Influence of Adhesive and Layer Composition on Compressive Strength of Mixed Cross-laminated Timber

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Different types of wood can be used for making cross-laminated timber (CLT), which is useful as a structural material. Therefore, to assess the viability of mixed cross-laminated timbers prepared with different adhesives, their compressive strength performances were evaluated. Laminae of Japanese larch, red pine, and yellow poplar were used to manufacture eight types of mixed CLTs, which were then tested in a universal testing machine for obtaining the compressive strength. The results were then compared to those obtained from the finite element (FEM) simulation of the CLTs at proportional limit load. The compressive strength of CLTs consisting of Japanese larch laminae, with a high modulus of elasticity, tended to increase. Mixed CLT with polyurethane adhesives showed an average compressive strength that was 14% lower than that of larch CLT, while mixed CLT consisting of red pine and yellow poplar showed an average compressive strength that was 18% lower than that of the larch CLT. The CLT prepared with phenol-resorcinol-formaldehyde adhesive yielded the highest compressive strength among the three adhesives. The FEM-predicted strengths were found to be close to the actual values in all specimens. The obtained results will be useful for selecting material and adhesive for future endeavors.

Keywords: Column; Compressive strength; FEM; Japanese larch; Mixed CLT; Red pine; Yellow poplar

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INTRODUCTION

Interest in eco-friendly building materials has been increasing owing to a desire for attaining global carbon neutrality. Wood and wood-based materials that have lower carbon emissions than concrete and steel are increasingly being used as building materials. Timber is a typical building material that exhibits a carbon storage effect (Schwenk *et al.* 2012). Most of the structural materials of timber are made up of softwood, which reflects its excellent mechanical properties. However, owing to climate change, the production of hardwood is more feasible, and multiple applications of hardwood are being developed (Kim 2020). Cross-laminated timber (CLT) is an engineering lumber similar to glulam, and it has recently been used as a structural material in high-rise wooden buildings. CLT is an innovative engineering lumber product that comprises cross-laminated layers stacked in the orthogonal direction of the grain. Since the early 2000s, the market for CLT has steadily grown due to increased demand as well as the Green building movement. Furthermore, the suitability of CLT for the construction of high-rise wooden buildings has already been established across the world (Foster *et al.* 2017; Sanner *et al.* 2017). In Korea, a five-story multipurpose building was built using larch, CLT, and glulam. Moreover, restrictions on the size of wooden buildings were recently abolished in the Korean Design standards (KDS 41 91 33:2018). More research is being conducted on the structural and qualitative performance of CLT using timber obtained from domestic tree species (Gong *et al.* 2018; Kang *et al.* 2019; Song *et al.* 2019; Kim 2020). Among mechanical properties, compressive strength of a structural material is an important design value for wooden buildings because excellent performance in compression is required to withstand the increased dead loads resulting from increasing building height; therefore, more research is being conducted on the compression performance of CLT (Oh *et al.* 2015; Wiesner *et al.* 2017; Brandner 2018; Wei *et al.* 2019).

In Europe and North America, spruce pine-fir or Douglas fir-larch timber species are commonly used in CLT for high-rise structures, with an average Poisson's ratio of 0.51 for a dry lumber at 12% moisture content. The average specific gravity of Japanese larch and red pine, which are the main species of structural lumber in southern Korea, is 0.52 and 0.46, respectively, and active research is being conducted with suitable materials for producing CLTs (Han *et al.* 2016; Choi *et al.* 2018; Song *et al.* 2019). However, a market survey of timber products (Korea Forest Service 2019) in Korea's general timber industry, which mainly produces timber and lumber, shows that the domestic wood usage proportion is 18%, and the domestic hard wood usage percentage is 0.46%, meaning that the resource is clearly underutilized.

For efficient use of timber, the grades of the major and minor layers of a CLT satisfying the design values may be established. The major layer is in the grain direction parallel to the load direction, and minor layer is perpendicular to the load and grain directions. The minor layer of the CLT that is to be used as flooring material does not require high bending performance according to the gamma method for predicting bending performance (CLT handbook 2019). The CLT design exhibits good strength performance even with relatively low-grade lumber as the minor layer; the choice of CLT materials can be broadened if larch is placed as the major layer and low-weight species can be used as the minor layer. Therefore, if the performance of mixed CLTs, using not only larch but also other species, is verified to be adequate, it is expected that their use will increase as the choice of materials increases. The Korean hardwood species of yellow poplar has a specific gravity of 0.46 and is similar to hemlock with a specific gravity of 0.45, which has been studied as a prospective CLT species in Canada (He *et al.* 2018).

