Journal of Wood Science (2018) 64:538–550
https://doi.org/10.1007/s10086-018-1741-9

ORIGINAL ARTICLE

Load sharing and weakest lamina effects on the compressive resistance of cross-laminated timber under in-plane loading

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Received: 9 February 2018 / Accepted: 30 May 2018 / Published online: 13 July 2018

Abstract

A new approach was developed to predict the compressive resistance of cross-laminated timber (CLT) using the compressive strength of small samples of different grade lamina from E12 and E8 larch, and E10 and E6 nut pine. CLT of three different thicknesses was manufactured using different grades of laminas from each species. To evaluate the compressive resistance of CLT, three different methods were employed. The first method was used to determine the compressive resistance, which was predicted by multiplying the compressive strength of lamina aligned with the loading direction, and the cross-sectional areas of the lamina. The second method is similar to the first method, but additionally considering the stiffness ratio of the laminas. The third method developed from the current study accounts for load sharing and weakest lamina effects in the prediction of compressive resistance. When the lower 5th percentile compressive resistance in a major direction was predicted using the first two methods, the difference between the experimental test and the predicted value ranged from 2.5 to 43.4%. However, when the compressive resistance in a major direction was predicted using the developed method from the current study, the difference between the experimental test and predicted value ranged from − 8.7 to 10.8%.

Keywords Compressive resistance · Cross-laminated timber · Load sharing · Weakest lamina · In plane

Introduction

High-rise wood buildings have been built around the world, and it would appear that taller buildings would be designed using cross-laminated timber (CLT) [1]. In high-rise building, since the vertical loads are accumulated, the compressive resistance of CLT is critical to identify and assess in the structural design of the building. The CLT compressive resistance should be predicted in a more reliable way. Brandner et al. [2] reviewed several state-of-the-art reports related to CLT. These referenced reports pointed out that although the CLT compressive resistance perpendicular-to-plane loading was investigated by several researchers [3–5], the CLT compressive resistance in-plane loading was rarely reported. Subsequently, there are two approaches for predicting the CLT compressive resistance under in-plane loading.

The first approach can be briefly described as follows. When utilizing the CLT, there are several layers of laminas usually stacked in a crosswise sequence. The compressive strength of a lamina perpendicular to the loading direction is approximately 10% of that of the lamina parallel to the loading direction [6]. Thus, when using the CLT, the compressive strengths of the cross layers in this example are assumed to be zero. As a result, the CLT compression resistance can be predicted by multiplying the compressive strength and cross-sectional area of the laminas parallel to the loading direction (Fig. 1, Eq. 1) [7]. Oh et al. [8] predicted the compressive strength of the CLT using this approach. The tested CLTs were three ply samples composed with one lamina grade (E11 from larch). They generated the lamina strengths using Monte Carlo simulation and showed a good agreement between the predicted CLT values and experimentally tested CLT values. The CLT can be manufactured from various lamina grades. Thus, there should be further validations that will be required for different combinations.

$$P_{\text{parallel}} = \sigma_c \times A_{\text{parallel}} \quad (1)$$

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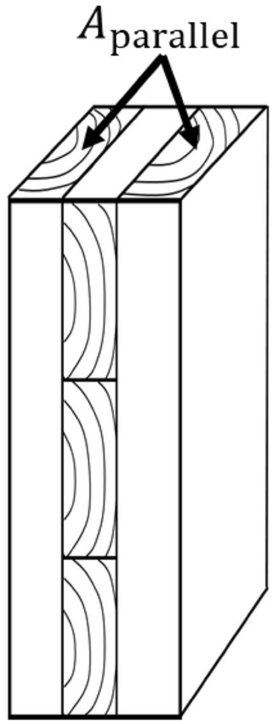

Fig. 1 Applied area for compression design (A_{parallel} cross-sectional area of lamina parallel to loading direction)

where P_{parallel} compressive resistance of CLT, σ_c compression strength of lamina parallel to the loading direction, A_{parallel} cross-section area of lamina parallel to the loading direction.

