Compressive Strength Properties Perpendicular to the Grain of Larch Cross-laminated Timber

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As timber tends to be weak against the load perpendicular to grains, it can be important to study the consequences of applying loads perpendicular to larch cross-laminated timber (CLT) composed of multiple larch laminae. Compression tests were conducted perpendicular to the in-plane and out-of-plane grains of Japanese larch CLT. Out-of-plane average compressive strength, average yield strength, and average compressive stiffness perpendicular to the grain of the larch CLT were 11.94 N/mm^2, 7.30 N/mm^2, and 7.30 N/mm^3, respectively, whereas the in-plane average compressive strength, average yield strength, and average compressive stiffness perpendicular to the grain of the larch CLT were 21.48 N/mm^2, 21.18 N/mm^2, and 18.72 N/mm^3, respectively. The in-plane compressive strength and yield strength showed a statistically significant relationship with the density of CLT, the modulus of elasticity measured by longitudinal vibration (MOE_{LV}), and the average MOE_{LV} of the laminae constructing the cross-laminated timber. The in-plane yield strength was affected by the MOE_{LV} of the outer laminae and the average MOE_{LV} of the larch cross-laminated timber. The compressive strength properties were most affected by the loading surface of the CLT. The variation between the moisture content and compressive strength properties of the CLT, however, was not statistically significant.

Keywords: Cross-laminated timber; Compressive strength; Perpendicular to the grain; In-plane; Out-of-plane; Larch

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INTRODUCTION

Cross-laminated timber (CLT) is an engineered wood panel made of laminae with thicknesses of around 20 to 60 mm, which are laminated orthogonally to the fiber direction to resist in the positive direction of the load (Song and Hong 2018). The first CLT was developed in Switzerland in the early 1990s. In the mid-1990s, a joint research team consisting of sawmilling industry practitioners and academics in Austria were instrumental in the development of today's CLT in slab form (Gagnon and Pirvu 2011; Schickhofer *et al.* 2010; Schickhofer 2013; Brandner 2013). In the wake of the green building movement in the early 2000s, however, the research and construction in this area began to increase thanks to the improved production efficiency of CLT, the product certification, and the improved marketing and distribution efforts (Mohammad *et al.* 2012). At present, European countries including Austria, Germany, Switzerland, Sweden, Norway, and the UK, as well as North America, Oceania, and Japan, are expanding their use of CLT primarily as the key material for multi-family apartments and public buildings (Song 2018).

CLT is suitable for load-bearing panels and shear walls due to its homogenized mechanical and physical properties stemming from its laminar structure (Zhou *et al*. 2014).

Therefore, the timber-based building system has a competitive edge over the lightweight timber frame building system in the construction of middle- and high-rise buildings. Furthermore, it can compete with various brick- and concrete-based building systems because the material is easy to handle during construction and allows for high-level prefabrication. This CLT construction method relies on a panel-panel structure in which the CLT itself becomes a wall, a floor, and a roof. As the CLT floor is located between the upper and lower walls, however, it can be considerably deformed due to excessive stress over time, as is the case in many high-rise buildings. In addition, a performance evaluation of the compressive strength perpendicular to the grain of CLT must be performed because timber- and wood-based materials generally have a lower measure of compressive strength perpendicular to the grain.

Serrano and Enquist (2010) calculated the compressive strength perpendicular to the grains of three-layer CLT (spruce) compression test specimens. They performed a full compression and line-type compression test on the plane perpendicular to the grains of each test specimen, according to EN 1995-1-1 (2006). It was reported after the test that the compressive strength was influenced by the size of the area to which the load was applied, the grain direction of the outermost lamina of the CLT, and the distance from the compressed area to the end-plane of the specimen to which the load was applied (Serrano and Enquist 2010). Ido *et al*. (2014) performed a partial compressive strength test in accordance with ISO 13910 (2005) by varying the number of Japanese cedar (*Cryptomeria japonica*) CLT layers, the grading of the laminae, and the direction of the grain in the CLT's outermost lamina relative to the loading direction. The test results showed that the grain's direction and the loading direction of the outermost lamina, with respect to the loading plate direction, influenced the compressive strength perpendicular to the grains. In contrast, the combination of different lamina grades and the number of layers of laminae did not have a significant effect. According to Bogensperger *et al*. (2011), cubic CLTs tested in accordance with EN 408 (2010) demonstrated 27% greater compressive strength and 50% greater compressive stiffness than glulam. The reason for this is that laminae are laminated only in a single direction, but in the case of CLT, they are cross-laminated to one another. Therefore, the adjacent laminae strengthen and support each other.