The bonding performance of the adhesives used for manufacturing CLT must fulfill the requirements set by the KS F 2081(2021). The adhesion performance of a single species of CLT made using PRF (phenol-resorcinol-formaldehyde) and polyurethane adhesives has been verified to some extent (Betti *et al.* 2016; Sikora *et al.* 2016; Song and Hong 2016; Dugmore *et al.* 2019; Kim and Jeon 2019). However, insufficient research has been conducted on the strength performance of mixed CLTs using different adhesives. Therefore, in this study, a strength test was conducted to evaluate the compression performance of mixed CLTs with larch, red pine, yellow poplar, and two types of adhesives, and it was then compared with the value predicted by the FEM.

EXPERIMENTAL

Materials

The species of laminae used for manufacturing the CLT included Japanese larch (*Larix kaempferi* Carr.) and red pine (*Pinus densiflora*) as the major layer and yellow poplar (*Liriodendron tulipifera* L.) as the minor layer. The laminae were 25 mm thick, 100 mm wide, and 3600 mm long with an average moisture content of 12%. The average air-dried specific gravities of larch, red pine, and yellow poplar were 0.52, 0.46, and 0.41, respectively (Fig. 1). In the case of Japanese larch lamina, the laminae were classified by dividing into three groups: those with MOE (Modulus of elasticity) greater than 11 GPa (Grade II), with MOE less than 10 GPa (Grade I), and random MOE (10 to 11 GPa).

A total of three types of adhesives were used to glue the lumbers together: Phenol-Resorcinol-Formaldehyde (D40), Poly-Urethane I (Ottocoll, P410), and Poly-Urethane II (Kestopur, G10).

