yang *et al.* (2021) reported that failure occurs and is transmitted at the boundary when compression and shear forces are applied due to the difference in density between early wood (300 kg/m^3) and lately wood (900 to 1,000 kg/m^3). Similar to the result of Yang *et al.* (2021), the failure of the boundary was shown by the difference in density.

Table 3. Compression Strength Result of Uninstalled and Installing Blocking Test

	Compression Strength (MPa)		Result of t-test depending on uninstalled and installing blocking
	Uninstalled blocking (F^{***} = 22.788)	Installing blocking (F^{***} = 19.272)	
Lumber	61.5^{b} (12.6%)	52.5^{bc} (4.9%)	t = −1.722
GLT	62.7^{b} (3.5%)	55.2^{c} (7.7%	t = −2.229
CLT	32.3^{a} (12.6%)	34.8^{a} (9.6%)	t = −1.173
Ply-lam CLT	54.2^{b} (3.6%)	47.8^{b} (11.9%)	t = −2.024

Fig. 9. Failure mode in uninstalled blocking compression test (lumber, GLT, CLT; buckling failure, Ply-lam CLT; buckling+delamination failure)

Adhesion Properties of the Materials

Adhesion is an important factor affecting the quality of the wood product such as GLTs. The block shear strength (BSS) and wood failure rate results are shown in Table 3. The BBS of the adhesive layer is the adhesive strength, strength of the adhesives at both ends of the adhesive layer, and the wood failure is an important index for adhesive quality (Li and Ren 2022).

Table 4. Block Shear Strength Result of Materials

Materials	Block Shear Strength (COV) (MPa) (F^{***} = 109.167)	Wood Failure Percent (%)
GLT	11.0^{c} (6.8%)	95 (2.5)
CLT	3.6^{a} (21.6%)	89 (10.3)
Ply-lam CLT	7.8^{b} (7.1%)	93 (3.4)
KS F 3021 (2022)	7.1	65%
KS F 2081 (2021)	1.0	65%

All materials showed more than 90% of wood failure, and GLT and CLT passed the adhesive strength and wood failure of KS F 3021 (2022) and KS F 2081 (2021), respectively (Fig. 10). In the case of ply-lam CLT, by arranging the fiber arrangement of the plywood face veneer and the fiber arrangement of the lumber identically and the bonding them, the BSS was 7.8 MPa and wood failure was 93%, passing the standard for GLT. In addition, BBS COV was 6.8% for GLT, 21.6% for CLT, and 7.1% for ply-lam CLT, and the variation in BSS of ply-lam CLT was similar to that of GLT.

Fig. 10. Failure mode of block shear strength test according to materials

Because of the soaking delamination test of GLT, CLT, and ply-lam CLT, the delamination rate of GLT and CLT was 0% and the glue line did not delaminate (Fig. 11). Ply-lam CLT showed a low delamination rate of 0.41%, and passed the delamination rate standard (parallel glue line 25%, perpendicular glue line 40%) of KS F 2081 (2021).

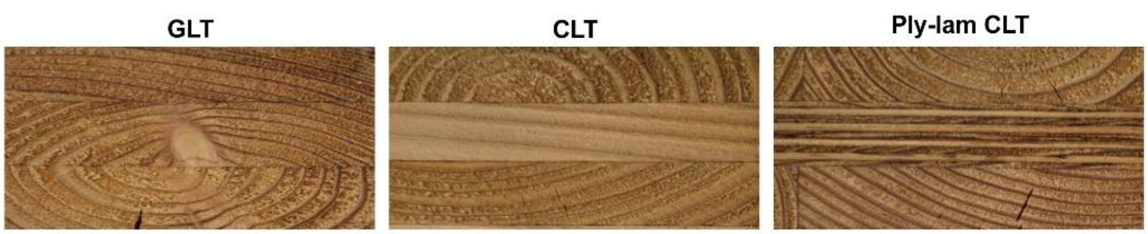

Fig. 11. Soaking delamination of GLT, CLT, and Ply-lam CLT

The BSS and delamination rate of GLT, CLT, and ply-lam CLT were compared. Ply-lam CLT exhibited a higher BBS than that of CLT, and the delamination rate also showed similar results to GLT and CLT with GLT. It was confirmed that ply-lam CLT can solve the deterioration of adhesive strength in the cross-layer of CLT and secure uniform adhesive strength at the level of GLTs. This can be applied as a method for improving the adhesion of large panels.

