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Prediction of withdrawal resistance for a screw in hybrid cross-laminated timber

Sung-Jun Pang[1], Kyung-Sun Ahn[2], Seog Goo Kang[3] and Jung-Kwon Oh[1,2*]

Abstract

The aim of this study was to predict the withdrawal resistance of a screw in hybrid cross-laminated timber (CLT) composed of two types of lamina layers. A theoretical model to predict the withdrawal resistance was developed from the shear mechanism between a screw and the layers in hybrid CLT. The parameters for the developed model were the withdrawal stiffness and strength that occurs when a screw is withdrawn, and the penetration depth of a screw in layers of a wood material. The prediction model was validated with an experimental test. Screws with two different diameters and lengths (Ø6.5 × 65 mm and Ø8.0 × 100 mm) were inserted in a panel composed of solid wood and plywood layers, and the withdrawal resistances of the screws were evaluated. At least 30 specimens for each group were tested to derive the lower 5th percentile values. As a result, the developed model predictions were 86–88% of the lower 5th percentile values of hybrid CLT from the properties of the lamina layer. This shows that the withdrawal resistance of hybrid CLT can be designed from the properties of its layer.

Keywords: Wood, Composites, Theoretical model, Withdrawal resistance, Screw, Cross-laminated timber

Introduction

Self-tapping screws have become more common as the use of the cross-laminated timber (CLT), wood-based panel laminated with orthogonal layers, has expanded, and they are commonly used to join CLT panels or to join CLT walls to a CLT floor. Self-tapping screws are characterized by tensile strength around 600–1200 MPa, diameters from 5–14 mm, thread lengths from 50–3000 mm, and inner/thread diameter ratios of 0.5–0.75 [1]. They usually do not need pre-drilling and provide fast installation with a high withdrawal resistance in wood materials. Recent research on self-tapping screws has been focused on the CLT panel shear connection [2], timber-to-timber joints [3–5], timber-to-steel joints [6–8], and timber-to-concrete joints [9–11].

The withdrawal resistance of self-tapping screws is crucial for tensile connections [12] and for estimating the rope effect of laterally loaded connections [13]. Structural design formulas for screws can be found in EN 1995–1-1 [14] and the National Design Specification (NDS) [15]. Several researchers have tried to improve the structural design formula. For example, Uibel and Blass [16] investigated the resistance of screws in CLT made of spruce with a characteristic density of 400 kg/m^3. The screws were placed perpendicular to the plane of the CLT or in the edges of the CLT. As a result, the authors derived regression models to predict the screws' withdrawal resistance in CLT, based on the Europe standard, and presented a revised formula. However, the presented formula was limited to CLT made of spruce. Therefore, Ringhofer et al. [17] investigated the withdrawal resistance of screws in glulam and CLT. They observed an increase of 7–25% on the lower 5th percentile value of a single layer for specimens had 3–7 layers. As a result, they proposed an adjustment factor based on the number of layers penetrated by the screws to predict the increased strength in the CLT compared to solid wood.

The withdrawal resistance of a screw can be normalized by the contact area (mm^2) between the screw inserted in a wood material and the wood material itself. Celebi

*Correspondence: jungoh@snu.ac.kr
[1] Research Institute of Agriculture and Life Sciences, Seoul National University, Gwanak-ro 1, Gwanak-gu, Seoul, South Korea
Full list of author information is available at the end of the article

and Kilic [18] investigated the withdrawal strength of screws and revealed that the withdrawal strength was not affected by the layer thickness. Özçifçi [19] analyzed the effects of pilot hole size, screw type, and layer thickness on the withdrawal strength of screws in laminated veneer lumber (LVL). Brandner et al. [20] investigated the effect of screw type, thread-grain angle, and pre-drilling on the withdrawal strength of screws in hardwood species.

In the case of CLT, the withdrawal strength of screws is affected by the density of the layer of the wood material [21]. There have been attempts to improve the CLT's performance and cost competitiveness by changing the cross layer to plywood or LVL. Choi et al. [22, 23] developed a Ply-lam panel which was composed of solid wood and plywood lamina. The price of plywood is lower than solid wood in the Asian market; thus, Ply-lam has advantages in terms of production cost. Moreover, the dimensional stability and thermal conductivity of Ply-lam was better than typical CLT [24–27], and fire-retardant treated plywood can be used for fire resistance improvement. The structural characteristic of Ply-lam under out-of-plane bending was also investigated [28], but the withdrawal resistance of screws in Ply-lam needs to be investigated to provide a reasonable design method.

In this study, a CTL with alternating cross layer was defined as a hybrid CLT. Several researchers investigated the structural properties of the hybrid CLT. Wang et al. [29] investigated the mechanical performances of a hybrid CLT composed of solid wood and laminated strand lumber (LSL). Pang et al. [30] investigated the bending capacities a hybrid CLT composed of solid wood and plywood lamina. Aicher et al. [31] investigated structural properties of a hybrid CLT composed of softwood (spruce) and hardwood (beech).

In the case of CLT, which is composed of layers with the same elasticity, the withdrawal resistance can be predicted by summing up the withdrawal resistance of the screws in each penetrated layer. However, in the case of hybrid CLT, composed of layers with different elasticity, the elasticity of each layer should be considered. In this study, a theoretical model to predict the withdrawal resistance for the hybrid CLT was developed and the model was validated with experimentally tested values.

Materials and methods

Prediction model

Figure 1 shows the shear mechanism between a screw and a hybrid CLT panel when the screw is pulled out by a withdrawal load. The withdrawal load is equal to the sum of the withdrawal resistance of each layer (Eq. 1). In other words, the sum of the withdrawal resistance of the layers is the withdrawal resistance of the hybrid CLT.

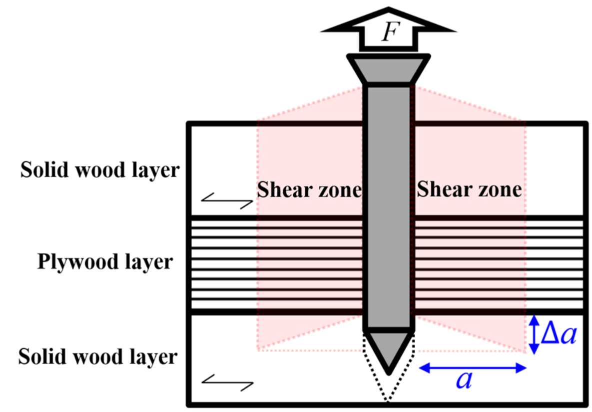

Fig. 1 Shear mechanism of screw in a panel composed of solid wood and plywood

$$R_{\mathrm{predict}} = R_s + R_p \quad (1)$$

R_{predict} = withdrawal resistance of hybrid CLT (N)

R_s = withdrawal resistance of solid wood layer (N)