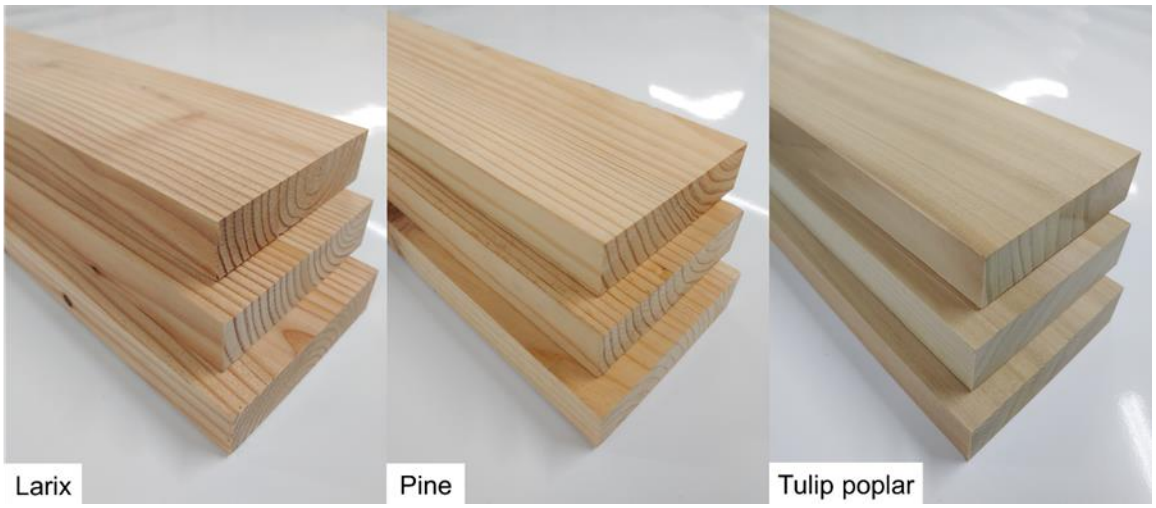

Fig. 1. Photographs of lumber pieces

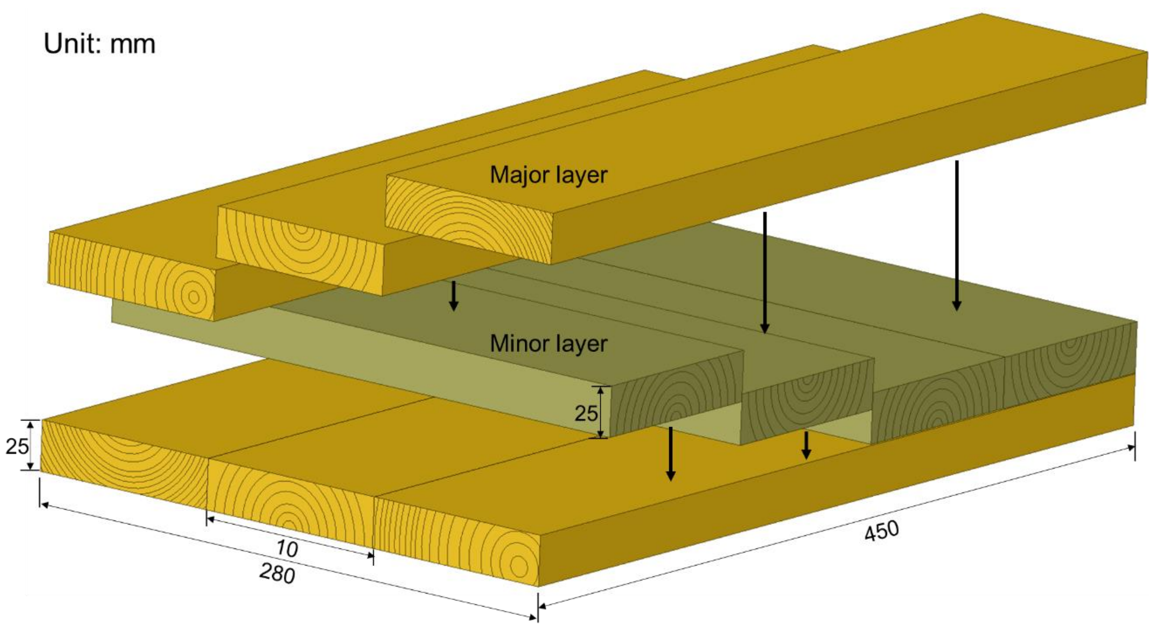

Fig. 2. Schematic diagram of cross-laminated timber

Methods

Manufacturing of CLT (Cross-laminated Timber)

The CLT was manufactured according to the manufacturing procedure in the CLT handbooks (Karacabeyli and Gagnon 2019). The CLT consisted of three plies, with two major and one minor layers. The major and minor layers were vertically crossed and laminated with adhesives and then pressed together at 0.9 MPa. The press time of the CLT was 4 h or more as recommended according to the adhesive type. The cross sections of the CLT were 210 cm^2 and 350 cm^2 (Fig. 2). Most of the types of CLTs were not graded, and the directions of the cross sections were randomly set during manufacturing. However, to confirm the influence of the layer composition on the compressive strength, the CLT specimens were manufactured according to the MOE grade of the larch lamina and the species of the minor layer (Lee *et al.* 2018). A total of 40 specimens were manufactured, 5 each with different species and types of adhesives, as listed in Table 1. The nomenclature of each test piece was defined as indicated in bold font in Table 1. The compressive test specimens of CLT were cut to a length of 450 mm to prevent buckling by setting the slenderness ratio to a short column.

Table 1. Results of Compressive Strength Test

<table>
<tr><th>Specimen</th><th>Major layer</th><th>Minor layer</th><th>Adhesive</th><th>Ply</th><th>Grade of major lamina</th></tr>
<tr><td>LLD</td><td rowspan="5">Japanese Larch</td><td rowspan="2">Japanese Larch</td><td>D40</td><td rowspan="8">3</td><td rowspan="6">Random</td></tr>
<tr><td>LLP</td><td>P410</td></tr>
<tr><td>LYD</td><td rowspan="6">Yellow poplar</td><td>D40</td></tr>
<tr><td>LYP</td><td>P410</td></tr>
<tr><td>LYG</td><td>G10</td></tr>
<tr><td>RYD</td><td>Red Pine</td><td rowspan="3">D40</td></tr>
<tr><td>LYD Ⅰ</td><td rowspan="2">Japanese Larch</td><td>Grade Ⅰ</td></tr>
<tr><td>LYD Ⅱ</td><td>Grade Ⅱ</td></tr>
</table>