In this study, compressive strength of larch CLT was performed according to ISO 13910 (2005) in order to evaluate the in-plane and out-of-plane compressive strength characteristic of the larch CLT in accordance with the modulus of elasticity of the larch lamina constituting the CLT, and to examine the factors affecting the compressive strength of the grains perpendicular to load.

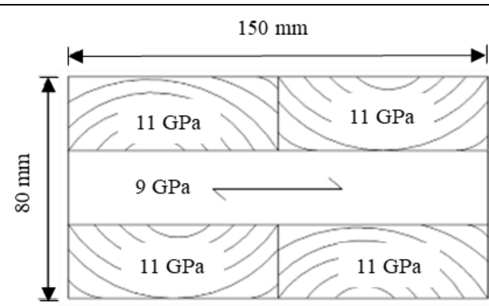
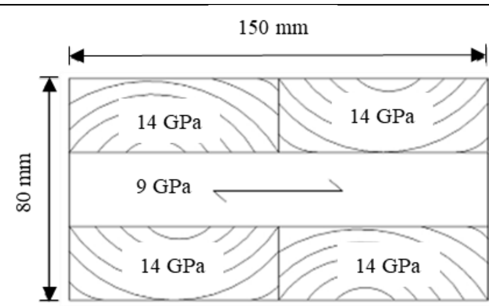
EXPERIMENTAL

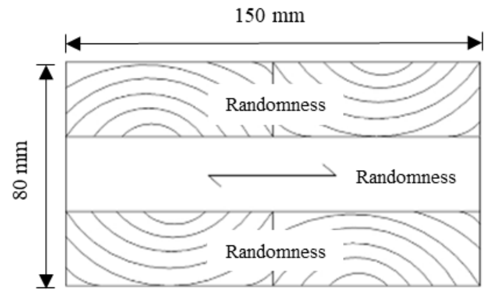
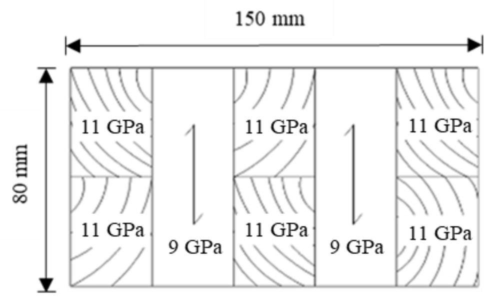
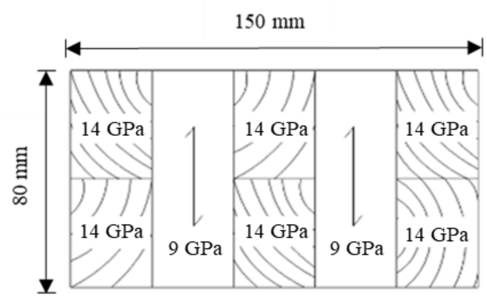
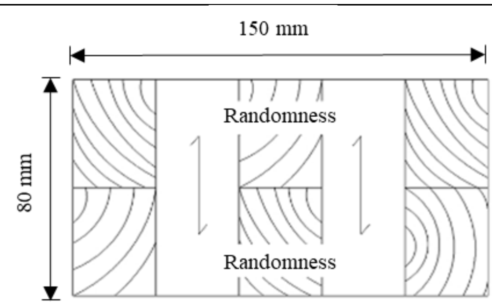
Materials

For the production of CLT, Japanese larch (*Larix kaempferi* Carr.) laminae (National Forestry Cooperative Federation, Yeoju-si, Republic of Korea) each measuring 27 mm (h) × 89 mm (w) × 3,600 mm (l) were used. The average air-dried moisture content of the laminae was 11%, and the average air-dried gravity was 0.53. The modulus of elasticities of the laminae were measured through longitudinal vibration (MOE_{LV}).