CONCLUSIONS

1. This study compared the mechanical properties of lumber, glued laminated timber (GLT) and cross-laminated timber (CLT), which are existing structural materials, to use as mechanical properties data for establishing standards for ply-lam CLT.

2. The modulus of elasticity (MOE) did not show any difference depending on the materials. The modulus of rupture (MOR) of lumber and GLT was higher than that of CLT and ply-lam CLT, and the MOR of CLT and ply-lam CLT showed no considerable difference. CLT and ply-lam CLT showed equivalent levels of MOR.
3. For compression strength, a compression test was conducted depending on whether blocking was installed. When a compression load was applied when the block was not installed, buckling was generated; therefore, the compression strength of lumber, GLT, and ply-lam CLT were equal except for CLT. When blocking was installed, GLT, lumber, ply-lam CLT, and CLT showed high compression strength.
4. The block shear strength (BSS) of ply-lam CLT passed the CLT standard of 1.0 MPa and GLT standard of 7.0 MPa. In addition, the wood failure of ply-lam CLT was 0.41%, which was very low. By arranging the surface layer of the plywood and fiber direction of lumber in the same direction, the adhesion between the plywood and lumber was improved, showing the level of BSS of the GLT.
5. Compared with CLT, ply-lam CLT showed the same level of bending properties, improved compression strength, and passed the GLT standard of 7.0 MPa in adhesive strength. In terms of the mechanical properties of the materials, it can be used with CLT, and as it is a material developed by reflecting the Korean wood industry, it is necessary to establish a standard.

ACKNOWLEDGMENTS

This study was carried out with the support of “R&D Program for Forest Science Technology (Project No. 2023495A00-2325-AA02)” provided by the Korea Forest Service (Korea Forestry Promotion Institute).

REFERENCES CITED

ASTM D198-15 (2015). “Standard test methods of static tests of lumber in structural sizes,” ASTM International, West Conshohocken, PA

ANSI/APA PRG 320 (2019). “Standard for performance-rated cross-laminated timber,” APA-The Engineering Wood Association, Tacoma, WA, USA

ASTM D2395 (2022). “Standard test methods for density and specific gravity (relative density) of wood and wood-based materials,” ASTM International, West Conshohocken, PA

Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., and Thiel, A. (2016). “Cross laminated timber (CLT): Overview and development,” *European Journal of Wood and Wood Products* 74(3), 331-351. DOI: 10.1007/s00107-015-0999-5

Byeon, J. W., Kim, T. H., Yang, J. K., Byeon, H. S., and Park, H. M. (2018). “Static bending performances of cross-laminated wood panels made with tropical and temperate woods,” *Journal of the Korean Wood Science and Technology* 46(6), 726-734. DOI: 10.5658/WOOD.2018.46.6.726

Choi, C., Yuk, C. R., Yoo, J. C., Park, J. Y., Lee, C. G., and Kang, S. G. (2015). “Physical and mechanical properties of cross laminated timber using plywood as core layer," *Journal of the Korean Wood Science and Technology* 43(1), 86-95. DOI: 10.5658/WOOD.2015.43.1.86

Choi, C., Kojima, E., Kim, K. J., Yamasaki, M., Sasaki, Y., and Kang, S. G. (2018). "Analysis of mechanical properties of cross-laminated timber (CLT) with plywood using Korean larch," *BioResources* 13(2), 2715-2726. DOI: 10. 15376/biores.13.2.2715-2726

Choi, G. W., Yang, S. M., Lee, H. J., Kim, J. H., Choi, K. H., and Kang, S. G. (2020). "A study on the block shear strength according to the layer composition of and adhesive type of ply-lam CLT," *Journal of the Korean Wood Science and Technology* 48(6), 791-806. DOI: 10.5658/WOOD.2020.48.6.791