R_p = withdrawal resistance of plywood layer (N)

From the shear mechanism in Fig. 1, the withdrawal strength of a screw can be derived, as shown in Eq. 2. The effective length of the shear zone (a in Fig. 1 and Eq. 2) is required for the shear mechanism theory, and it will be related to the spacing or end distance. The modified withdrawal stiffness ($G_{\mathrm{withdrawal}}$) includes the withdrawal stiffness (G) and the effective length of the a, as shown in Eq. 2. In this study, the modified withdrawal stiffness for each layer was measured by experimental test:

$$S_{\mathrm{withdrawal}} = \frac{F_{\max}}{A_{\mathrm{contact}}} = \frac{F_{\max}}{2 \cdot \pi \cdot r \cdot d} = G \cdot \frac{\Delta a}{a} = G_{\mathrm{withdrawal}} \cdot \Delta a \quad (2)$$

$S_{\mathrm{withdrawal}}$ = withdrawal strength when a screw was pulled out (MPa); $F_{\max}$ = maximum load measured by experimental test (N); A_{contact} = contact area between screw and wood layer (mm^2); r = half of outer diameter of screw (mm); d = penetration depth of screw (mm); G = withdrawal stiffness when a screw was pulled out in a lamina (MPa); Δa = displacement of screw (mm); a = effective length of shear zone when screw was pulled out (mm); $G_{\mathrm{withdrawal}}$ = modified withdrawal stiffness for withdrawal behavior (N/mm^3).

The withdrawal resistance of hybrid CLT is determined by the withdrawal stiffness of each layer. Each layer carries different load capacities that are directly proportional to its relative withdrawal stiffness and penetration depth. A low withdrawal stiffness does not share a significant amount of the load. Similarly, a high withdrawal stiffness layer shares large amounts of the load. Cramer and Wolfe [32] applied this concept to predict load distributions among trusses of various stiffnesses. Pang and Jeong [33] also applied this concept to predict the compressive resistance of CLT. When a screw in hybrid CLT was withdrawal, the vertical deflections of all the layers in the hybrid CLT was identical. Thus, Eq. 3 can be derived from Eq. 2. If Eq. 3 is rearranged to solve for the withdrawal resistance of each layer, Eq. 4 can be derived:

$$\Delta a = \frac{R_s}{G_s \cdot 2 \cdot \pi \cdot r \cdot d_s} = \frac{R_P}{G_p \cdot 2 \cdot \pi \cdot r \cdot d_p} \quad (3)$$

$$R_s = \frac{G_s \cdot d_s}{G_p \cdot d_p} R_p \; or \; R_p = \frac{G_p \cdot d_p}{G_s \cdot d_s} R_s \quad (4)$$

$\Delta a =$ displacement of screw (mm); R_s = withdrawal resistance of solid wood layer (N); G_s = modified withdrawal stiffness for withdrawal behavior in solid wood layer (N/mm^3); r = half of outer diameter of screw (mm); d_s = penetration depth of screw in solid wood layer (mm); R_p = withdrawal resistance of plywood layer (N); G_P = modified withdrawal stiffness for withdrawal behavior in plywood layer (N/mm^3); d_p = penetration depth of screw in plywood layer (mm).

Substituting Eq. 4 into Eq. 1 leads to Eq. 5. Equation 5 shows that a specific layer carries a load in proportion to its relative withdrawal stiffness and penetration depth:

$$R_{predict} = \left(\frac{G_s \cdot d_s}{G_p \cdot d_p} + 1\right) R_p \text{ or } \left(\frac{G_p \cdot d_p}{G_s \cdot d_s} + 1\right) R_s \quad (5)$$

$R_{predict}$ = withdrawal resistance of hybrid CLT(N); G_s = modified withdrawal stiffness for withdrawal behavior in solid wood layer (N/mm^3); d_s = penetration depth of screw in solid wood layer (mm); G_P = modified withdrawal stiffness for withdrawal behavior in plywood layer (N/mm^3); d_p = penetration depth of screw in plywood layer (mm); R_p = withdrawal resistance of plywood layer (N); R_s = withdrawal resistance of solid wood layer (N).

Finally, Eq. 6 can be derived to predict the withdrawal resistance of screws in hybrid CLT by replacing the withdrawal resistance with withdrawal strength and contact area. The developed model reflects the load sharing effect of the layers, and the load sharing is assumed to be constant until ultimate failure occurs at the weakest layer. When a layer reaches its ultimate withdrawal resistance, the other layers also contribute to the withdrawal resistance in an amount equaling the ratio of the withdrawal stiffness to the penetration depth. The ultimate withdrawal resistance of a layer is determined by the withdrawal strength and penetration depth of screw. The withdrawal strength of each layer was assumed to be the lower 5th percentile value, and those values were then used to predict the lower 5th percentile value of hybrid CLT. In this way, the two withdrawal resistance values of hybrid CLT were predicted from the withdrawal resistance two layers. The smaller of the two predicted values was used as the withdrawal resistance of the hybrid CLT:

$$R_{predict} = \min\left[\left(\frac{G_s \cdot d_s}{G_p \cdot d_p} + 1\right) S_P \cdot 2 \cdot \pi \cdot r \cdot d_p, \left(\frac{G_p \cdot d_p}{G_s \cdot d_s} + 1\right) S_s \cdot 2 \cdot \pi \cdot r \cdot d_s\right] \quad (6)$$

$R_{predict}$ = withdrawal resistance of hybrid CLT (N); G_s = modified withdrawal stiffness for withdrawal behavior in solid wood layer (N/mm^3); d_s = penetration depth of screw in solid wood layer (mm); G_s = modified withdrawal stiffness for withdrawal behavior in plywood layer (N/mm^3); d_p = penetration depth of screw in plywood layer (mm); S_s = withdrawal strength of solid wood layer when a screw was pulled out (MPa); S_p = withdrawal strength of plywood layer when a screw was pulled out (MPa).

Table 1 Specifications of lamina materials

	Solid wood	Plywood
Density (kg/m^3)[a]		
Average	578.89	708.40
COV[b]	0.11	0.04
5th percentile	478.79	659.93
Specific gravity		
Average	0.50[c]	0.66[d]
Species	*Larix kaempferi*	
Moisture contents	13.23	7.93

[a] Calculated by Eq. 1 with air-dry weight and air-dry volume of lamina material

[b] Coefficient of variation

[c] From Korean Design Standard [35]

[d] Calculated by Eq. 2 with oven-dry weight and oven-dry volume of lamina material

Experimental test materials

Materials

Lamina

Table 1 shows the air-dry density, specific gravity, and moisture contents for solid wood and plywood lamina. The density of the solid wood was calculated by Eq. 7, using the air-dry weight and air-dry volume at the test moisture content [34]. All of the specimens were made from the larch (*Larix kaempferi*) species. The specific gravity for the larch species is tabulated in the Korean Design Standard [35], but the specific gravity for plywood was not tabulated in the standard. Thus, the specific gravity of plywood was calculated from the oven-dry weight and oven-dry volume using Eq. 8.