Grade Ⅰ : MOE < 10 GPa, Grade Ⅱ : MOE > 11 GPa

Test Method of CLT Compression Strength

The CLT compressive strength test used a loading speed of 2 mm/min so that the specimen was destroyed in less than one min in accordance with EN 408. The compressive strength test exerted a maximum load of 2000 kN with the UTM (Universal testing machine) and measured the deformation and load together (Fig. 3). The total deformation of CLT length under compressive load was applied. The longitudinal compressive strength (σ) of each specimen was calculated using the maximum load and cross-sectional area of the member. Compressive strength was calculated using Eq. 1. The slenderness ratio of the three-ply CLT specimens calculated using Eq. 2 was 13.0,

$$\sigma = P_{max}/A \qquad (1) \qquad\qquad \lambda = \frac{k \cdot L}{r_{min}} = \frac{k \cdot L}{\sqrt{\frac{I_{min}}{A}}} \qquad (2)$$

where σ is the compressive strength (MPa), $P_{\max}$ is the maximum load (N), A is the cross sectional area of specimen (mm^2), λ is the slenderness ratio, L is the length of column (mm), k is the effective length factor, $r_{\min}$ is the radius of rotation angle for the buckling axis (mm), and $I_{\min}$ is the minimum moment of inertia (mm^4).

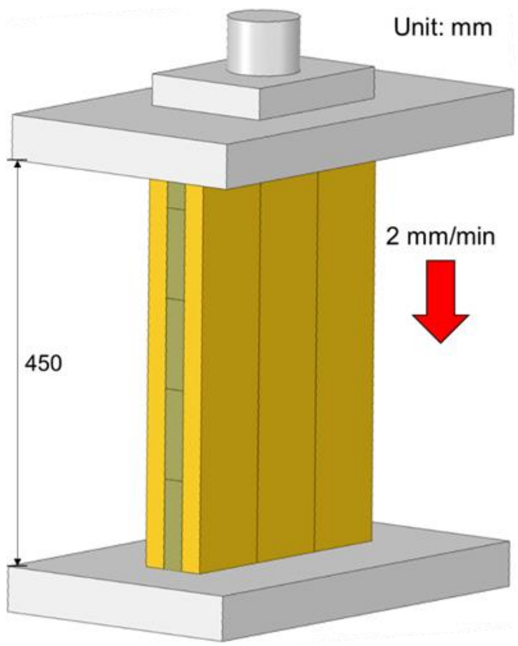

Fig. 3. Schematic diagram of compressive strength test and 200t UTM

CLT Compression Strength Prediction through Finite Element Analysis (FEM)

The behavior and deformation of the mixed CLT was analyzed using FEM (Finite element analysis) under an applied compressive load. The analytical model of ANSYS mechanical R3 software was used to create 0.5 mm elements of the mixed CLT specimens, as shown defined in Fig. 4. The data used in the analytical model were taken from literature and are listed in Table 2 (Ross 2010; Wargula 2021). The boundary condition for the FEM of CLT was applied by the actual deformation of the CLT at the maximum compressive load.

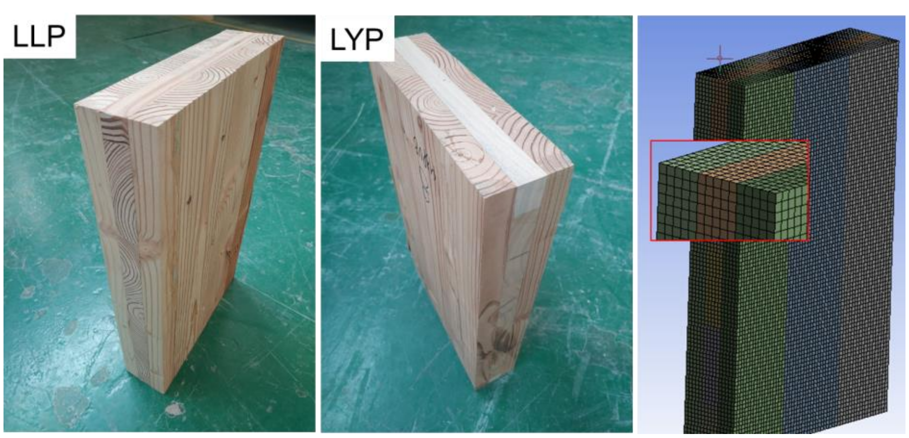

Fig. 4. CLT photograph and FEM-model structure

Table 2. Mechanical Parameters of Lamina of Species used in Finite Element Simulations taken from Ross (2010) and Wargula (2021)

