Analysis of Mechanical Properties of Cross-laminated Timber (CLT) with Plywood using Korean Larch

Chul Choi,[a] Erina Kojima,[b] Kyung-Jung Kim,[a] Mariko Yamasaki,[b] Yasutoshi Sasaki,[b] and Seog-Goo Kang [a,]*

The bending strength of hybrid wooden-core laminated timber (HWLT), a composite material made from existing cross-laminated timber (CLT) and plywood, was analyzed. Using plywood makes it possible to decrease the bending strength of the starting material. Korea Larch (*Larix kaempferi* Carr.) was used as plywood because of its popularity in Korea. To analyze HWLT's bending properties, each component (lamina, plywood) was tested for bending, compression, and tensile strengths. The results showed that the HWLT's bending strength depended on the plywood's number of plies. With an increased number of plies, plywood's bending strength decreased, and also HWLT's bending strength decreased. Most of the failure showed in-plate shear failure of plywood. This result meant that use of reinforced plywood made it possible to increase HWLT's bending strength for structural material.

Keywords: Hybrid Wooden-core Laminated Timber (HWLT); Korean Larch; Plywood; Bending strength; Material analysis

*Contact information: a: Department of Biobased materials, College of Agriculture & Life Science, Chungnam National University, 99 Daehangno, Yuseong-gu, Daejeon 305-764, Korea; b: Timber Engineering Laboratory, Department of Biosphere Resources Science, Nagoya University, Nagoya, Japan; * Corresponding author: lachesis@cnu.ac.kr*

INTRODUCTION

There has been recent growth in interest in wooden housing, and since 2010 there has been increased building of wooden structures. For a 99 m^2 house, around 177,000 m^3 of timber is needed. However, according to the Korea Forest Service status of the production, import, and distribution market, most timber structures are made from imported wood, rather than domestic wood (Korea Forestry Promotion Institute 2015; Korea Forest Service 2015).

It is not surprising that when analyzing the current state of domestic wood in detail, the growing stock of Korea is about 900 million m^3. According to the 2014 Korea Forest Service status, although 9 million m^3 of domestic wood were logged, only 60% of the logs (5 million m^3) were used, mostly for low-value products such as pulp chips, pellets, boards; and only 16% of the logs were used for sawn wood (Korea Forest Service 2015, 2016). Because Korea's forests have the disadvantage of having low and small diameter woods, it is hard to use domestic woods for structural lumber. In addition, according to references, in Japan, 46.9% of domestic wood is used as sawn wood and plywood (Ministry of Agriculture, Forestry and Fisheries 2015; Korea Forest Service 2016). However, in Korea only 31.8% of the domestic wood has the same use. Furthermore, according to the 2015 Japan status of self-sufficiency by uses, 47% of wood is used as sawn wood and 36% is veneer as plywood (a 6% increase). However, most of the pulp chip supply relies on imports (Ministry of Agriculture, Forestry and Fisheries 2015; Korea Forest Service 2016).

One of the high value and efficient uses of domestic wood is plywood, which is one of the major industries in Korea. In the history of Korea's plywood industry, the consumption of plywood increased in the 1930s due to its low prices and the active construction industry after Korea's independence. Plywood has a better dimensional stability than solid wood and is used in wide panel wood products. In 2014, the domestic production amount of plywood was about 470,000 m^3, and its main uses were for construction, furniture, instruments, and ships (Korea Forestry Promotion Institute 2015; Korea Forest Service 2015). The manufacturing process of plywood involves 0.5-mm- to 1.5-mm-thick veneer made by a rotary lathe. These veneers are then cross-laminated in odd numbers with a thermosetting resin.