The size of the solid wood lamina was 25 mm (thickness) × 100 mm (width) × 2700 mm (length), and the moisture content (MC) was 12 ± 2%. The size of the plywood was 24 mm (thickness) × 1200 mm (width) × 2400 mm (length), and the MC was 7 ± 1%. The grades of the plywood and solid wood laminas were No. 1 and No. 3, respectively, according to NIFoS #2018-8 [36]. The laminas were cut to a 200 mm length for the withdrawal test:

$$\rho = \frac{W_{air-dry}}{V_{air-dry}}. \tag{7}$$

ρ = density of lamina material at the test moisture content (kg/m^3); $W_{air-dry}$ = air-dry weight (kg); $V_{air-dry}$ = air-dry volume (m^3):

$$SG = \frac{W_{oven-dry}}{V_{oven-dry}}/1000. \tag{8}$$

SG = specific gravity of lamina material based on oven-dry weight and oven-dry volume; $W_{oven-dry}$ = oven-dry weight (kg); $V_{oven-dry}$ = oven-dry volume (m^3).

Ply-lam

The Ply-lam panel was manufactured by gluing the solid wood and plywood laminas. Figure 2 shows the layer composition of the Ply-lam, which consisted of 5 layers for a total thickness of 123 mm. Phenol resorcinol formaldehyde resin (PRF resin) adhesive was used to glue the flat surface of the five layers. The amount of glue spread over the layers was 200 g/m^2, and the five stacked layers were pressed together under a pressure of 0.8 MPa for 8 h. The thickness of the adhesive layer was thin, about 0.1 mm, and the effect of the adhesive layer was not considered in this study. The manufactured Ply-lam panel was cut to a size of 300 (width) × 200 mm (length) for the withdrawal test.

Screws

To evaluate the withdrawal resistance of a screw inserted in wood materials, two types of screws (Vinzenz Harrer GmbH, Austria) were inserted in solid wood lamina, plywood lamina, and ply-lam specimens. Table 2 shows the specifications of the screws. The diameter and length for first type of screw (Ø6.5 × 65 mm) were 6.5 mm and 65 mm, and those for the second type of screw (Ø8.0 × 100 mm) were 8.0 mm and 100 mm.

Withdrawal resistance test

To determine the input parameters of the developed model (Eq. 6), withdrawal tests on the laminas were carried out. The withdrawal test for Ply-lam was conducted

Table 2 Specifications of screws [37]

Self-tapping screw	Ø6.5 x 65 mm	Ø8.0 x 100 mm
Tensile strength (MPa)	≥ 600	≥ 600
Modulus of elasticity (MPa)	210,000	210,000
Outer thread diameter (mm)	6.50	8.00
Inner thread diameter (mm)	3.25	5.30
Inner thread diameter ratios	0.50	0.66
Length (mm)	65.00	100.00
Tip length (mm)	5.6	11.5
Head diameter (mm)	10.00	13.00
Pitch (mm)	2.80	3.60

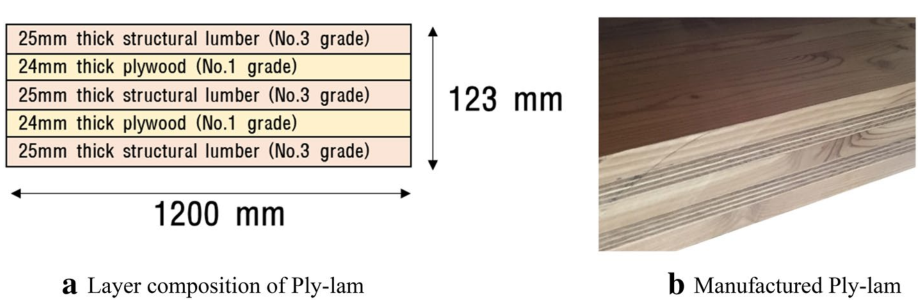

Fig. 2 Ply-lam composition

Table 3 Specimens and test results depending on the test configurations

Group	Wood material		Screw		Repetition	Withdrawal resistance			Withdrawal strength[c] (MPa)
	Type	Thickness (mm)	Diameter x length (mm)	Penetration depth (mm)		Average (kN)	COV[a]	5th percentile value[b] (kN)	
Solid-6.5[d]	Solid wood	24	6.5 × 65	24	30	4.32	0.20	2.85	5.81
Solid-8.0			8.0 × 100	24	32	4.49	0.19	3.19	5.29
Plywood-6.5	Plywood	24	6.5 × 65	24	30	5.43	0.07	4.77	9.74
Plywood-8.0			8.0 × 100	24	30	6.10	0.06	5.47	9.07
Ply-lam-6.5	Ply-lam	123	6.5 × 65	33	32	5.30	0.17	3.76	6.72
Ply-lam-8.0	(25-24-25-24-25)[e]		8.0 × 100	70	32	13.96	0.10	12.00	8.16

[a] Coefficient of variation

[b] Lower 5th percentile value

[c] Lower 5th percentile value divided by the contact area between the screw inserted in the wood material and the wood material (Eq. 2)

[d] Diameter of screw (mm)

[e] Parentheses show thickness of each layer (from bottom to top)