Species	Moduli of Elasticity (GPa)			Shear Moduli (GPa)			Poisson's Ratios		
	E_L	E_R	E_T	G_{LR}	G_{LT}	G_{RT}	ν_{LR}	ν_{LT}	ν_{RT}
Larix kaempferi	11	0.41	0.43	1.94	2.68	2.68	0.66	0.64	0.89
Liriodendron tulipifera	12.80	1.18	0.55	0.96	0.88	0.14	0.32	0.38	0.52
Pinus densiflora	10.50	0.44	0.36	0.84	2.18	2.18	0.44	0.45	0.94

at approximately 12% moisture content

RESULTS AND DISCUSSION

Compressive Strength of Larch CLT and Mixed Species CLT

To know the effect of layer composition and adhesive type on the strength performance of the CLTs, the compressive properties of the CLT specimens were compared. The average compressive strength of the LYD II specimens using larch as the major layer, with an MOE of 11 GPa or more, was 27.7 MPa, which was the highest among all types of CLT specimens. The LYD specimens were made using yellow poplar in the minor layer and having a different grade of Japanese larch in the major layer. The average compression strength of LYD II specimens with higher non-destructive modulus of elasticity grades was 14% higher than that of the LYD I specimens. This is because the compressive strength of a CLT is less influenced by the minor layer and is mainly affected by the strength of the major layer (Tuhkanen *et al.* 2018).

The compressive strength of three-ply specimens (LLD, LLP) consisting of larch exhibited a difference depending on the adhesive type used for manufacturing the CLT. The LLD specimens with PRF adhesive exhibited an average compressive strength of 27 MPa, while the larch specimens with the polyurethane adhesive exhibited a 5% lower compressive strength than that of the LLD type (Fig. 5, Table 2).

The maximum compressive strengths of the mixed CLTs (LYD, LYP, LYG) consisting of yellow poplar were slightly less than the larix CLT and had a difference between compressive strengths were observed depending on the adhesive types. Specimens (LYD) with PRF adhesive displayed the highest strength. When the polyurethane adhesive was used for making CLT, the compressive strengths and ratios of P_{max}/P_y of LYG specimens were higher than that of LYP ones, and the coefficient of variation decreased by 20% compared to that of LYD strength. It was found that the adhesive used for manufacturing the mixed CLT should be selected depending on the species of lamina.

The average compressive strength of the mixed CLT comprising red pine as a major layer was 19.4 MPa, which is 28% lower than that of the larch CLT. The specific gravity of the major layer was different for the Japanese larch and red pine.