Choi, G. W., Yang, S. M., Lee, H. J., Kim, J. H., Choi, K. H., and Kang, S. G. (2021) "Evaluation of flexural performance according to the plywood bonding method of ply-lam CLT," *Journal of the Korean Wood Science and Technology* 49(2), 107-121. DOI: 10.5658/WOOD.2021.49.2.107

Chang, S. J., Wi, S. H., and Kim, S. M. (2019). "Thermal bridging analysis of connections in cross-laminated timber buildings based on ISO 10211," *Construction and Building Materials* 213, 709-722. DOI: 10.1016/j.conbuildmat.2019.04.009

Chang, S. J., Wi, S. H., Kang, S. G., and Kim, S. M. (2020). "Moisture risk assessment of cross-laminated timber walls: Perspectives on climate conditions and water vapor resistance performance of building materials," *Building and Environment* 168, article 106502. DOI: 10.1016/j.buildenv.2019.106502

Chang, S. J., Kang, Y. J., Kim, B. Y., Yang, S. W., and Kim, S. M. (2021). "Assessment of effect of climate change on hygrothermal performance of cross-laminated timber building envelope with modular construction," *Case Studies in Thermal Engineering* 28, article 101703. DOI: 10.1016/j.csite.2021.101703

Dong, W., Wang, Z., Zhou, J., and Gong, M. (2021). "Experimental study on bending properties of cross-laminated timber-bamboo composites," *Construction and Building Materials* 300, article 124313. DOI: 10.1016/j.conbuildmat.2021.124313

Dong, Y., Cui, X., Yin, X., Chen, Y., and Guo H. (2019). "Assessment of energy saving potential by replacing conventional materials by cross laminated timber (CLT)-A case study of office building in China," *Buildings* 9(5), 858. DOI: 10.3390/app9050858

Frank, J. W., and Robert, L. W. (1920). "Composite Lumber," U.S. Patent No. 1465383A. Washington, D.C: U.S. Patent and Trademark Office

Fujimoto, Y., Tanaka, H., Morita, H., and Kang, S. G. (2021). "Development of ply-lam composed of Japanese Cypress laminae and Korean larch plywood," *Journal of the Korean Wood Science and Technology* 49(1), 57-66. DOI: 10.5658/WOOD.2021.49.1.57

ISO 16696-1 (2019). "Timber structures-cross laminated timber-Part 1: component performance, production requirements and certification scheme," International Organization for Standardization.

Kang, C. W., Hashitsume, K., and Kolya, H. (2023). "A resonator installed in a wooden puzzle board greatly enhances sound absorption capability at low frequency: A new approach," *Results in Engineering.* 17, article 101021. DOI: 10.1016/j.rineng.2023.101021

Kim, S. H., Kim, D. H., Jo, J. I., Kim, J. H., Lee, S. H., Choi, J. K., and Kim, N. H. (2021). "A comparative study on the physical and mechanical properties of Dahurian larch and Japanese larch grown in Korea," *Wood Research* 66(3), 415-426. DOI: 10.37763/wr.1336-4561/66.3.415426

KS F 2081 (2021). "Cross laminated timber," Korea Agency for Technology and Standards, Seoul, Korea.

Kurzinski, S., Crovella, P., and Kremer, P. (2022). "Overview of cross-laminated timber (CLT) and timber structure standards across the world," *Mass Timber Construction Journal* 5(1), 1-13. DOI: 10.55191/MTCJ.2022.1

Li, J. H., Rismanchi, B., and Ngo, T. (2019). "Feasibility study to estimate the environmental benefits of utilising timber to construct high-rise buildings in Australia," *Building and Environment* 147, 108-120. DOI: 10.1016/j.buildenv.2018.09.052

Li, H., Wang, B. J., Wei, P., and Wang, L. B. (2019). "Cross-laminated timber (CLT) in China: A state-of-the-art," *Journal of Bioresources and Bioproducts* 4(1), 22-30. DOI: 10.21967/jbb.v4i1.190