Although the amount of domestic plywood production has remained the same, the amount of imported plywood has increased. Most imported low-price plywood comes from China or East-South Asia. According to the status of the Forest Service, the increase in imports of plywood is due to a lack of development of new plywood applications, which has caused a decrease in the sales of the plywood industry (National Institute of Forest Science 2015; Ministry of Land, Infrastructure and Transport 2016). While structural glued laminated timber is popular abroad, it is hard to manufacture in Korea. Glued laminated timber is laminated in such a way that the fibers are parallel to each other, and it is commonly used in columns and beams. After the 1990s, glued laminated timber began to be used as a structural material. Timber products of approximately 20 mm thickness were laminated in parallel, with respect to their thickness and width direction, with the adhesive. This glued laminated timber can be categorized into various forms, such as straight-laminated timber, curved-laminated timber, I-form laminated timber, *etc.* In the Japan Agricultural Standard, glued laminated timber is classed as either horizontal laminated timber or vertical laminated timber depending on the stress direction (JAS 2010). The standard of structural glued laminated timber is critically dependent upon the allowable stress because these materials are used for structures. In addition, structural glued laminated timber that is intended for structures is intentionally laminated to improve its strength. However, this timber is unsuitable in Korea because of the short height and small diameters of the trees in the Korean forests.

Cross-laminated timber (CLT) has plywood and glued laminated timber characteristics, is developed for its use as low-grade wood, and currently garners local and global interest as massive timber. In the early 1990s, CLT was introduced in Austria (Mohammad *et al.* 2012; Karacabeyli and Douglas 2013; Grasser 2015). In the middle of the 1990s, Austria started to develop CLT for commercialization, and CLT construction methods continued to develop until the early 2000s. As shown in Fig. 8, CLT is cross-laminated with more than 3 pieces of wide glued laminated timber (Mohammad *et al.* 2012). Construction structures made of CLT are lighter than existing concrete-steel structures, and CLT is also able to reduce construction days and human resources because it can be pre-cut in a manufacturing factory. In 2011, the amount of CLT production in the world was about 475,000 m^3, with Central Europe and North America having the highest levels of production (Schickhofer 2013).

Most countries that consume CLT and glued laminated timber use their domestic woods. In Europe and North America, Douglas fir, spruce-fir, Hem-fir, and yellow pine are used for lamina, and recently Japan has begun to use larch and hinoki cypress. However, it is hard to find enough good quality wood for CLT and glued laminated timber lamina in Korea. In addition to that, a larger-sized press (the maximum size is 1220 × 2440 mm^2 press) does not exist in Korea. Therefore, it is hard to apply the aforementioned CLT manufacturing system to the existing production facilities.

In severely disadvantageous situations, using domestic wood for high-valuable application is necessary. It is especially necessary to focus on glued laminated timber, CLT, and the use of native woods, not only using native woods as pulp, but also pellet as low value products. In Korea, it is hard to make quality lamina because most of the forest is natural forest, which means that only short wood of a small diameter is available. Therefore, it is important to change the existing manufacturing system of CLT and glued laminated timber to have a more competitive price with imports. To utilize domestic wood as structural lumber, it is necessary to utilize new structures and improve or replace the existing manufacturing methods. This article is focused on plywood core glued laminated timber, which has been reported to have mechanical strength and dimensional stability equivalent to that of existing CLT (Choi *et al*. 2015).

For the development of a new CLT suitable for Korea's forest status, this thesis analyzed the mechanical properties and strength probabilistic distribution of hybrid wooden-core laminated timber (HWLT), which is a composite material made from existing CLT and plywood. For the experiment, North American Douglas fir, commonly used for structural lumber, was used as the lamina specimen. For the plywood specimen, the typical softwood domestic Larch were both utilized. This thesis analyzed the bending property of HWLT, the mechanical properties (bending, compression, and tensile strength), and the elastic modulus of each material component (lamina, plywood), to investigate the factors that influence the bending property of HWLT.

EXPERIMENTAL

Materials

Veneer for plywood

Short grain core veneers of *Larix kaempferi* Carriere (Sunchang Co., Ltd., Incheon, Korea) were used for the manufacturing of HWLT and for material experiments. The dimensions of the original veneers were 1,220 mm × 2,440 mm × 2.2 mm, and the dimensions for the veneers cut with a table saw were 600 mm × 600 mm. Veneers were dried before making plywood, and the final average moisture was 3 to 4%.