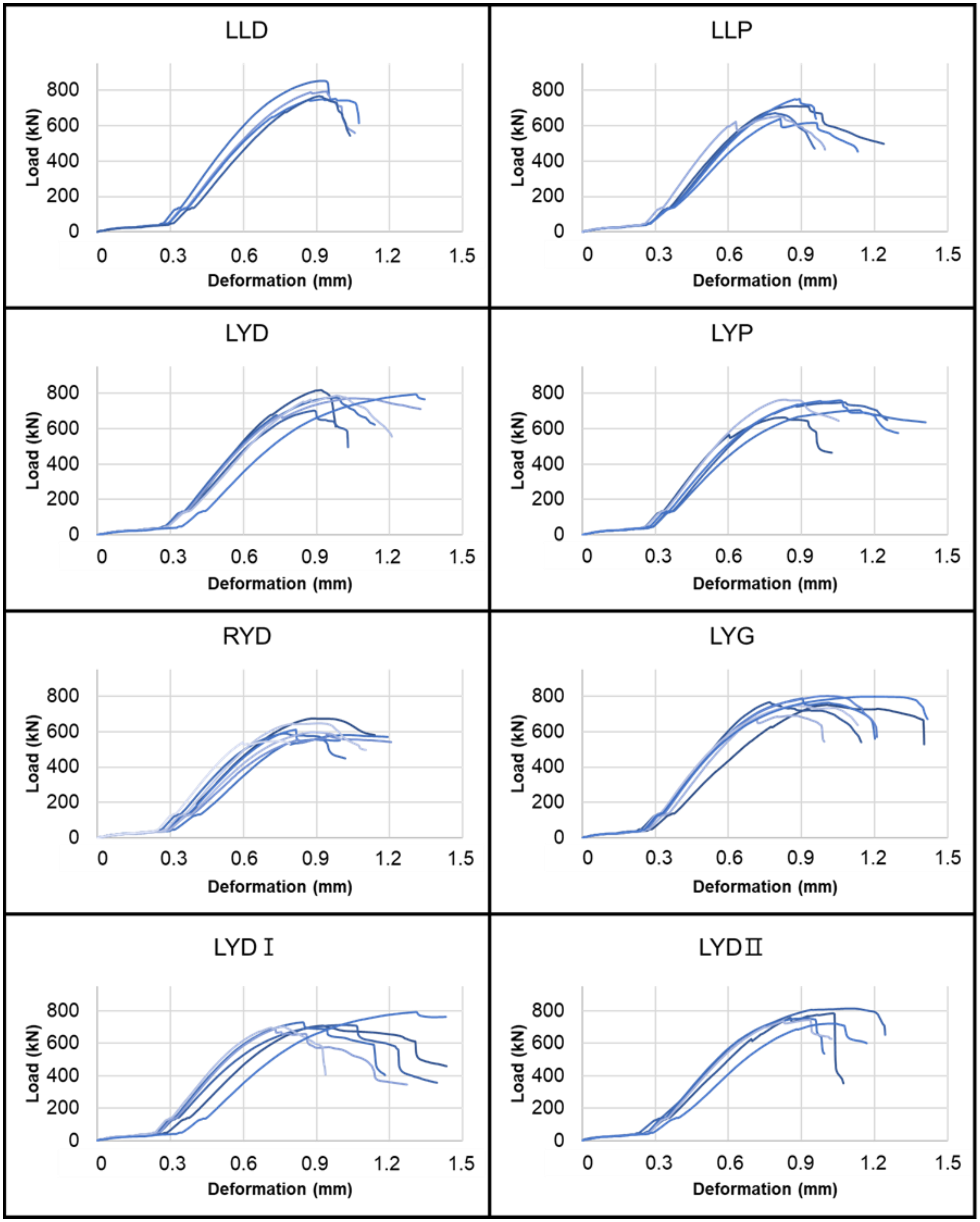

Fig. 5. Load-deformation response for CLT specimens

Table 3. Results of Compressive Strength Test on CLT Types

Specimens	Ave. P_{max} (kN)	Ave. P_p* (kN)	P_{max} / P_p	Compressive Strength(σ_{cp})			Failure mode
				(MPa)	**Strength ratio	***CV(%)	
LLD	792	568	1.39	27	1	5.8	1,3
LLP	685	532	1.29	25.6	0.95	6.7	2
LYD	775	576	1.35	27.4	1.01	5.0	1,3
LYP	729	462	1.58	22	0.81	5.9	2
LYG	764	466	1.64	22.2	0.82	4.9	2,3
RYD	593	408	1.45	19.4	0.72	6.2	3
LYD Ⅰ	693	463	1.50	22	0.82	5.8	1,3
LYD Ⅱ	763	581	1.31	27.7	1.02	4.7	1,3

***** P_p: Compressive load at proportional limit
** Strength ratio: Ratios of compressive strength of CLT types with respect to LLD
***CV: coefficient of variation (standard deviation divided by the mean)

Compressive Failure Mode of Larch CLT and Mixed CLT

After the compressive strength test of CLT, the compressive failure modes of the CLT types were compared as follows:

Mode 1: Rolling shear splitting at minor layer
Mode 2: Interfacial failure at glued line
Mode 3: Crushing and splitting at major layer

In the failure mode of the cross-laminated specimens (LLD) consisting of only Japanese larch with the PRF adhesive, complex crushing and splitting (Mode 3) in the major layer and rolling shear splitting (Mode 1) at the minor layer were observed, as shown in Fig. 6. Interfacial failure at the glued line of the LLD was rare because the bonding of the PRF adhesive was resilient to the internal splitting of the layers. The rolling shear splitting failure resulted in a lower compressive strength of the larch CLT. In the case of the LLP specimens with polyurethane adhesive, interfacial failure at the glued line along with splitting of the major layer was observed (Mode II). Cohesive failures at the glued line indicate that the integration between the major and minor layers was less than that of the LLD specimens. The lower average compression strength of the LLP specimens than that of the LLD specimens was concluded from the failure mode. Specimens of LYD, LYD I, and LYD II as mixed larch CLT with PRF adhesive were mostly observed to fail owing to the crushing and splitting failure (Mode III) of the major layers; however, the failure of the minor layer was rare. These results are attributed to the better rolling shear strength of yellow poplar than that of Japanese larch as a minor layer (Rara 2021). The LYP specimens consisting of Japanese larch and yellow poplar with polyurethane adhesive were observed to have interfacial failure at the glued line due to poor bonding performance, which is also the failure mode of the LLP specimen (Mode II). The strength reduction of the CLT specimens with polyurethane adhesives is observed by the interfacial failure at the glued line.