In the second approach, the net cross-section area was applied to calculate the CLT compressive resistance [9]. The net cross-section area reflects the relative MOE of laminas in CLT (Eq. 2). The MOEs of laminas perpendicular to the loading direction were assumed to be zero, as noted in the first Method 1. As a result, the CLT compressive resistance can be predicted by multiplying the net cross-section area and the compressive strengths of laminas parallel to the loading direction.

$$A_{\text{net}} = \sum_{i=1}^{n} \frac{E_i}{E_c} \times A_i \tag{2}$$

where A_{net} net cross-sectional area (mm^2), E_i modulus of elasticity of ith laminas parallel to the loading direction (MPa), $E_c$modulus of elasticity of reference laminas (MPa), A_i the loading area of ith laminas parallel to the loading direction (mm^2).

In this case, the same lamina grades are used for all parallel layers in the American CLT standard [10], additionally the different lamina grades can also be used for the parallel layers similar to the Japanese CLT standard [11]. In the latter case, the different loads will be applied to the various laminas depending on the axial stiffness. Therefore, when utilizing this particular mechanism, it is shown that the load is dispersed depending on the lamina grades, and needs to be carefully assessed and considered for predicting the compressive resistance of the applicable CLT. However, the existing two methods do not reflect this mechanism as described.

In this study, a new approach was developed for predicting the CLT compressive resistance under in-plane loading. The new approach and the two existing methods were experimentally compared to determine a reliable method for the compressive resistance of CLT made from different lamina grades parallel to the loading direction.

Materials and methods

Specimens

In this experiment, two species, larch (*Larix kaempferi*, 560 kg/m^3) and pine (*Pinus koraiensis*, 430 kg/m^3), were used for laminas of 100 mm (width) × 30 mm (thickness) × 3600 mm (length). The laminas were not connected by finger joint. There were four lamina grades, namely E8 and E12 for larch, E6 and E10 for pine, which were used for manufacturing the CLT specimens (Table 1). The moisture contents of the laminas and CLT specimens were in the range of 7.20–9.03% and 6.27–8.22%, respectively. The oven-dry weight of specimens was measured after compression test and the moisture contents were calculated by Eq. 3.

$$\text{Moisture content (\%)} = \frac{\text{(Initial weight)} - \text{(Oven dry weight)}}{\text{(Oven dry weight)}} \times 100 \tag{3}$$

The produced laminas were graded according to Korean Standard F3021 [12]. The laminas were classified by modulus of elasticity (MOE) measured by a machine stress rating (MSR), then each lamina was given a grade which specifies a corresponding minimum MOE to satisfy the assessment review. For example, the noted grade E8 of lamina should have recorded the MOE of 8 GPa or higher.

To measure the actual compressive resistance of CLT, there were three different thickness 90, 120, 150 mm of CLT were manufactured using two different lamina grades for each species (Fig. 2). Table 2 shows the nomenclature of CLT specimens with respect to species, the number of layers, and the CLT thickness. The first letter indicates the lamina species that was used in this study. The second letter indicates the number of layers. The last number indicates the thickness (mm) of the CLT specimen that was used in this experiment.

Table 1 Compressive strength of each lamina grade

Lamina grade	Species	MOE[a] (GPa)	Number of specimens	Moisture contents (%)	Compressive strength (MPa)				
					Average	COV[b] (%)	Weibull distribution		
							Scale	Shape	5% WPE[c]
E12[d]	Larch	12–13	30	8.01	58.8	13.6	62.6	7.5	42.0
E8	Larch	8–9	30	9.03	45.9	17.0	49.3	6.2	30.4
E10	Pine	10–11	30	8.17	45.5	15.7	48.6	6.8	31.4
E6	Pine	6–7	30	7.20	31.7	18.0	34.3	5.6	20.2