The laminae were classified as in-plane or out-of-plane according to the surface to which the pressure was applied. Additionally, the laminae were fabricated in three types according to the combination of the MOE_{LV} values of the laminae (Table 1). The out-of-plane test specimens (Series-A1, Series-A2, and Series-A3) were assembled in three layers, and the in-plane specimens (Series-B1, Series-B2, and Series-B3) were assembled in five layers. The in-plane test specimens were made to have five layers because the three-layer in-plane specimen from the preliminary test demonstrated low accuracy due to its rotation during the compression test. Therefore, in this study, the rotation of the test specimens was effectively limited by increasing the force area through the fabrication of five-layer in-plane test specimens. The MOE_{LV} combinations according to the test specimen when fabricating the specimen were as follows. Series-A1 and B1 were the test specimens that combined the MOE_{LV} of the longitudinal laminae with 11 GPa and the MOE_{LV} of the transverse laminae with 9 GPa, respectively. Series-A2 and B2 were the test specimens that combined the MOE_{LV} of the longitudinal laminae with 14 GPa and the MOE_{LV} of the transverse laminae with 9 GPa, respectively. Series-A3 and B3 randomly combined laminae from 7 to 19 GPa. Phenol-resorcinol formaldehyde (PRF) was used as an adhesive (Kangnam Chemical, Seoul, South Korea), and adhesive was applied to the laminae flatwise and edgewise before they were pressure-glued. The glue spread was set at 400 g/m^2 (single spread), and the pressing pressure was set at 0.98 MPa. After being hardened for 24 h, the specimens were cured at room temperature for 1 week. After curing, the out-of-plane specimens were shaved down to a piece measuring 80 mm (h) × 150 mm (w) × 480 mm (l) while the in-plane specimens were shaved down to a piece measuring 80 mm (h) × 135 mm (w) × 480 mm (l). A total of 10 specimens were fabricated for each series. The average density of the fabricated CLT specimens was 544.5 kg/m^3.

Table 1. Compression Test Program Summary

Series	Loading Direction to the Specimen	Size and Configuration of the Specimens	Combination of Lamina MOE_{LV} Values	Density (kg/m^3)
A1	Out-of-plane		Symmetry	528.8
A2	Out-of-plane		Symmetry	571.3

A3	Out-of-plane		Randomness	533.2
B1	In-plane		Symmetry	548.9
B2	In-plane		Symmetry	539.7
B3	In-plane		Randomness	544.8

Methods

Compression test

The compressive strength test of the larch CLT for loads perpendicular to the grains was conducted in accordance with the ISO 13910 (2005) standard. For the compression test, a universal hydraulic testing machine (UTM) was used, which is capable of compressing up to 500 kN. The test specimens were placed between two steel-bearing plates, as shown in Fig. 1. The displacements were measured by installing displacement transducers on the left and right sides of the steel-bearing plates. The loading rate was set at 3 mm/min. The test was performed until the failure of the specimen or until the two displacement transducers were deformed up to 20 mm on average. The compressive strength ($f_{c,90}$), yield strength ($f_{c,90,y}$), and compressive stiffness (K_c) were calculated based on the load deformation curve of the test according to ISO 13910 (2005) (Fig. 1 and Table 2).

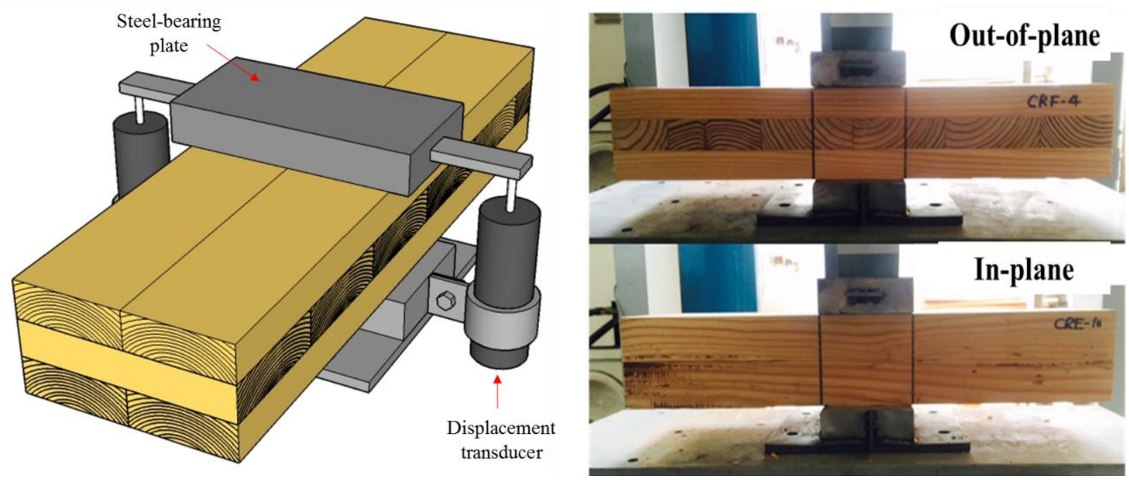


Fig. 1. Schematic diagrams and photographs of the compression test set-up for larch CLT (Song 2018)