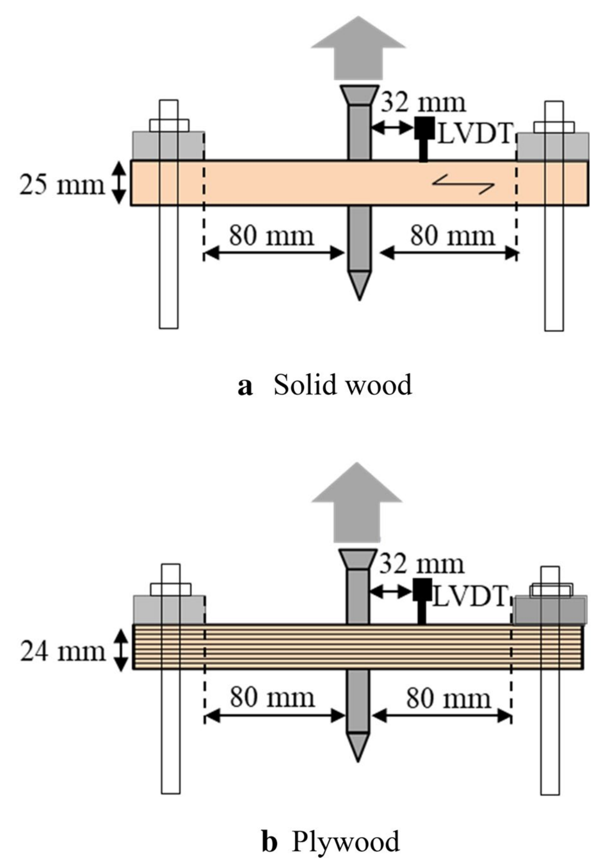

Fig. 3 Withdrawal test configurations for solid wood and plywood

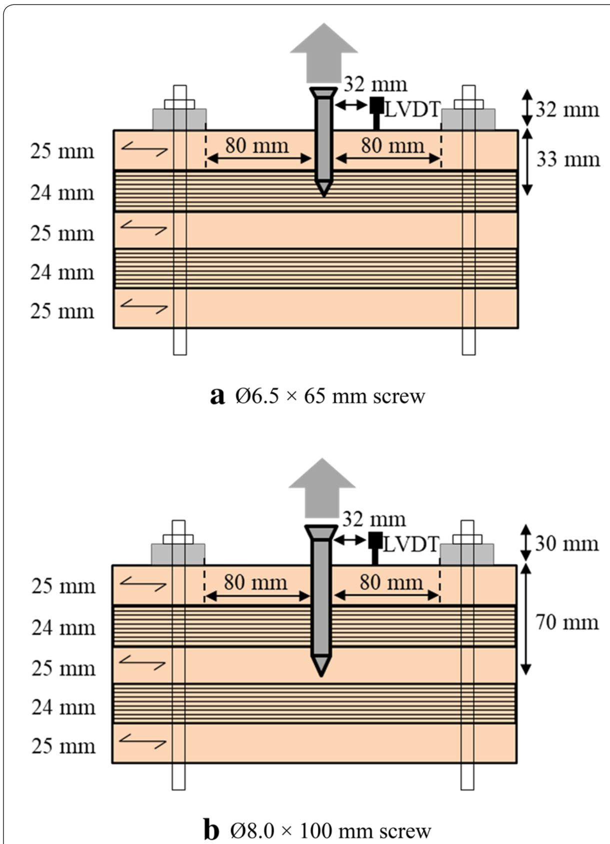

Fig. 4 Penetration depth for Ply-lam specimen (odd layer: solid wood; even layer: plywood)

to verify the predicted values derived from the developed model. Table 3 shows the specimen nomenclature and the condition of the specimens in the withdrawal resistance test. The nomenclature of the six groups of specimens was determined depending on the specimen type and the diameter of the penetrated screw.

For solid wood and plywood lamina, the screws penetrated through the full thickness of the specimens, as shown in Fig. 3. The thickness of the solid wood and plywood lamina was equal to the penetration depth of screws. Figure 4 shows the withdrawal test configuration for the Ply-lam specimens. The penetration depth of the Ø6.5 × 65 mm screws was 33 mm and that for the Ø8.0 × 100 mm screws was 70 mm. To connect the screw to the test machine, 30 mm of the screw, as measured from the screw head, could not be inserted into the Ply-lam specimen. When measuring the modified withdrawal stiffness ($G_{\text{withdrawal}}$), if the displacement of screw (Δa in Fig. 1) is measured within the effective length of the shear zone (aa in Fig. 1), an inaccurate $G_{\text{withdrawal}}$ is measured. Since the exact effective length (a) was not known, it was assumed that it would not exceed four times the screw diameter according to the spacing of screws recommended by NDS [15]. Thus, to measure the displacement of the screw, a wood block was placed 32 mm away from the screw and the Linear Variable Displacement Transducers (LVDT) was placed on the wood block, as shown in Fig. 5. The distance was about five times the diameter of the Ø6.5 × 65 mm screw and four times the diameter of the Ø8.0 × 100 mm screw.

At least 30 specimens for each group were tested to determine the lower 5$^{\text{th}}$ percentile value of the withdrawal resistance of the screws. The load speed was determined, so that the screw could be pulled out from the specimens within 1–2 min after applying the load, according to the KS F ISO 9087 standard [38]. The applied load speed was 7 mm/min for the Ø6.5 × 65 mm screws and 10 mm/min for the Ø8.0 × 100 mm screws.

The withdrawal strength of a screw in lamina was determined by dividing the maximum withdrawal load by the contact area between the screw inserted in the specimen and the wood specimen itself (Eq. 2). The withdrawal stiffness of the screw was determined from Eq. 9. It was assumed that the behavior of withdrawal resistance of the screw is linearly elastic. The load–displacement curve of withdrawal behavior was not complete linear, but the withdrawal stiffness was calculated at the linear part of the load–displacement curve between 10 and 40% of max load according to the ISO 6891 standard [39]:

$$G_{\text{withdrawal}} = \frac{F_{0.4} - F_{0.1}}{2 \cdot \pi \cdot r \cdot d \cdot (a_{0.4} - a_{0.1})}. \tag{9}$$

$G_{\text{withdrawal}}$ = modified withdrawal stiffness for withdrawal behavior (N/mm^3); G_{lamina} = modified withdrawal stiffness for withdrawal behavior (N/mm^3); $F_{0.1}$ and $F_{0.4}$ = the loads corresponding to 10% and 40% of the ultimate load $P_{\max}$, respectively (kN); r = half of outer diameter of screw (mm); d = penetration depth of screw (mm); $a_{0.1}$ and $a_{0.4}$ = displacements corresponding to $P_{0.1}$ and $P_{0.4}$, respectively (mm).

Lower 5th percentile value

Characteristic values of the test specimen were determined by nonparametric lower 5$^{\text{th}}$ percentile point estimate. The test values were arranged in ascending order. Beginning with the lowest value, $i/(n+1)$ was calculated. The lower 5$^{\text{th}}$ percentile value was interpolated by Eq. (10):

$$\text{Lower 5th percentile value} = \left[\frac{5}{100}(n+1) - (j-1)\right]\left[x_j - x_{(j-1)}\right] + x_{(j-1)}, \tag{10}$$

where n: total number of samples, j: the lowest order of the test value when $i/(n+1) \geq 0.05$, i: the order of the test value, x_i: ith value.