[a]Modulus of elasticity

[b]Coefficient of variation

[c]Parametric 5th percentile point estimate using Weibull distribution fit

[d]E-rated grade which was determined by average of localized MOEs in a lamina

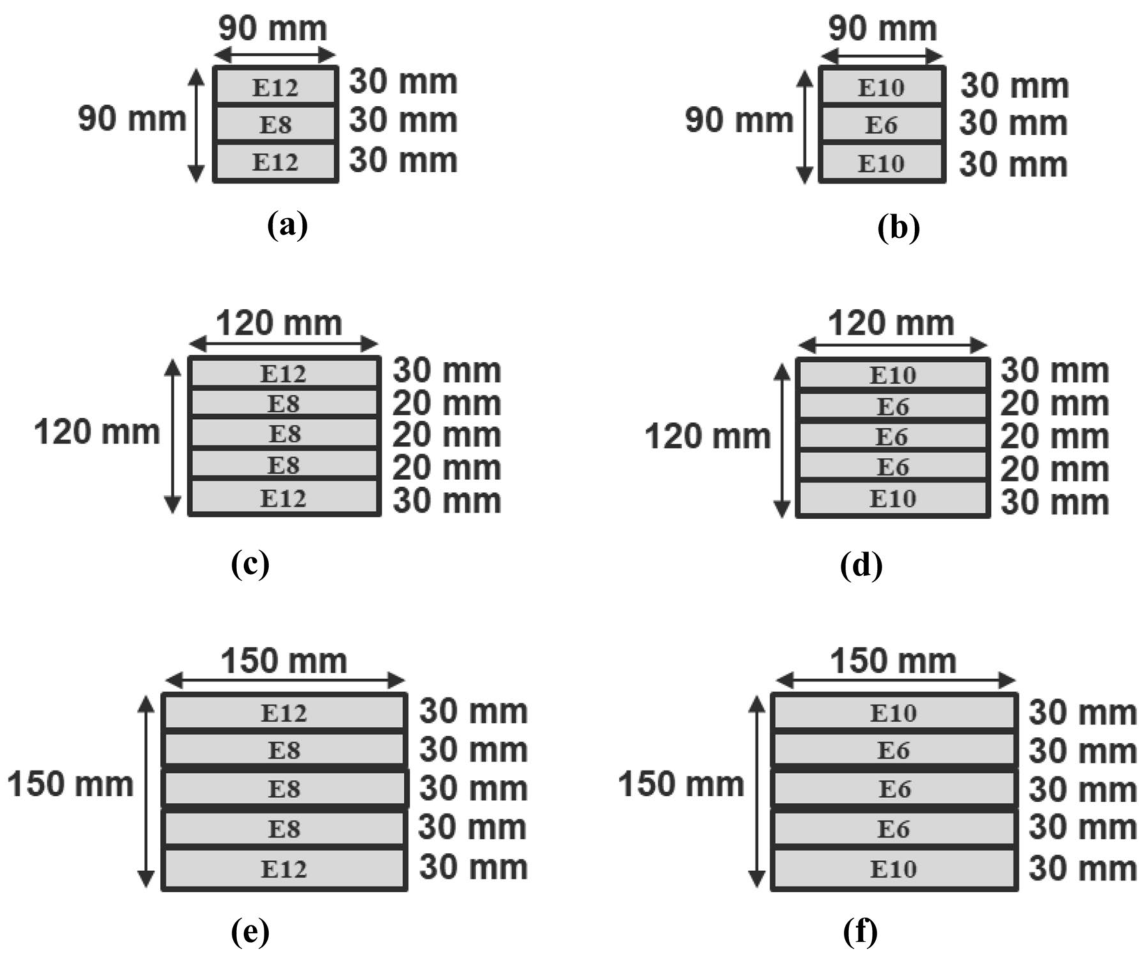

Fig. 2 Lamina grades and lay-up of CLT specimens

Compressive strength of different grade lamina

There were 30 specimens that were randomly extracted from each lamina grades to reflect the localized compressive strength of the corresponding lamina grade. The dimension of specimen was 30 mm (width) × 30 mm (thickness) × 120 mm (length) (Fig. 3a). The compression test was carried out using a universal test machine (UTM, SFM-20 Model, USA) according to ASTM D143 [13]. The loading

Table 2 Actual compressive resistance and specification for cross-laminated timber

Type	Species	Number of layers (grade of lamina)	Dimensions (mm)			Loading direction	Actual compressive resistance of CLT (kN)		
			Thickness (thickness of lamina)	Width	Length		AVE[a]	COV[b]	5% WPE[c]
L[d]-3[e]-90[f]	Larch	3 layers (E12/E8/E12)	90 (30/30/30)	90	300	Major	234.4	6.1	198.6
						Minor	118.8	5.8	101.7
L-5-120		5 layers (E12/E8/E8/E8/E12)	120 (30/20/20/20/30)	120	300	Major	424.3	4.8	373.1
						Minor	204.8	9.0	160.7
L-5-150		5 layers (E12/E8/E8/E8/E12)	150 (30/30/30/30/30)	150	300	Major	620.7	7.0	511.0
						Minor	426.6	6.1	361.1
P-3-90	Pine	3 layers (E10/E7/E10)	90 (30/30/30)	90	300	Major	189.3	11.4	136.8
						Minor	83.0	12.8	58.4
P-5-120		5 layers (E10/E7/E7/E7/E10)	120 (30/20/20/20/30)	120	300	Major	322.4	11.2	235.2
						Minor	160.7	8.1	128.4
P-5-150		5 layers (E10/E7/E7/E7/E10)	150 (30/30/30/30/30)	150	300	Major	484.8	5.8	414.6
						Minor	301.7	9.9	228.6