Table 2. Compressive Strength Properties (ISO 13910 (2005))

Compressive Strength	Yield Strength	Compressive Stiffness
$f_{c,\,90} = F_{ult} / A$ or $f_{c,\,90} = F_{20} / A$ F_{ult} is the value of the applied load (kN) at the time of failure (ultimate load). F_{20} is the load (kN) at a 20mm deformation.	$f_{c,\,90,\,y} = F_y/A$ F_y is the load (kN) at the intersection of a line parallel to the elastic slope of the load deformation curve and offset by 2 mm (Figure 2).	$k_{c,\,90} = (\Delta F/\Delta e)/A$ $\Delta F/\Delta e$ is the elastic slope of the load deformation curve.
A: Compression area of CLT by steel plate (mm^2)		

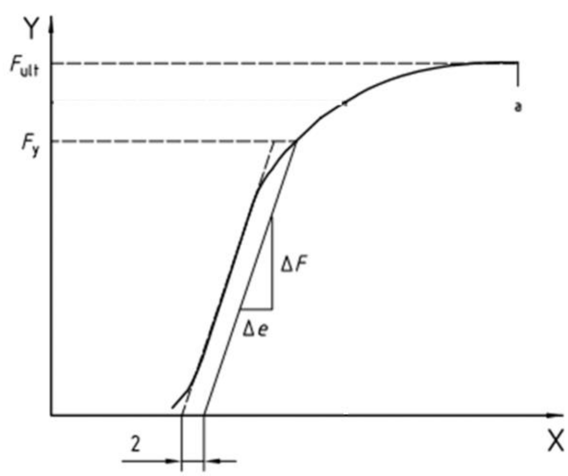


Fig. 2. Definition of the compression load perpendicular to the grain in accordance with ISO 13910 (ISO 13910 (2005))

The yield strength was calculated as follows. First, the load at the intersection of the original load deformation curve was obtained by offsetting the elastic slope of the original deformation curve parallel to the X-axis by 2 mm. Then the yield strength was calculated by substituting the load with the matching variable in the equation.

To identify the factors affecting the compressive strength properties of larch CLT, t-test of the independent variables with the statistical significance under the 95% confidence level was performed. The t-test was performed using Microsoft Excel Version 2016 (Microsoft Corporation, v. 2016, Redmond, WA, USA).

RESULTS AND DISCUSSION

Load-deformation Curve

Figure 3 shows the load deformation curves from the compression test.