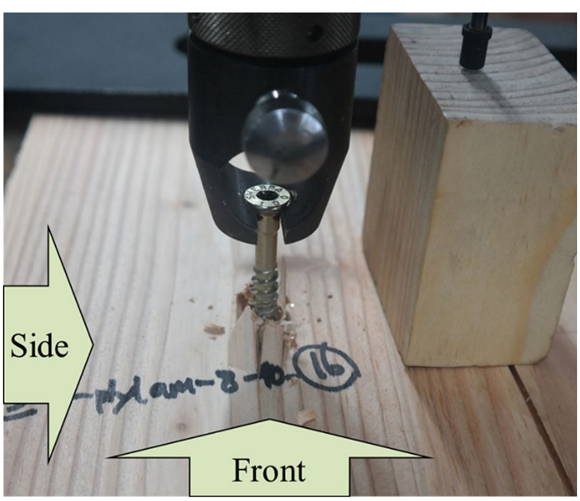

Fig. 5 Failure mode of withdrawal test

Results and discussion

Failure mode and load–distribution curve

The possible failure modes in the withdrawal test of the screws are screw failure or wood material failure [40, 41]. In this test, splitting failure of the fiber of the outer wood layer appeared in all specimens, as shown in Fig. 5. The failure occurred only around the screw and did not reach the wood block. Figure 6 shows the withdrawal load and displacement curves of the specimens, in which the maximum load resistance was close to the 5$^{\text{th}}$ percentile value of the test group. The withdrawal resistance of the screws in the specimens reached its maximum load within a 2 mm displacement and then gradually decreased as the displacement increased.

To observe a failure mode at the maximum load was not easy due to the small displacement. When the screw

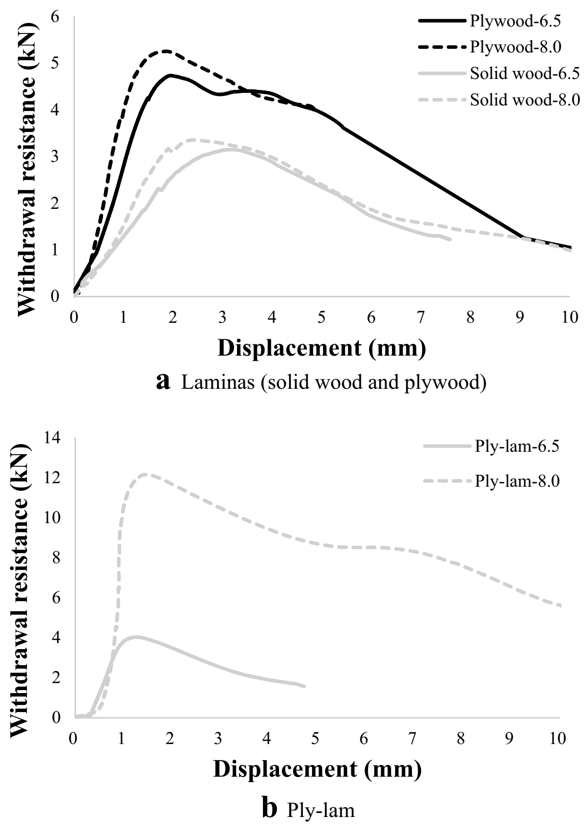

Fig. 6 Withdrawal resistance and displacement curve of test specimens

was completely removed from the wood material, wood powder was attached to the screw threads (Fig. 7a). Thus, it is reasonable to assume that shear failure of the wood in contact with the thread of the screw happened when the maximum load was reached. After the shear failure, the friction between the screw and the wood material was reduced and the load capacity was decreased.

Figure 7b, c shows cross-sections of the Ply-lam specimen from front and side views. Because the withdrawal stiffness of each layer is different, the withdrawal load would have been transferred to the layers according to their relative withdrawal stiffness and their contact area with the layer. Finally, when the withdrawal load reached its maximum, the shear stress of a layer would have exceeded the withdrawal strength of the layer.

Distribution of withdrawal capacity

The experimental test results are presented in Table 3. Figure 8 shows the distribution of the withdrawal capacity of the screws in lamina (solid wood and plywood). The withdrawal resistance distributions for plywood are located to the right side of the solid wood withdrawal resistance distributions, indicating their larger values (Fig. 8a). In particular, the mean value (5.43 kN) and lower 5th percentile values (4.77 kN) for plywood with Ø6.5 × 65 mm screws were higher than those for solid wood with Ø8.0 × 100 mm screws (mean value: 4.49 kN and lower 5th percentile value: 3.19 kN). In this study, the penetration depth of the screws was similar for the lamina test. The withdrawal resistances of solid wood and plywood specimens increased by 12% and 15%, respectively, at the Ø8.0 × 100 mm screws compared to the Ø6.5 × 65 mm screws. The withdrawal resistance of plywood specimens increased by 60% for the Ø6.5 × 65 mm screws and 58% for the Ø6.5 × 65 mm screws compared to the solid wood specimens. The density of plywood (708.40 kg/m^3) was higher than that of solid wood (578.89 kg/m^3). Therefore, the withdrawal resistance of screws in lamina was more affected by the density of the wood material than the diameter of the screw.

However, the withdrawal resistances of the screws were divided by the contact area between the screw and the lamina to derive the withdrawal strengths of the screws in laminas, which were shown to decrease as the diameter of the screw increased (Table 3). When the screw diameter increased from 6.5 to 8.0 mm in solid wood, the withdrawal strength decreased from 18.2 to 16.6 MPa. In plywood, the withdrawal strength decreased from 30.5 to 28.4 MPa as the diameter of the screw increased from 6.5 to 8.0 mm. Figure 8b shows the distributions of withdrawal strengths of screws in laminas. The small size screw specimens, Solid wood-6.5 and Plywood-6.5, are located to the right side of the Ø8.0 × 100 mm screw specimens, Solid wood-8.0 and Plywood-8.0, indicating their withdrawal strength value. This result seems to display the same phenomenon as the size effect of timber: the strength decreases as the size of the timber increases [42].

Figure 9 shows the distribution of the withdrawal capacity of screws for Ply-lam. In the case of Ply-lam, as the diameter increased from 6.5 to 8.0 mm, the penetration depth also increased from 35 to 70 mm. Thus, the specimen groups with larger diameter screws showed higher withdrawal resistance (Fig. 9a).

In the case of withdrawal strength, the lower 5th percentile value of the Ø6.5 × 65 mm screw specimens (6.72 MPa) was lower than that of the Ø8.0 × 100 mm screw specimens (8.16 MPa), because the penetrated lamina layer and the penetrated length of the screws were different. However, the distributions of the two differently sized screws in the Ply-lam specimens tended to overlap and were located between the distributions for solid wood and plywood lamina (Fig. 9b). This shows that the withdrawal strength determined by the withdrawal behavior of screws can be normalized