Lamina

The lumbers for the lamina were produced from North American Douglas fir (Shindaerim Sawmill, Incheon, Korea). The dimensions for each lumber were 150 mm × 1,200 mm × 15 mm, and their moisture content was lower than 9%.

Adhesives

Phenol-formaldehyde adhesive (Sunchang Co., Ltd., Incheon, Korea) was used for the plywood manufacturing, and the resorcinol-phenol-formaldehyde adhesive (Oshika Co., Tokyo, Japan) was used for the HWLT. All of the properties of the two types of adhesive are listed in Table 1. Calcium carbonate (Samchun Chemical, Pyeongtake, Korea) was used as the hardener of the phenol-formaldehyde adhesive, and the hardner was added 5% of adhesive Nonvolatile Contents (N.V.C). The flour was used as extender. The usage ratio was the less than 10 w.t%. The hardener components of resorcinol-phenol-formaldehyde are listed in Table 2.

Table 1. Physical and Chemical Properties of the Adhesives

Resin Type	Temperature (°C)	Viscosity (cPs)[a]	pH	Nonvolatile Content (N.V.C) (%)
Phenol formaldehyde	18	110	12.1	42.8
Resorcinol-phenol-formaldehyde	19	180	8.3	54.2
[a] The viscosity was measured for Zahn cup (No. 3) according to ASTM D1084-16 (2016), the temperature of the fluid was 19 °C				

Table 2. Components of the Resorcinol-phenol-formaldehyde Hardener

Ingredients	wt.%
Paraformaldehyde	45 to 55
Coconut shell flour	45 to 55

Methods

Test specimen manufacturing- Plywood

Veneers of a 2.2-mm-thickness from the Korean Larch species were used as the plywood testing specimens. The spread volume of the phenol-formaldehyde adhesive was 140 g/m^2 on both sides. The hot press cycle was carried out at a temperature of 140 °C, unit pressure of 0.1 MPa, and under a pressure time of 3 min after the middle layer is reached 90 °C. Two different numbers of plies (3-ply and 5-ply) were manufactured, and their densities are shown in Table 4.

Hybrid wooden-cores laminated timber (HWLT)

For the manufacturing of the HWLT, Douglas fir and resorcinol-phenol-formaldehyde adhesive were used. The amount of adhesive used was 140 g/cm^2. The cold press cycle was carried out at room temperature, a unit pressure of 0.1 MPa, and an under pressure time of 6 h. The HWLT's construction is shown in Fig. 1.

Fig. 1. HWLT components structure

Table 3. Press Cycle for Plywood and HWLT Manufacturing

	Plywood	HWLT
Time	3 min. after the middle layer is reached 90 °C	6 hour
Temperature	140 °C	25 ± 3 °C
Unit pressure	0.1 MPa	0.1 MPa

Mechanical properties- Bending strength

The bending properties of the HWLT and lamina were measured according to KSF 2208 (2014) and KSF 2159-1 (2007) standards, and a universal testing machine (Tinius olsem Ltd., H50K-ST, Redhill, England) was used to measure the modulus of rupture (MOR) and the modulus of elasticity (MOE). The crosshead speed was 10 mm/min, the MOR and MOE were measured by the 4-points method, and the span length was 48 times the specimen's thickness. The bending strength of the plywood was measured by KSF 3113 (2004), and the universal testing machine (Fig. 2) was used to measure the MOR and MOE. The crosshead speed was 10 mm/min, and the MOR and MOE were measured by the 3-points method. The span length was 24 times the specimen's thickness.

Fig. 2. Universal testing machine (H50K-ST, Tinuius olsem Ltd., Redhill, England)

Compression strength

The compression strength of lamina and plywood were measured according to KSF 2158-1 (2007) and KSF 3113 (2004), respectively, and the same universal testing machine mentioned previously was used to measure the ultimate compressive strength (UCS). The crosshead speed was 5 mm/min.