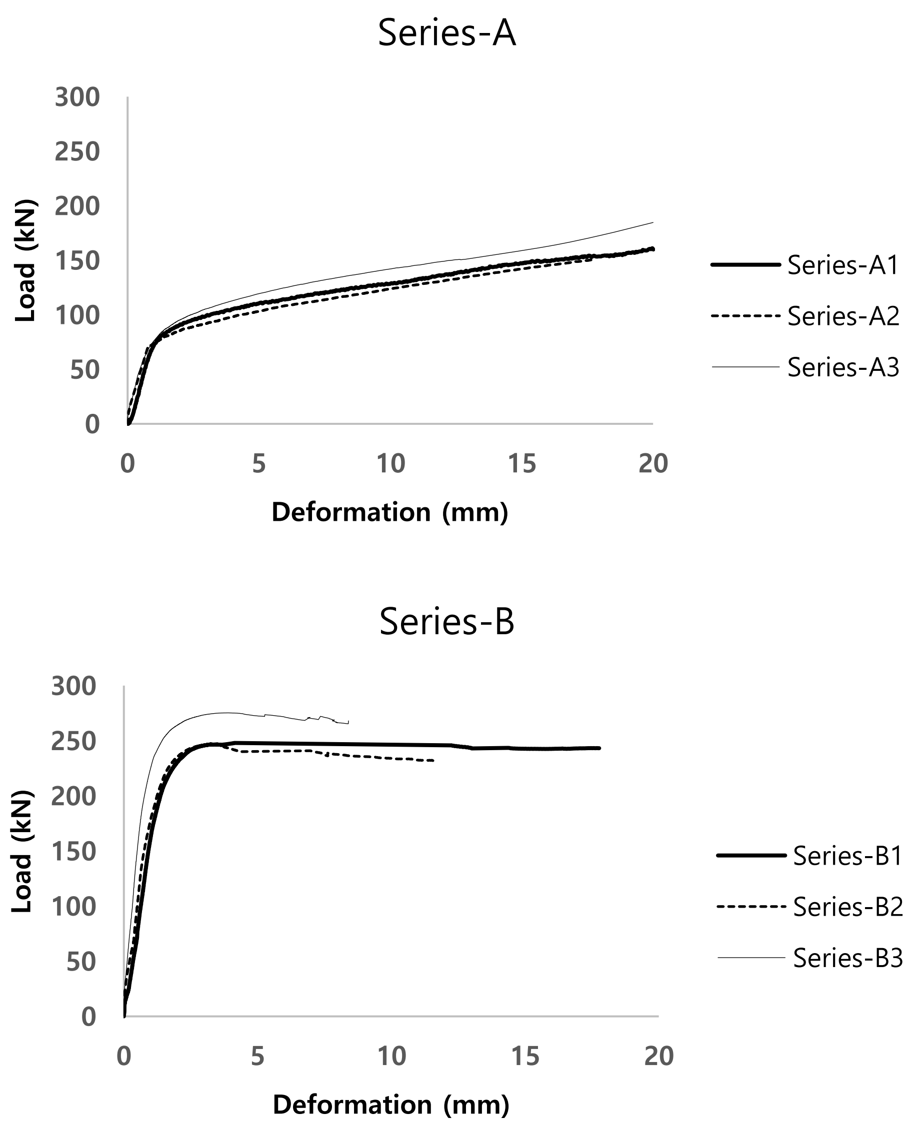


Fig. 3. Average load-deformation curves from compression tests perpendicular to grain, larch CLT

In general, when an out-of-plane force is applied, the load does not decrease but gradually increases even when the deformation amount exceeds 20 mm. This tendency was the same as in the test conducted by Ido *et al*. (2006) performed with a solid wood according to ISO 13910 (2005). The same result was also obtained in a compression test conducted by Serrano and Enquist (2010) with a narrow steel bar to obtain the load deformation curve of CLT perpendicular to the grains (Ido *et al*. 2006; Serrano and Enquist 2010; Bleron *et al*. 2011; Leijten *et al*. 2012). The early slope of the load deformation curve for the specimens to which the in-plane force was applied steeply increased. After the maximum load was reached, the load slightly decreased. Only the deformation increased, however, without the fluctuation of the load, as it started to decrease before the application of the load due to the failure of the specimen. Thus, unlike the out-of-plane specimen test, the tests of most of the in-plane specimens were terminated before the specimens were deformed by up to 20 mm. In contrast, there was no difference in maximum load between the in-plane specimens with over 20 mm deformation and the other in-plane specimens with less than 20 mm deformation.

Compressive strength properties for larch CLT

The compressive strength properties perpendicular to the grains of the larch CLT are shown in Table 3. The difference in compressive strength between the out-of-plane and in-plane test specimens to which the load was applied was large, but there was no difference in strength according to the MOE_{LV} combination. The in-plane compressive strength was 1.8 times greater than the out-of-plane compressive strength, and the yield strength and stiffness were 2.9 and 2.5 times greater, respectively. These results were 35 and 21% higher than the out-of-plane and in-plane compressive strengths of the Japanese cedar CLT, respectively, which was tested with the same specifications. Additionally, the yield strength was determined to be 25% higher for the out-of-plane test specimens and 26% higher for the in-plane test specimens. The ratio of the in-plane compressive strength properties to the out-of-plane compressive strength properties of the larch CLT ($f_{c,\,90}$: 1.8 times; $f_{c,\,90,\,y}$: 2.9 times; K_c: 2.5 times) was similar to that of the Japanese cedar CLT ($f_{c,\,90}$: 2.0 times; $f_{c,\,90,\,y}$: 2.9 times; K_c: 2.6 times) (Ido *et al*. 2014).