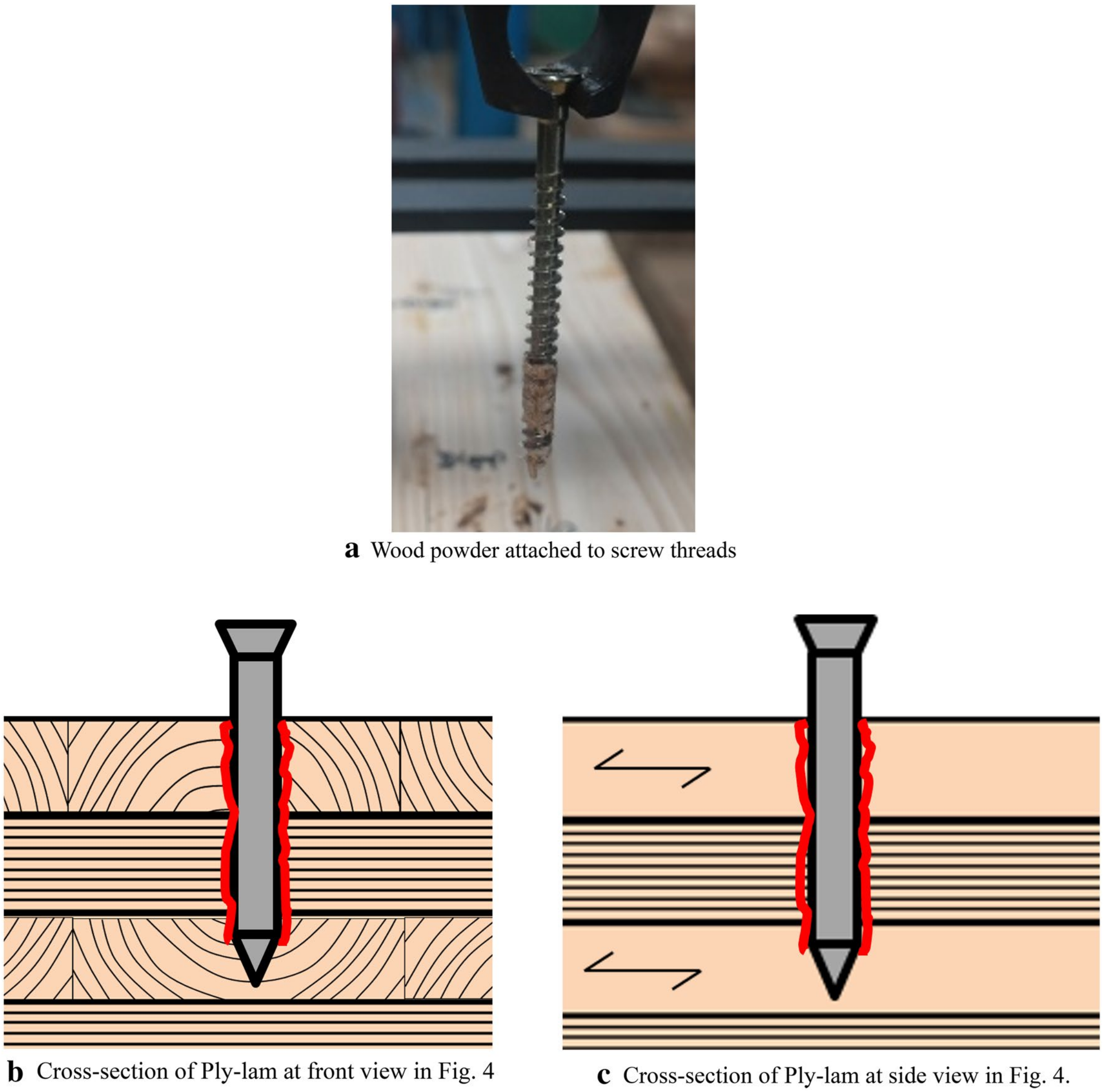

Fig. 7 Shear failure of wood material by thread of screw

by a strength (MPa) unit, such as tension, compression, and bending strength for timber.

In Fig. 9b, the cumulative probability of the Ø6.5 × 65 mm screws and the Ø8.0 × 100 mm screws was reversed between the lower part and the higher part. It is considered that the variation of the wood material penetrated by the screws was affected. The penetration depth of the Ø8.0 × 100 mm screw was 70 mm, and the penetration depth of the Ø6.5 × 65 mm screw was 30 mm. Thus, the screw with the deeper penetration depth showed less variation.

Validation of developed model

Table 4 shows the comparisons of predicted and tested values for Ply-lam. The predicted values from the model developed in this study showed ratios of 0.86–0.88 with respect to the experimental values. In the case of the Ø6.5 × 6.5 mm screws (Ply-lam-6.5), the predicted value was 3.31 kN, which was 88% of the test value. In the case of the Ø8.0 × 100 mm screws (Ply-lam-8.0), the predicted value was 10.46 kN, which was 87% of the test value. When the withdrawal resistance of Ply-lam was predicted from input parameters derived by the average values of the experimental values of Ø6.5 and Ø8.0 screws, it also showed a similar accuracy. This indicates that the

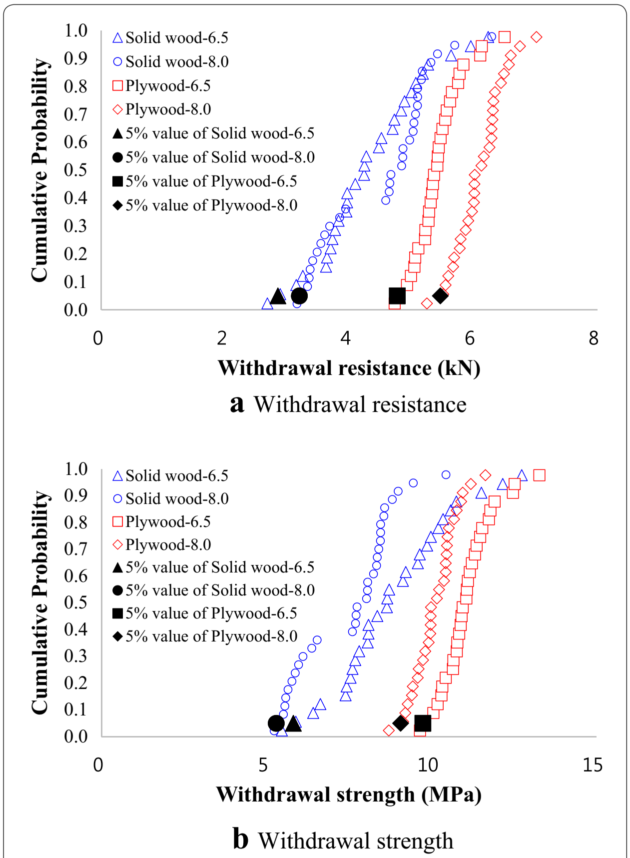

Fig. 8 Distribution of withdrawal capacity for lamina depending on the diameter of screws