Li, M. and Ren, H. (2022). "Study on the interlaminar shear properties of hybrid cross-laminated timber (HCLT) prepared with larch, poplar and OSB," *Industrial Crops and Products* 189, article 115756. DOI: 10.1016/j.indcrop.2022.115756

Martin, B., Mohamed, Z. M. S., and Srba, J. (2012). "Formaldehyde emission monitoring from a variety of solid wood, plywood, blockboard and flooring products manufactured for building and furnishing materials," *Journal of Hazardous Materials* 221-222, 68-79. DOI: 10.1016/j.jhazmat.2012.04.013

Pang, S. J., Lee, H. J., Yang, S. M., Kang, S. G., and Oh, J. K. (2019) "Moment and shear capacity of ply-lam composed with plywood and structural timber under out-of-plane bending," *Journal of Wood Science* 65(1), 68. DOI: 10.1186/s10086-019-1847-8

Pang, S. J., Ahn, K. S., Kang, S. G., and Oh, J. K. (2020). "Prediction of withdrawal resistance for a screw in hybrid cross-laminated timber," *Journal of Wood Science* 66(1), 79. DOI: 10.1186/s10086-020-01926-8

Pang, S. J., Lee, H. S., and Oh, J. K. (2023). "Lateral load carrying capacities of particleboard shear walls made by gluing with timber studs," *BioResources* 18(1), 1072-1095. DOI: 10.15376/biores.18.1.1072-1095

Soti, R., Ho, T. X., and Sinha, A. (2021). "Structural performance characterization of mass plywood panels," *Journal of Materials in Civil Engineering* 33(10), article 04021275. DOI: 10.1061/(ASCE)MT.1943-5533.0003902

Song, Y. J., and Hong, S. I. (2016). "Evaluation of bonding strength of larch cross-laminated timber," *Journal of the Korean Wood Science and Technology* 44(4), 607-615. DOI: 10.5658/WOOD.2016.44.4.607

Suh, J.S., Hwang, S. W., Hwang, K. H., Jeong, G. Y., and Joung, H. H. (2012). "Shear strength of nailed connection of domestic plywood as a substitute for OSB," *Journal of the Korean Wood Science and Technology* 40(4), 287-293. DOI: 10.5658/WOOD.2012.40.4.287

Vairo, M., Pignatta Silva, V., and Hideyoshi Icimoto, F. (2023). "Behavior of cross-laminated timber panels during and after an ISO-fire: an experimental analysis," *Results in Engineering.* 17, article 100878. DOI: 10.1016/j.rineng.2023.100878

Wang, Z., Fu, H, Gong, M., Luo, J., Dong, W., Wang, T., and Chui, Y. H. (2017). "Planar shear and bending properties of hybrid CLT fabricated with lumber and LVL," *Construction and Building Materials* 151, 172-177. DOI: 10.1016/j.conbuildmat.2017.04.205

Yang, S.M., Lee, H. H., and Kang, S. G. (2021). "Research trends in hybrid cross-laminated timber (CLT) to enhance the rolling shear strength of CLT," *Journal of the*

Korean Wood Science and Technology 49(4), 336-359. DOI: 10.5658/WOOD.2021.49.4.336

Zhou, Q., Gong, M., Chui, Y. H., and Mohammad, M. (2014). "Measurement of rolling shear modulus and strength of cross laminated timber fabricated with black spruce," *Construction and Building Materials* 64, 379-386. DOI: 10.1016/j.conbuildmat.2014.04.039

Zhao, X., Ma, Z. O., Chen, B. Y., Shang, Y. P., and Song, M. L. (2022). "Challenges toward carbon neutrality in China: Strategies and countermeasures," *Resources, Conservation and Recycling* 176, article 105959. DOI: 10.1016/j.resconrec.2021.105959

Article submitted: June 13, 2023; Peer review completed: July 8, 2023; Revised version received and accepted: August 4, 2023; Published: August 16, 2023.
DOI: 10.15376/biores.18.4.6971-6985