In the case of RYD specimens with red pine, which has a lower specific gravity than Japanese larch, it was observed that the major layer failed by crushing and splitting (Mode III).

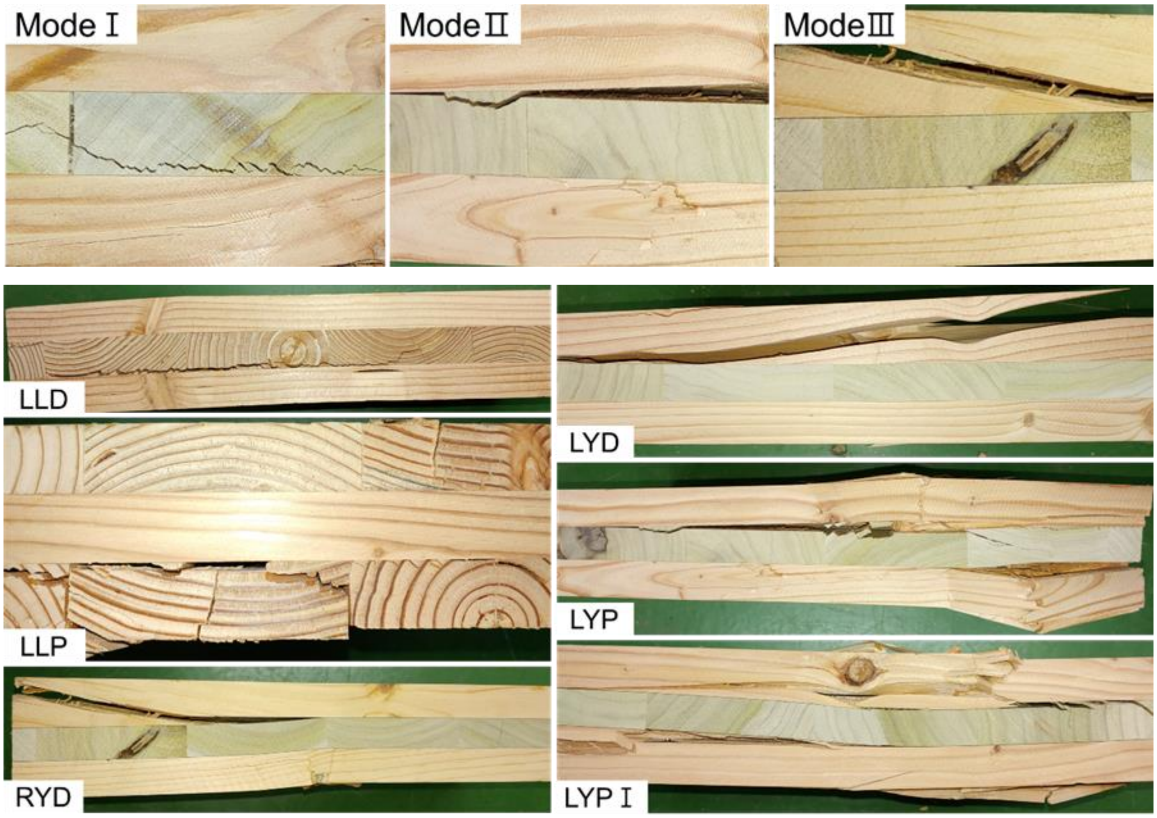

Fig. 6. Failure modes of CLT specimens

Prediction of Strength with Finite Element Analysis (FEM) in Mixed CLT

The FEM-calculated compressive strength of the CLT with an applied proportional limit load was compared to the actual compressive strength (Table 4), and the prediction model is shown in Fig. 7.

Table 4. Comparative Analysis of Actual and Predicted Compressive Strengths in CLT

Specimens	σ_{max} (kN)	σ_{cp} (MPa)	σ_{pred}* (MPa)	σ_{max} / σ_{pred}	σ_{cp} / σ_{pred}
LLD	37.7	27	28.3	1.33	0.95
LYD	36.9	27.4	27.4	1.35	1.00
RYD	28.2	19.4	20.6	1.37	0.94

* σ_{max} and σ_{cp} are the maximum and proportional limit compressive strengths, respectively.
* σ_{pred} was calculated using FEM based on the proportional limit load.