Table 3. Properties of the Compressive Strength Perpendicular to the Grain for Larch CLT

Series	Density (kg/m^3)	$MOE_{LV,\,CLT}$ (MPa)	$f_{c,90}$ (MPa)	$f_{c,90,\,y}$ (MPa)	K_c (N/mm^3)
A1	528.8 (0.054)*	5.90 (0.098)	11.20 (0.091)	7.33 (0.13)	6.83 (0.362)
A2	571.3 (0.045)	6.12 (0.062)	11.70 (0.047)	6.70 (0.067)	7.80 (0.274)
A3	533.2 (0.025)	6.10 (0.09)	12.91 (0.081)	7.88 (0.086)	8.21 (0.312)
B1	548.9 (0.043)	5.91 (0.071)	21.06 (0.051)	20.66 (0.051)	14.80 (0.122)
B2	539.7 (0.031)	6.93 (0.056)	20.69 (0.054)	20.38 (0.064)	20.71 (0.218)
B3	544.8 (0.033)	5.83 (0.055)	22.71 (0.06)	22.51 (0.064)	20.65 (0.252)

$MOE_{LV,\,CLT}$: Modulus of elasticity of the CLT determined using the natural frequency of the longitudinal vibration; ( )*: Coefficient of variation

The determination of the compressive strength according to EN 1995-1-1 (2006) and ASTM D143-14 (2014) is similar to the determination of the yield strength according to ISO 13910 (2005). The yield strength values in this study were 34% higher than those obtained by Sereno and Enquist (2010) and Gasparri *et al*. (2016) (Table 4). Such differences in the measured values were due to the difference between the shape (*e.g*., line and point) of the bearing plate and the position (*e.g.*, center and edge) at which the load was applied to the specimen. As shown in this study and in the previous studies by Serrano and Enquist, when force is applied to the center of the CLT test specimen, CLT is supported by the textures of the adjacent wood grains. As in the study by Gasparri *et al*. (2016), a higher compressive strength value can be obtained than when force is applied to the edge of the test specimens (Augustin *et al*. 2006; Serrano and Enquist 2010). Another cause of such a difference in compressive strength is the difference in the determination method of the strength properties of each test criterion for the load-strain curves. In ASTM D143-14 (2014) and ISO 13910 (2005), the compressive strength is determined at the intersection of the original load deformation curves after offsetting it with the fixed values of 1 and 2 mm, respectively, along the deformation axis, regardless of the height of the specimen. In EN 1995-1-1 (2006), in contrast, the compressive strength is determined by offsetting the elastic region of the load deformation curve being tested by 0.01 h (h: specimen height) along the deformation axis. In particular, as EN 1995-1-1 (2006) offsets the straight lines intersecting 10 and 40% of the points of the maximum compressive strength values, the initial compressive stiffness according to the test specimens were considered (Leijten *et al*. 2012). As such, the compressive strength was determined through a method more rigorous than the previous two methods. Therefore, the highest compressive strength value was determined based on ISO 13910 (2005), and a relatively low value was determined based on ASTM D143-14 (2014) and EN 1995-1-1 (2006). In addition, it is also believed that differences in specific gravity depending on the species of the laminae constituting the CLT resulted in differences in yield strength between various studies.

Table 4. Previous Research Studies Overview

Authors	Species	Density$_{CLT}$ (kg/m^3)	Test Criterion	Loading Direction	Test Series	No. of Test Specimens	$f_{c,90}$ (MPa)	$f_{c,90,y}$ (MPa)
Song and Hong (2018)	Japanese larch	544	ISO 13910 (2005)	Out-of-plane	Series-A	30	11.94	7.62
				In-plane	Series-B	30	21.48	18.72
Ido *et al*. (2014)	Japanese cedar	408	ISO 13910 (2005)	Out-of-plane	Group-1, 5, 9	15	8.88	6.12
				In-plane	Group-2, 6, 10	15	17.73	17.47
Serrano and Enquist (2010)	Spruce	427	EN 1995-1-1 (2006)	Out-of-plane	B2, C2	13	5.35	-
Gasparri *et al*. (2016)	Spruce, pine, fir (SPF)	439	EN 408 (2010)	Out-of-plane	A1, B1	13	4.75	-
			ASTM D 143-14 (2014)		A1, B1		4.60	-