Tensile strength

The tensile strength of the lamina and plywood were measured according to KSF 2207 (2014), and the same universal testing machine was used to measure the ultimate tensile strength (UTS). The crosshead speed was 2 mm/min.

For the tensile strength of plywood, Kuwamura (2010) reported that the mechanical properties of plywood, and its tensile strength can be obtained by the lumber's tensile testing method (Kuwamura 2010).

Table 4. Test Specimen Dimensions

Type	Mechanical Properties	Width (mm)	Thickness (mm)	Span (mm)	Sample Number
HWLT	Bending strength	40	40	Thick × 13	12
Lamina	Bending strength	50	-	Thick × 48	30 to 40
	Compression strength	25	-	100	
	Tensile strength	Fig. 2			
Plywood	Bending strength	50	-	Thick × 24	40 to 50
	Compression strength	25	-	50	
	Tensile strength	Fig. 2			

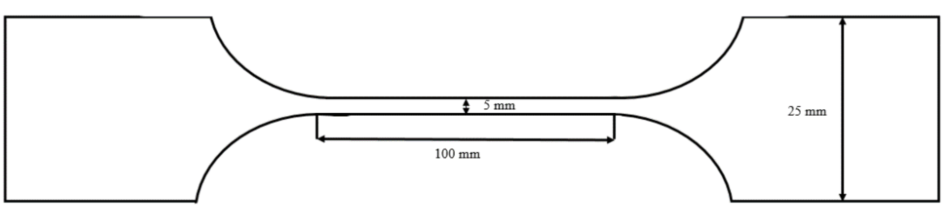


Fig. 3. Specimen for the tensile test

Statistical analysis

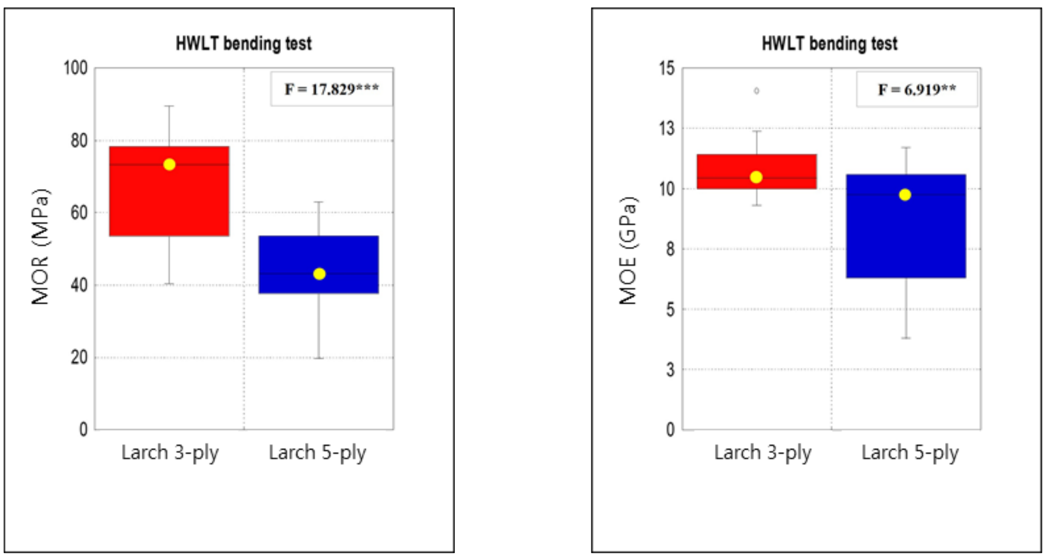
All of the experiments were statistically analyzed ($p < 0.05$) using SPSS 22 (IBM, V22.0.0, New York, USA) to verify the significance of the strength results according to the species of plywood or the structure. For Figs. 3, 6, and 10 below, * represents $p < 0.05$, ** represents $p < 0.01$, and *** represents $p < 0.001$.