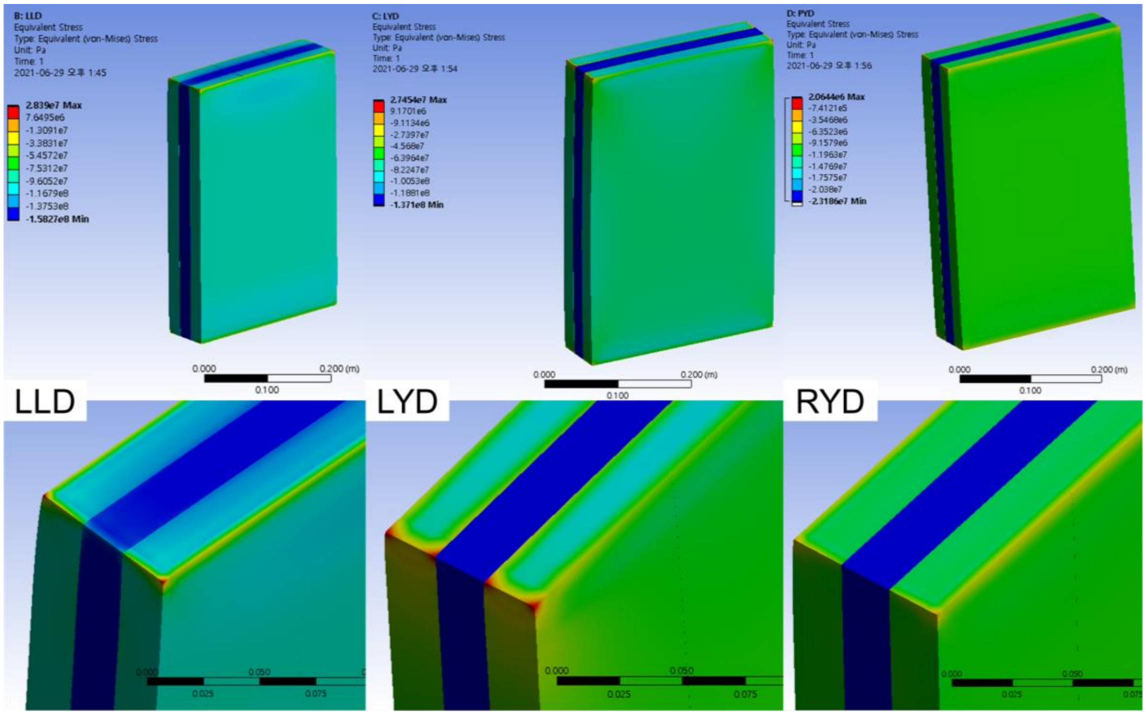

Fig. 7. Stress distribution of CLT specimens under compressive load calculated by FEM analysis

The actual strength data of CLT with PRF adhesive was selected, as it exhibited crushing and splitting failure, which is a typical failure mode of compressive specimens. The predicted strength of LYD was a closer match to the actual value than for LLD and RYD at the proportional load limit. The maximum compressive strength of the CLT was approximately 1.3 times higher than the predicted strength.

CONCLUSIONS

A compressive strength test was conducted to evaluate the compressive strength of the mixed cross-laminated timber (CLT) with yellow poplar, and the actual strength was compared with the strength predicted by finite element (FEM) simulation. The following conclusions were drawn:

1. The compressive strength of CLTs consisting of Japanese larch laminae with high modulus of elasticity (MOE) tended to be high. The mixed CLT with red pine lamina as the major layer had 28% lower strength than that with the Japanese larch.
2. The CLT with phenol-resorcinol-formaldehyde (PRF) adhesive yielded the highest compressive strength among three adhesives. In the case of mixed CLT using Japanese larch and yellow poplar, the compressive properties were different between the two polyurethane adhesive types depending on the bonding performance.
3. The compressive failure mode was divided into three modes. In the case of larch CLT with PRF adhesives, crushing and splitting failure modes were observed in the major layer, along with high strength performance. Rolling shear failure in the minor layer mainly occurred for the CLTs with PRF adhesives. In the case of mixed CLT using

yellow poplar as a minor layer, the specimens failed by rolling shear failure in the minor layer or interfacial failure at the glued line due to poor bonding.

4. The FEM-predicted compressive strength of the CLT at proportional limit load agreed well with the actual strength. The stress distribution profile obtained by FEM analysis showed that the minor layer of the mixed CLT can undergo rolling shear deformation.

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