[a] Average value

[b] Coefficient of variation

[c] Parametric 5th percentile point estimate using Weibull distribution fit

[d] Species; *L* larch, *P* pine

[e] Number of layers

[f] Thickness of cross-laminated timber (mm)

rate was 0.5 mm/min. The compressive strength of lamina was calculated using Eq. 4.

$$\sigma_{\text{lamina}} = P_{\max} / A \tag{4}$$

where σ_{lamina} compressive strength of lamina (MPa), $P_{\max}$ the maximum load carrying capacity (N), A the loading area of small specimen (mm^2).

Compressive resistance of CLT

Since the CLT has major and minor directions [7], the CLT specimens for the two in-plane loading were prepared according to the specifications noted in the Fig. 3b–g. The number of repetitions was 10, and there were a total of 120 CLT specimens [six lamina combinations (Fig. 2) × two loading directions × 10 repetitions] that were prepared for this experiment.

The compression test for the CLT specimens was carried out using a UTM equipped with 2000 kN load cell according to ASTM D198 [14]. The loading rate was 2 mm/min. The actual compressive resistances of CLT specimens were defined as the measured maximum load-carrying capacity (Eq. 5).

$$P_{\text{CLT-actual}} = P_{\max} \tag{5}$$

where $P_{\max}$ the maximum load – carrying capacity (N).

Prediction of compressive resistance of CLT

Generation of the lamina compressive strength

The compressive strengths of laminas are required to predict the compressive resistance of the CLT. Several researchers [15–18] investigated to find suitable parametric models for representing strength properties of Korean species. Two parameter (2P) weibull distribution was revealed as a suitable model and Oh et al. [8] and Pang et al. [19] used this model to generate the compression and tensile strength of larch laminas. In this study, the compressive strengths for each lamina were also generated using two parameter (2P) Weibull distribution (Eq. 6). The scale parameter (η) and the shape parameter (α) for each lamina grade were derived by the experimental test. A random number between 0 and 1 was inserted into p for generating the lamina compressive strength.

$$\text{Weibull point estimate (WPE)} = \eta\left[-\ln(1-p)\right]^{1/\alpha} \tag{6}$$

where η Weibull scale parameter, p percentile as a decimal, α Weibull shape parameter.