Failure mode

For Series-A1, A2, and A3 with out-of-plane loads, only local pressure was caused by the steel-bearing plates in the outermost lamina. This generally occurred even without the failure of the specimen if the deformation exceeded 20 mm. In some test specimens, however, the outermost lamina failed perpendicular to the grains. As the failure started to develop from the outermost lamina and reached the middle lamina, as shown in Figure 4b, the test was terminated before the maximum load was measured or before the deformation amount increased up to 20 mm. When quarter-sawn lumber was included in the outermost layers, it failed much more than when flat-sawn lumber was included, but this did not affect the compressive strength. When force was applied to the in-plane test specimen, it failed completely, from the steel-bearing plates to the end plane along the glue line between the longitudinal and transverse layers (Fig. 4c, d). Such a failure profile was due to the fact that the test specimen was short, and failure still occurred despite the fact that the test specimens were 6 times longer than their thickness, in accordance with ISO 13910 (2005).

The aforementioned finding was due to the shear strength of the larch CLT between the lamina and the adhesive, which was calculated to be 2.6% more than the shear strength of the glulam made of the same species (Park *et al*. 2009; Song and Hong 2016). For the partial compression test of CLT in accordance with ISO 13610 (2005), further research on the appropriate length of the in-plane test specimen is required.

Fig. 4. Failure modes of the compression test specimens (Song 2018)

Factors affecting the compressive strength properties perpendicular to the grain of CLT

As shown in Table 5, the strength properties of the in-plane specimens were not affected by most of the independent variables, but the yield strength was statistically significant because the *p*-values for the MOE of the outer lamina and the mean elasticity of the lamina were less than 0.05, respectively. This meant that the MOE of the laminae up to the yield point affected the compressive strength of the out-of-plane specimens. The MOE_{LV} of the laminae, however, did not affect the determination of the compressive strength after the yield point. Unlike what occurred with the out-of-plane test specimens, when the in-plane test specimens were applied directly only to the outer laminae, the compressive strength properties were not statistically significant to the MOE_{LV} of the outer laminae. In the case where the in-plane test specimens were applied directly to all the laminae, the compressive and yield strengths were affected by the density of the CLT, the $MOE_{LV,CLT}$, and the average MOE_{LV} of the laminae constructing the CLT, respectively. The loading surface of the CLT affected the compressive strength properties the most.

Table 5. Statistical Significance between the Parameters and the Compressive Strength Properties

Strength Properties		Density	Moisture Content	$MOE_{LV,CLT}$	MOE_{LV} of Outermost Lamina	$MOE_{LV,Ave}$	Loading Direction to the Specimen
Compressive strength	In-plane	0.2776	0.2627	0.3237	0.1046	0.8139	4.4E-35
	Out-of-plane	0.0141	0.2474	0.0096	0.0665	0.0048	
Yield strength	In-plane	0.9355	0.1136	0.9942	0.0394	0.0021	9.9E-45
	Out-of-plane	0.0282	0.3653	0.0218	0.1278	0.0111	
Compressive stiffness	In-plane	0.3895	0.6258	0.8923	0.5527	0.5468	7.3E-17
	Out-of-plane	0.4961	0.9741	0.7477	0.1168	0.2790	

p-value: 5% level of significance; $MOE_{LV,CLT}$: Modulus of elasticity of the CLT determined using the natural frequency of longitudinal vibration; MOE_{Ave}: Average modulus of elasticity of the laminae constructing the CLT

CONCLUSIONS

A compressive strength test of Japanese larch cross-laminated timber (CLT) against a load perpendicular to the grain was performed in accordance with ISO 13910 (2005). The following are the results that were obtained.

1. The in-plane compressive strength properties (compressive strength, yield strength, and compressive stiffness) of the larch CLT were determined to be 1.8, 2.9, and 2.5 times higher, respectively, than the out-of-plane compressive strength properties.
2. The compressive strength based on ISO 13910 (2005) was determined to be higher than the references based on ASTM D143-14 (2014) and EN 408 (2010).
3. The in-plane compressive and yield strengths showed statistically significant relationships to the density of the CLT, the modulus of elasticity measured by longitudinal vibration (MOE_{LV}), and the average MOE of the laminae when constructing the CLT. The MOE_{LV} of the outer lamina and the average MOE of the laminae constructing the CLT influenced the observed in-plane yield strength. The CLT's loading surface had the greatest effect on all the compressive strength properties, but the CLT's moisture content was not statistically significant with any compressive strength property.

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