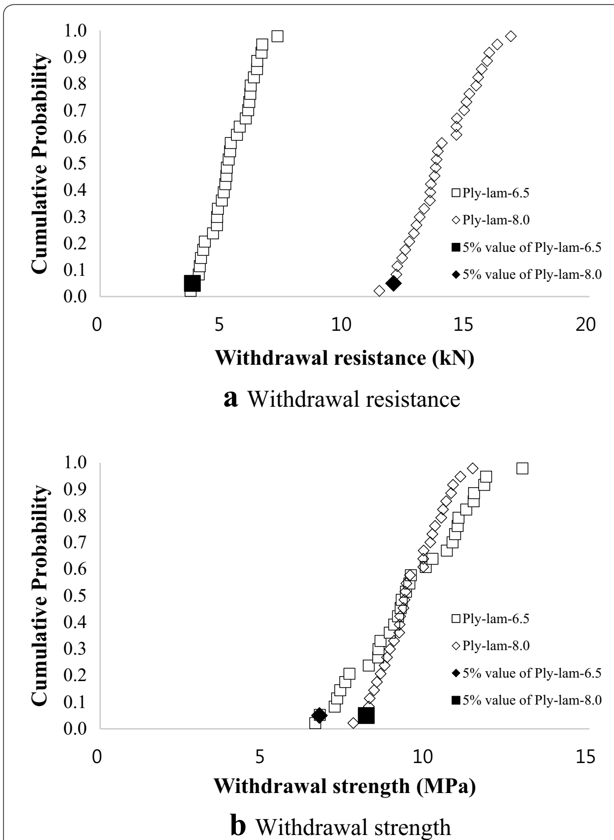

Fig. 9 Distribution of withdrawal capacity for Ply-lam depending on the diameter of screws

withdrawal resistances of screws of other diameters or lengths could be predicted using the equivalent values which are independent of the dimension of the screws. Thus, the equivalent values in this study are applicable for screws with diameters between Ø6.5 and Ø8.0.

As mentioned above, the predicted values were underestimated the test value about 13%. In this study, the withdrawal resistance of screw in Ply-lam specimens were predicted by the modified withdrawal stiffness ($G_{withdrawal}$) for each layer, which was measured by the individual lamina test. In the test, the distance between screw and the supporting plates was 80 mm for all specimens, and the effect of bending stress may be different between the single layer and CLT specimens as the stiffness of the specimens is different. Thus, the withdrawal stiffness of the screw in the single layer would have been measured to be less than that in Ply-lam, and the actual withdrawal stiffness of lamina in Ply-lam would have been stiffer than that measured in the single lamina test. In addition, Ringhofer et al. [17] reported the effect of the number of layers penetrated by the screws in CLT. They revealed that an increase of 7–25% on the lower 5th percentile value of a single layer for CLT had 3–7 layers. Therefore, the number of layers penetrated by the screw in Ply-lam may have resulted in the test values that was higher than the predicted values.

Conclusions

In this study, a theoretical model to predict the withdrawal resistance in Ply-lam was developed from the Ply-lam properties. The model was based on the shear mechanism between a screw and Ply-lam layers. The withdrawal strength, withdrawal stiffness, and penetration depth of a screw in Ply-lam layers were used as the input parameters. When the predicted values were compared with the experimental test values, the predicted values were 86–88% of the test values. The lower 5th percentile values of the withdrawal strength of the screws in the layers were determined, and the results show that the withdrawal resistance of Ply-lam is conservatively predicted using the developed model.

Table 4 Results of measured and predicted withdrawal resistance for Ply-lam

	Input parameters				Predicted values (kN)			Test value (kN)	Ratio[h]
	S_sa	S_pb	G_sc	G_pd	R_se	R_p[f]	Determined value[g]		
Ply-lam[i]- 6.5[j]	5.81[k]	9.74[k]	0.00522[k]	0.00628[k]	3.31	4.61	3.31	3.76	0.88
Ply-lam-8.0	5.29[k]	9.07[k]	0.00426[k]	0.00769[k]	11.01	10.46	10.46	12.00	0.87
Equivalent									
Ply-lam-6.5	5.55[l]	9.41[l]	0.00474[l]	0.00699[l]	3.23	3.72	3.23	3.76	0.86
Ply-lam-8.0					10.44	12.01	10.44	12.00	0.87

[a] S_s = withdrawal strength of solid wood layer when a screw was pulled out (MPa)

[b] S_p =withdrawal strength of plywood layer when a screw was pulled out (MPa)

[c] G_s = modified withdrawal stiffness for withdrawal behavior in solid wood layer (N/mm^3)

[d] G_P = 0.17*em*modified withdrawal stiffness for withdrawal behavior in plywood layer (N/mm^3)

[e] R_p = withdrawa resistance predicted by Eq.6 with the withdrawa strength of plywood (N)

[f] R_s = withdrawal resistance predicted by Eq.6 with the withdrawal sthrength of solid wood (N)

[g] R_s = smaller value of R_p andR_s

[h] Predicted value/test value

[i] Hybrid cross-laminated timber, cross layers replaced by plywood

[j] Diameter of screw (mm)

[k] Experimental value of the corresponding screw in lamina

[l] Average of the experimental values of Ø6.5 and Ø8.0 screws in lamina

In addition, the effect of the penetration depth of the screw in a specific layer was investigated using the developed model. When the penetration depth of the screw increased in the plywood layer, the withdrawal resistance of the Ply-lam increased more significantly than when the penetration depth of the screw increased in a solid wood layer. This effect increased as the diameter of the screw increased because of the larger contact area. This means that a high withdrawal resistance can be designed in hybrid CLT by changing the penetration depth of the specific layers.

Abbreviations

CLT: Cross-laminated timber; NDS: National design specification; LVL: Laminated veneer lumber; LSL: Laminated strand lumber; LVDT: Linear variable displacement transducers.

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Authors' contributions

SJP analyzed the data and wrote this manuscript. KSA designed the experimental setup and performed the experimental test. SGK developed the main material, Ply-lam, and controlled the manufacturing. JKO managed this research. All authors read and approved the final manuscript.

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Availability of data and materials

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Competing interests

The authors declare they have no competing interest.

Author details

[1] Research Institute of Agriculture and Life Sciences, Seoul National University, Gwanak-ro 1, Gwanak-gu, Seoul, South Korea. [2] Department of Agriculture, Forestry and Bioresources, Seoul National University, Gwanak-ro 1, Gwanak-gu, Seoul, South Korea. [3] Department of Bio-Based Materials, Chungnam National University, 99 Daehak-ro, Yuseong-gu, Daejeon, Republic of Korea.