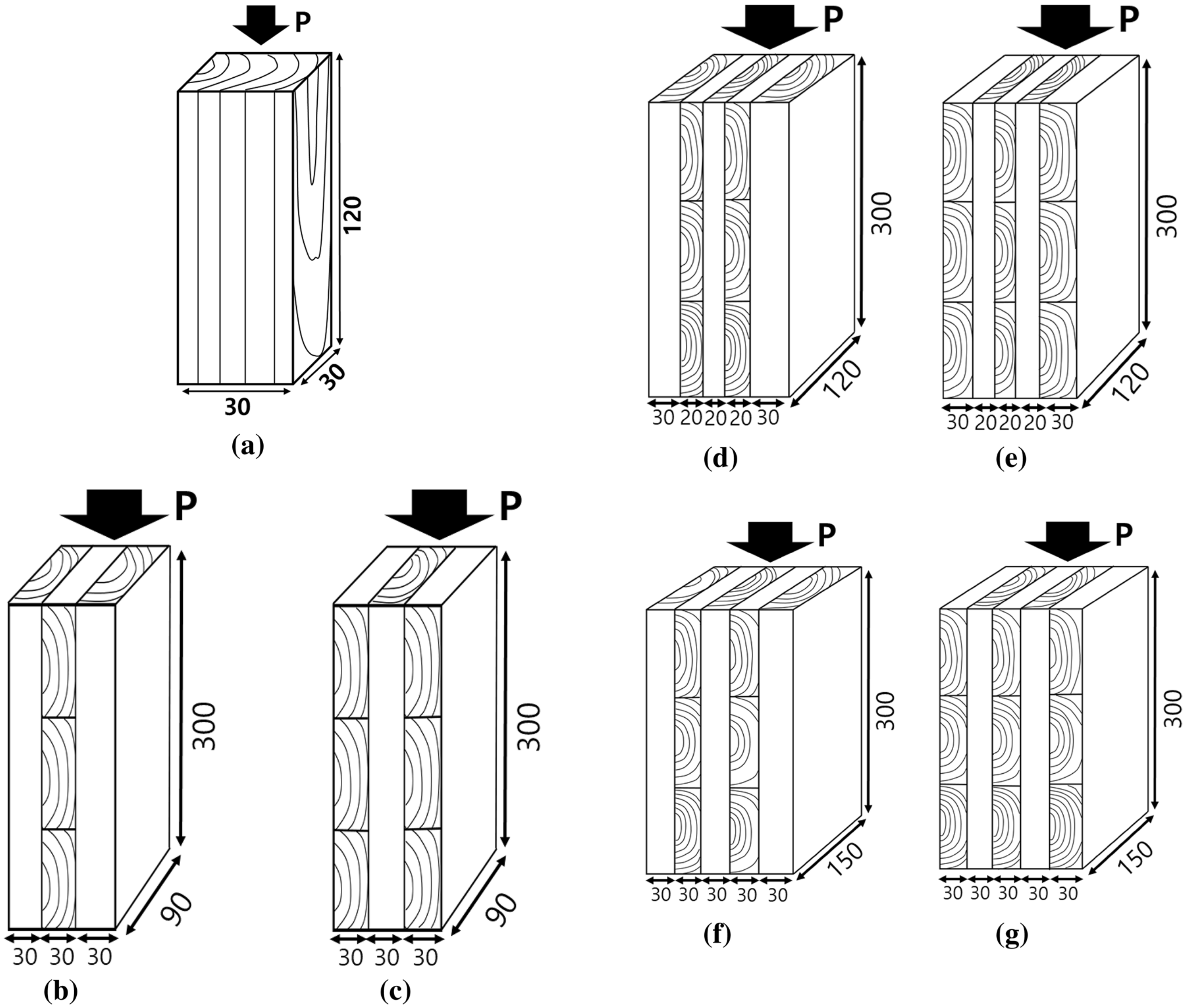

Fig. 3 Specimens for compression test (mm)

Lower 5th percentile strength

The parametric point estimate was derived based on the two parameter (2P) Weibull distribution (Eq. 6). In the Eq. 5, when the p was 0.05, the calculated value was lower 5th percentile point estimate. The scale parameter (η) and the shape parameter (α) were derived for compressive strength of different grade lamina and CLTs.

Method 1

The compressive resistance of CLT can be predicted by multiplying the compressive strength of lamina and the area of the layers where the grain direction of lamina is run parallel to the loading direction (Eq. 1). Equation 7 was derived from Eq. 1 which was used for accounting for two different grade laminas, as used for outer or inner layers. To predict compressive resistance of CLT using method 1, the compressive strength of each lamina parallel to the loading direction ($\sigma_{\text{lamina},i}$) was randomly generated by Eq. 6 and multiplied by the corresponding area of each layer, and the calculated compressive resistances for each layer were summed.

$$P_{\text{CLT-predicted by method1}} = \sum_{i=1}^{n} \sigma_{\text{lamina},i} \times A_i \tag{7}$$

where $P_{\text{CLT-predicted by method1}}$ predicted CLT compressive resistance by method 1 (N), $\sigma_{\text{lamina},i}$ compressive strength of lamina in ith layer (MPa), A_i the loading area of ith layer parallel to the loading direction (mm^2), n the number of layers parallel to the loading direction.

Method 2

The compressive resistance of each layer was predicted by multiplying the net cross-section area (Eq. 2) of each layer with the compressive strength of the corresponding lamina. The compressive resistance of CLT was calculated by summing the predicted compressive resistance of each layer (Eq. 8). The MOE of outer lamina was applied for E_c and the MOE of ith lamina was applied for E_i.

$$P_{\text{CLT}-\text{predicted by method2}} = \sum_{i=1}^{n} \frac{E_i}{E_c} \times \sigma_{\text{lamina},i} \times A_i \tag{8}$$

where $P_{\text{CLT}-\text{predicted by method2}}$ predicted CLT compressive resistance by method 2 (N), $\sigma_{\text{lamina},i}$ compressive strength of lamina in ith layer (MPa), A_i the loading area of ith layer parallel to the loading direction (mm^2), n the number of layers parallel to the loading direction.