RESULTS AND DISCUSSION

HWLT Bending Strength Characteristics

HWLT bending strength

Figures 4(a) and (b) show the MOR and MOE results according to the number of plywood layers of HWLT manufactured using domestic larch. A decrease in the MOR of the HWLT was observed with an increase in the number of plywood layers. The MOR results were 67.8 MPa ± 15.1 MPa for 3-ply plywood, and 43.9 MPa ± 12.6 MPa for 5-ply plywood. As the number of plywood layers increased, the in-plate shear force of the plywood was larger than the tensile force. As the result, in-plate shear failure was increased 83% to 92%. It was noted that the in-plate shear force due to an increase in the number of plywood layers caused a greater effect than the tensile force, and it caused a decrease in strength. The MOE values were 10.8 GPa ± 1.4 GPa for a 3-ply plywood, and 8.6 GPa ± 2.6 GPa for 5-ply plywood. The statistical analysis of the MOR and MOE values indicates that the MOR and MOE were different according to the number of plywood layers.



(a) MOR (b) MOE

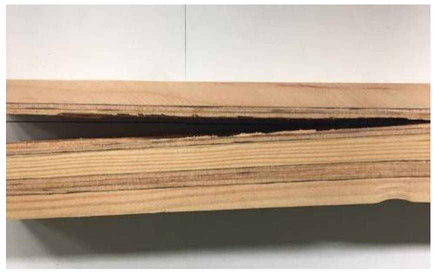
Fig. 4. Bending test results of HWLT with Korean larch plywood

Bending property of plywood

Figure 6 shows the graphs of the MOR and MOE results as a function of the number of plywood layers (3-ply or 5-ply) of the bending test. As the number of plywood layers increased, the MOR values decreased. Korean Larch showed a MOR value of 85.6 MPa ± 15.9 MPa for 3-ply, and a value of 61.3 MPa ± 22.0 MPa at 5-ply. As shown in Fig. 5, the shear failure increased more than the tensile failure as the number of plywood layers increased. Therefore, the number of plywood layers influenced the MOR of plywood. The MOE of the Korean Larch plywood was 10.2 GPa ± 1.8 GPa and 8.2 GPa ± 3.5 GPa, also for 3-ply and 5-ply, respectively.

(a) Tensile failure

(b) In-plate shear failure (plywood)