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References

1. Dietsch P, Brandner R (2015) Self-tapping screws and threaded rods as reinforcement for structural timber elements—a state-of-the-art report. Constr Build Mater 97:78–89
2. Loss C, Hossain A, Tanner T (2018) Simple cross-laminated timber shear connections with spatially arranged screws. Eng Struct 173:340–356
3. Tomasi R, Crosatti A, Piazza M (2010) Theoretical and experimental analysis of timber-to-timber joints connected with inclined screws. Constr Build Mater 24:1560–1571
4. Schiro G, Giongo I, Wendel S, Riccadonna D (2018) Piazza M. Testing of timber-to-timber screw-connections in hybrid configurations. Constr Build Mater 171:170–186
5. Izzi M, Polastri A (2019) Low cycle ductile performance of screws used in timber structures. Constr Build Mater 217:416–426

6. Loss C, Piazza M, Zandonini R (2016a) Connections for steel–timber hybrid prefabricated buildings. Part I: experimental tests. Constr Build Mater 122:781–798
7. Loss C, Piazza M, Zandonini R (2016b) Connections for steel–timber hybrid prefabricated buildings. Part II: innovative modular structures. Constr Build Mater 122:796–808
8. Loss C, Piazza M, Zandonini R (2014) Experimental tests of cross-laminated timber floors to be used in timber-steel hybrid structures. In: Proceedings of WCTE 2014 conference. Quebec, Canada, August.
9. Du H, Hu X, Xie Z, Wang H (2019) Study on shear behavior of inclined cross lag screws for glulam-concrete composite beams. Constr Build Mater 224:132–143
10. Kavaliauskas S, Kazimieras-Kvedaras A, Valiunas B (2007) Mechanical behaviour of timber-to-concrete connections with inclined screws. J Civ Eng Manag 13:193–199
11. Marchi L, Scotta R, Pozza L (2017) Experimental and theoretical evaluation of TCC connections with inclined self-tapping screws. Mater Struct 50(3):180
12. Karacabeyli E, Douglas B (2013) Chapter 5 connections. In: CLT Handbook: Cross-Laminated Timber US Edition. FPInnovations, Pointe-Claire
13. Jockwer R (2014) Structural behaviour of self-tapping screws–theory. In: Proceedings of COST Workshop–Highly Performing Timber Structures: Reliability, Assessment, Monitoring and Strengthening. Biel, Switzerland, September, pp 83–90
14. European Standard EN 1995 (2004) Design of timber structures. Part 1-1: General—Common rules and rules for buildings. The European Committee for Standardization
15. National Design Specification for Wood Construction with Commentary (2018) American Wood Council. Leesburg, VA
16. Uibel T. Blass HJ (2007) Edge joints with dowel type fasteners in cross-laminated timber. In: Proceedings of the 40th CIB-W18 Meeting. Bled, Slovenia
17. Ringhofer A, Brandner R, Schickhofer G (2015) Withdrawal resistance of self-tapping screws in unidirectional and orthogonal layered timber products. Mater Struct 48:1435–1447
18. Celebi G, Kilic M (2007) Nail and screw withdrawal strength of laminated veneer lumber made up hardwood and softwood layers. Constr Build Mater 21:894–900
19. Özçiftçi A (2009) The effects of pilot hole, screw types and layer thickness on the withdrawal strength of screws in laminated veneer lumber. Mater Des 30(7):2355–2358
20. Brandner R, Ringhofer A, Reichinger T (2019) Performance of axially-loaded self-tapping screws in hardwood: properties and design. Eng Struct 188:677–699
21. Ringhofer A, Brandner R, Blaß HJ (2018) Cross laminated timber (CLT): design approaches for dowel-type fasteners and connections. Eng Struct 171:849–861
22. Choi C, Yuk CR, Yoo JC, Park JY, Lee CG, Kang SG (2015) Physical and mechanical properties of cross laminated timber using plywood as core layer. J Korean Wood Sci Tech 43:86–95
23. Choi C, Kojima E, Kim KJ, Yamasaki M, Sasaki Y, Kang SG (2018) Analysis of mechanical properties of cross-laminated Timber (CLT) with plywood using Korean larch. BioResources 13:2715–2726
24. Park JH, Kang Y, Lee J, Chang SJ, Wi S, Kim S (2019) Development of wood-lime boards as building materials improving thermal and moisture performance based on hygrothermal behavior evaluation. Constr Build Mater 204:576–585
25. Chang SJ, Wi S, Kim S (2019) Thermal bridging analysis of connections in cross-laminated timber buildings based on ISO 10211. Constr Build Mater 213:709–722
26. Chang SJ, Wi S, Kang SG, Kim S (2020) Moisture risk assessment of cross-laminated timber walls: Perspectives on climate conditions and water vapor resistance performance of building materials. Build Environ 168:106502
27. Chang SJ, Wi S, Lee J, Lee H, Cho H, Kim S (2017) Analysis of cooling and heating energy demands of wooden houses with cross-laminated Timber (CLT) using domestic plywood as core materials. J Korean Soc Living Environ Sys 24(6):752–759
28. Pang SJ, Lee HJ, Yang SM, Kang SG, Oh JK (2019) Moment and shear capacity of Ply-lam composed with plywood and structural timber under out-of-plane bending. J Wood Sci 65:1–10
29. Wang Z, Gong M, Chui YH (2015) Mechanical properties of laminated strand lumber and hybrid cross-laminated timber. Constr Build Mater 101:622–627
30. Pang SJ, Lee HJ, Ahn KS, Oh JK (2020) Sensitivity of censored data analysis to determine the characteristic value of structural timber. J Wood Sci. https://doi.org/10.1186/s10086-020-01885-0
31. Aicher S, Hirsch M, Christian Z (2016) Hybrid cross-laminated timber plates with beech wood cross-layers. Constr Build Mater 124:1007–1018
32. Cramer SM, Wolfe RW (1989) Load-distribution model for light-frame wood roof assemblies. J Struct Eng 115:2603–2616
33. Pang SJ, Jeong GY (2018) Load sharing and weakest lamina effects on the compressive resistance of cross-laminated timber under in-plane loading. J Wood Sci 64:538–550
34. BS EN 384 (2010) Structural timber—determination of characteristic values of mechanical properties and density. British Standards Institution
35. KDS 41 33 05:2016 (2016) Korean Design Standard for connection of timber structure. Korea Construction Standard Center
36. NIFoS notification No. 2018-8 (2018) Standard and specification of wood products - structural lumber. National Institute of Forest Science
37. ETA 18, 0083 (2018) SHERPA CLT-Connector. Austrian Institute of Construction Engineering, Vienna, Austria
38. KS F ISO 9087 (2004) Determination of nail and screw holding power under axial load application for wood. International Organization for Standardization
39. ISO 6891 (1983) Timber structures—joints made with mechanical fasteners – General principles for the determination of strength and deformation characteristics
40. Lin HT, Tsai MT, Wonodihardjo AS (2018) Withdrawal resistance and failure mode of semi-circular wooden composite with different fasteners. Key Eng Mater 765:295–299
41. Maleki S, Najafi SK, Ebrahimi G, Ghofrani M (2017) Withdrawal resistance of screws in structural composite lumber made of poplar (*Populus deltoides*). Constr Build Mater 142:499–505
42. Moshtaghin AF, Franke S, Keller T, Vassilopoulos AP (2016) Experimental characterization of longitudinal mechanical properties of clear timber: random spatial variability and size effects. Constr Build Mater 120:432–441

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