Method 3

Low stiffness member does not transfer significant load. Similarly, very stiff member transfer large amounts of load. Cramer and Wolfe [20] applied this concept for predicting load distributions among various stiffness trusses. In a compression test for the CLT, all the layers in the CLT were shown to have the same vertical deflection, but each layer carries different load capacities which are directly proportional to its relative stiffness and area. The load distributions among layers can be derived as follows.

Considering the five layers of the CLT, the CLT has three layers parallel to the loading direction. The deformation of the three layers in the loading direction would be identical (Eq. 9). If Eq. 9 is rearranged by applied load in each layer, Eq. 10 can be derived.

$$\frac{P_1 L}{E_1 A_1} = \frac{P_2 L}{E_2 A_2} = \frac{P_3 L}{E_3 A_3} \tag{9}$$

$$P_1 = \frac{E_1 A_1}{E_2 A_2} P_2 = \frac{E_1 A_1}{E_3 A_3} P_3 \tag{10}$$

where P_1 the applied load for layer 1 (N), L the initial length of CLT specimen (mm), E_1 the stiffness of layer 1 (MPa), A_1 the loading area of layer 1 (mm^2), P_2 the applied load for layer 2 (N), E_2 the stiffness of layer 2 (MPa), A_2 the loading area of layer 2 (mm^2), P_3 the applied load for layer 3 (N), E_3 the stiffness of layer 3 (MPa), A_3 the loading area of layer 3 (mm^2).

The sum of the each load supported by each layer is equal to the load that the CLT can support (Eq. 11)

$$P_1 + P_2 + P_3 = P_{\text{CLT}} \tag{11}$$

where P_{CLT} the applied load for CLT (N).

Substituting Eq. 10 into Eq. 11 leads to Eq. 12. The Eq. 12 shows that a specific layer carries a load in proportion to its relative stiffness and area.

$$P_{\text{CLT}} = \frac{E_1 A_1 + E_2 A_2 + E_3 A_3}{E_1 A_1} P_1 \tag{12}$$

As a result, Eq. 13 can be derived for predicting compressive resistance of CLT, which reflects the load sharing effect. Although the load sharing effect is derived from Eq. 9 to 12 assuming elastic behavior of layers, the load sharing effect assumed constant until ultimate failure occurs at the weakest lamina.

$$P_{\text{CLT},\ i} = \frac{\sum_{j=1}^{n} E_j A_j}{E_i A_i} \sigma_{\text{lamina},\ i} \times A_i \tag{13}$$

where $P_{\text{CLT},\ i}$ the compressive resistances of CLT in case that ith layer fails (N), n the number of layers parallel to the loading direction, E_j the stiffness of jth layer (MPa), A_j the loading area of jth layer (mm^2), E_i the stiffness of ith layer (MPa), A_i the loading area of ith layer (mm^2), $\sigma_{\text{lamina},i}$ compressive strength of lamina in ith layer (MPa).

When a weakest layer fails, the load-carrying capacity of the CLT will be decreased after ultimate state. The compressive resistance of CLT could be determined by the lowest value of individual layers among all layers parallel to the loading direction.

$$P_{\text{CLT}-\text{predicted-by-method3}} = \min(P_{\text{CLT},\ i}) \tag{14}$$

where $P_{\text{CLT}-\text{predicted by method3}}$ predicted CLT compressive resistance by method 3 (N).

Results and discussion

Compressive strength of lamina

The failure modes of lamina specimens were crushing or shearing by the compression test (Fig. 4a, b). Especially, these failures obviously occurred around knots (Fig. 4c). The higher lamina grade in the same species had higher compressive strength (Table 1). In the larch samples, the average and lower 5th percentile compressive strength for E12 grade were approximately 28 and 38% higher than those for E8 grade, respectively. In pine species, the average and lower 5th percentile compressive strength for E10 grade were approximately 43 and 55% higher than those for E6 grade, respectively.