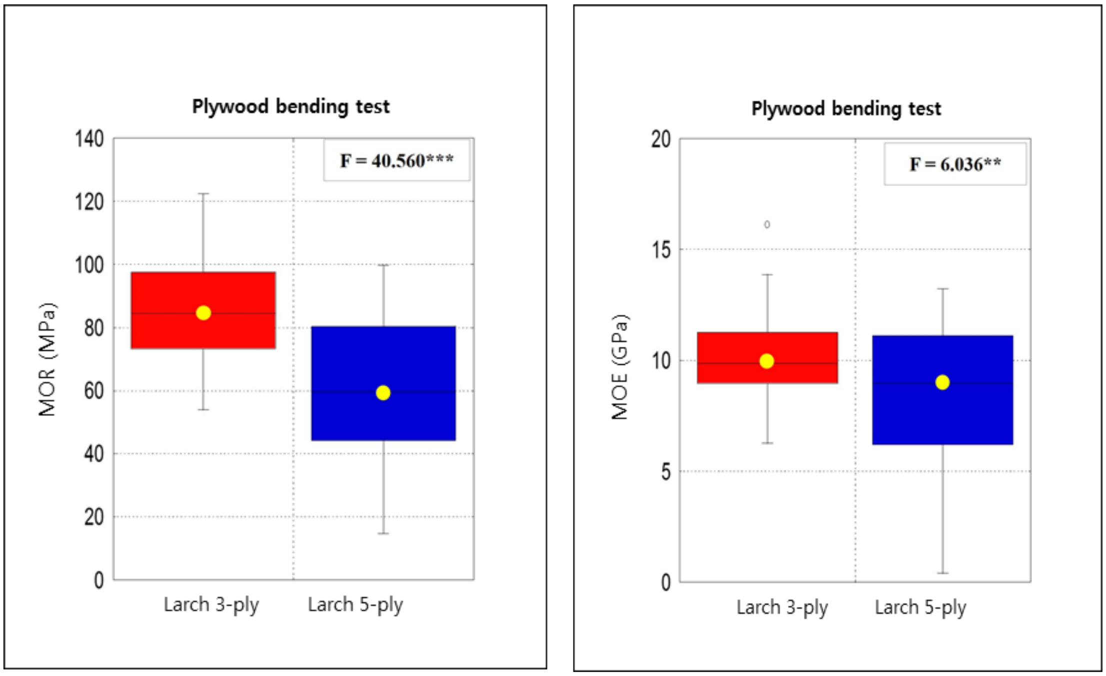


(c) Adhesive failure

Fig. 5. Typical failure types of HWLT

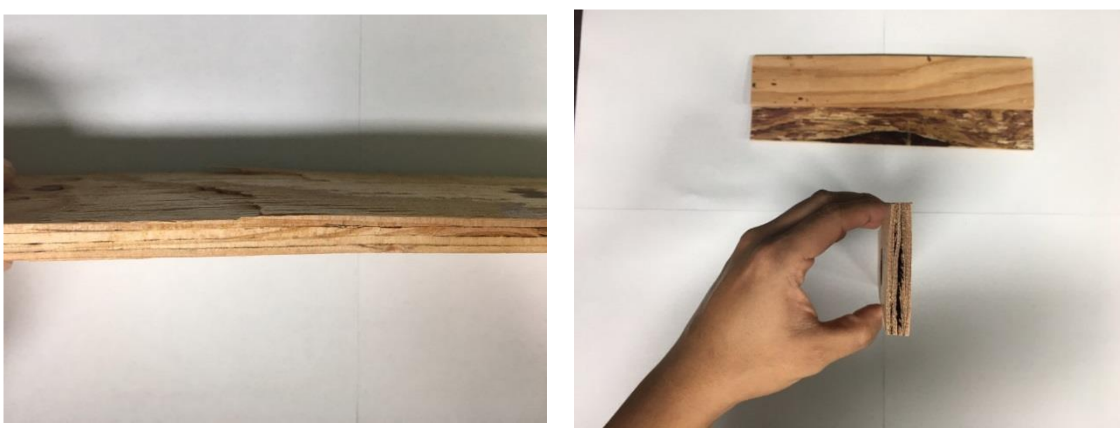
Table 6. Mechanical Properties Test Results of Lamina

Thickness	Classification	MOR	MOE	UCS	UTS
6 mm	Mean	99.71	15.48	43.29	92.82
	Standard deviation	22.95	3.44	9.33	16.74
9 mm	Mean	101.49	15.40	47.79	84.36
	Standard deviation	20.99	2.56	7.10	20.72
Significant differences (F value)		0.085	0.010	4.358**	1.015



(a) MOR (b) MOE

Fig. 6. Plywood bending test results of Korean Larch plywood



(a) Tensile failure (b) Lamina failure

Fig. 7. Typical failure type of plywood

In the statistical analysis, there were significant MOR differences with the varied number of plywood layers. Similarly, for MOE, there were significant differences between the 3-ply and 5-ply plywood layers. Plywood bending failure showed similar with HWLT's bending failure. In the result, when increasing the number of plies of plywood, wood part failure decreased 96% to 68%. According to these results (HWLT's and plywood's bending tests), HWLT's bending failure and plywood's were similar, and HWLT's in-plate failure is caused by plywood's bending properties.

Compression strength of plywood

Figure 8 shows the UCS results according to the number of plywood layers (3-ply or 5-ply). For Korean larch, the results were 10.2 MPa ± 1.9 MPa and 8.0 MPa ± 3.3 MPa for 3-ply and 5-ply, respectively. In the statistical analysis, there were no significant differences in the different numbers of plywood layers of domestic larch.

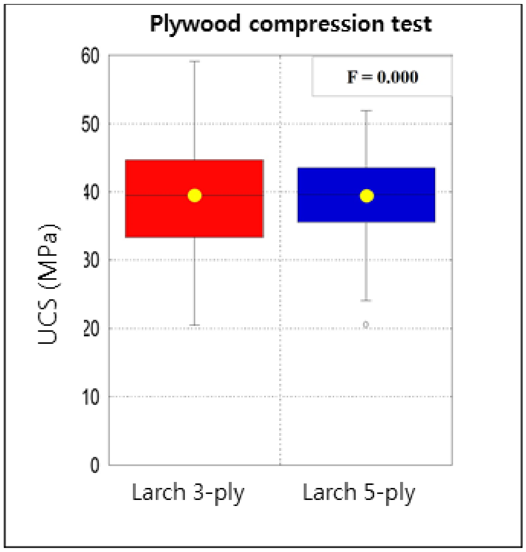


Fig. 8. UCS results of plywood

Tensile strength of plywood

Figure 9 is a graph showing the UTS results according to the number of plywood layers (3-ply/5-ply). The UTS of Korean larch plywood was 50.77 MPa ± 11.63 MPa at 3-ply, and 39.71 MPa ± 12.92 MPa at 5-ply. From the statistical analysis, it was found that there were significant differences between the two layers.

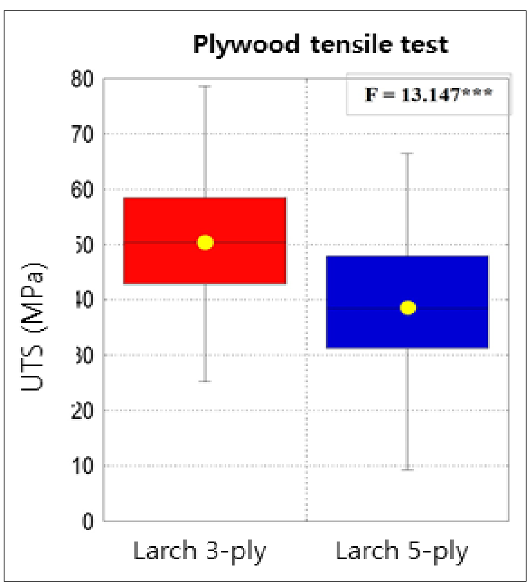


Fig. 9. UTS results of plywood

CONCLUSIONS

This study investigated what components and mechanical properties affect the bending properties of hybrid wooden-core laminated timber (HWLT). This was done by analyzing each of the components and their mechanical properties (bending, compression, tensile). Conclusions were as follows:

1. First, the HWLT has a modulus of rupture (MOR) of F255 grade (25.5 Mpa), or more, when compared with the results of the Japanese Agricultural Standard (JAS) glued laminated timber. In addition, under some conditions, the result was above the highest grade of F435 (43.5 MPa). This approach was used because a CLT standard has not been established in Korea.
2. The HWLT showed a significant difference in the MOR according to the number of plywood layers. As the number of plywood layers increased, it was found that the MOR decreased due to either adhesive failure or the in-plate force of plywood. It was considered that as the number of plywood layers is increased, the shear force and adhesive force of plywood had a greater influence on the strength of HWLT.
3. Korean larch plywood underwent bending, compression, and tensile experiments. The results of the bending test showed that the number of plywood layers affected the MOR values. In the analysis of the failure type of HWLT, the in-plate shear force increased as the number of plywood layers increased. This type of failure seemed to have a great influence on the MOR of plywood.
4. The analysis of the overall results showed that the major factors that influenced the bending properties of HWLT were the thickness and number of layers of plywood. In particular, plywood was able to increase the thickness or number of veneers, unlike lamina. However, similar to the results, when the number of layers of the plywood increased, a greater in-plate shear force was generated and the overall strength of HWLT decreased.
5. Therefore, by increasing the thickness of the veneer rather than increasing the number of layers of the plywood, it is possible to maintain the strength of HWLT while preventing the in-plate shear force.

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