When the species was different, the higher grade lamina did not have higher compressive strength, as compared to the results of the lower grades. The average compressive strength of the E10 grade (45.5 MPa) was slightly

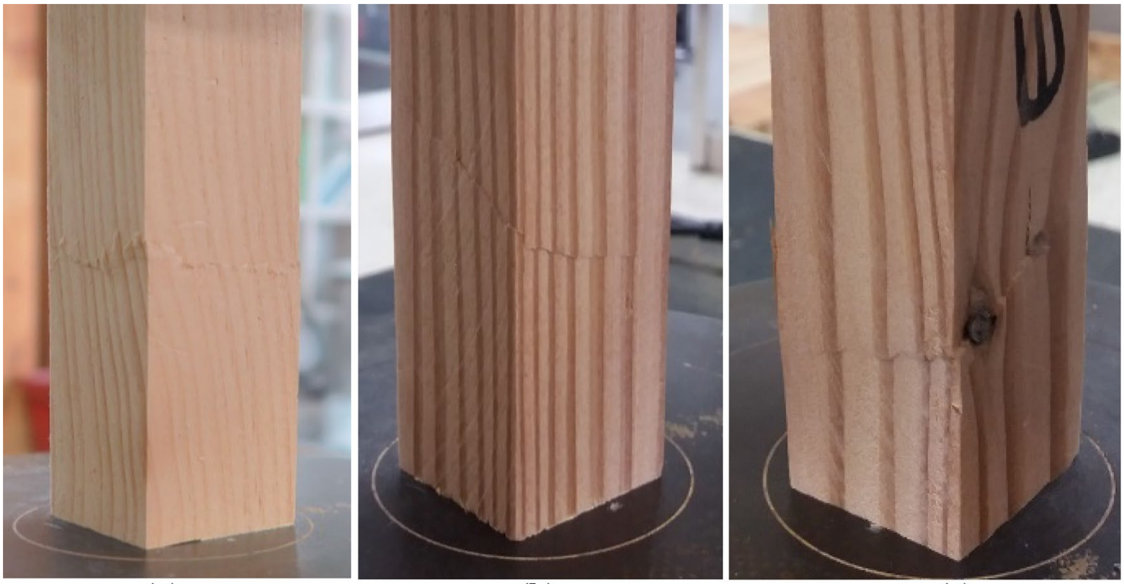

Fig. 4 Failure modes of lamina specimens

less than E8 grade (45.9 MPa). The 5th percentile compressive strength of E10 grade (31.4 MPa) also was not significantly higher than the E8 grade (30.4 MPa). This result shows that the compression strength of lamina was significantly related to the species as well as MOE grades. These results were in line with research results by Green and Kretschmann [21] where it was found that the compressive strengths of the same MOE lumber were different depending on the lumber species. Thus, the database for compressive strength of laminas was constructed by the species and grade in this study.

Compressive resistance of CLT

In the CLT compression test, crushing failure appeared around the knot (Fig. 5). The load-carrying capacity of CLT was continuously decreased when a crushing failure happened in a lamina (Fig. 6). The actual compressive resistances of CLTs (Table 2) show that the larger size specimen had higher compressive resistance. The increase of compressive resistance was analyzed according to the area ratios. The gross cross-sectional area (A_{gross}) of each specimen was 90×90, 120×120, and 150×150 mm^2 for 90, 120, and 150 mm thick CLT in both major and minor directions. Thus, the A_{gross} ratio was 1:1.78:2.78 for 90, 120, and 150 mm thick CLT.

In case of major direction, the area of layers parallel to the loading direction ($A_{parallel}$) was 60×90, 80×120, and 90×150 mm^2 for 90, 120, and 150 mm thick CLT. The $A_{parallel}$ ratio was 1:1.78:2.50 for 90, 120, and 150 mm thick CLT (Fig. 7a). The average compressive resistance ratio of 120 mm thick CLT to 90 mm thick CLT was 1.81 for larch CLT and 1.70 for pine CLT, which were similar to the A_{gross} ratio and $A_{parallel}$ ratio. The compressive resistance ratio of 150 mm thick CLT to 90 mm thick CLT was 2.65 for larch CLT and 2.56 for pine CLT, which were smaller than the A_{gross} ratio, but higher than the $A_{parallel}$ ratio. It shows that the compressive resistance can be overestimated

Fig. 5 Failure mode of cross-laminated timber (crushing)

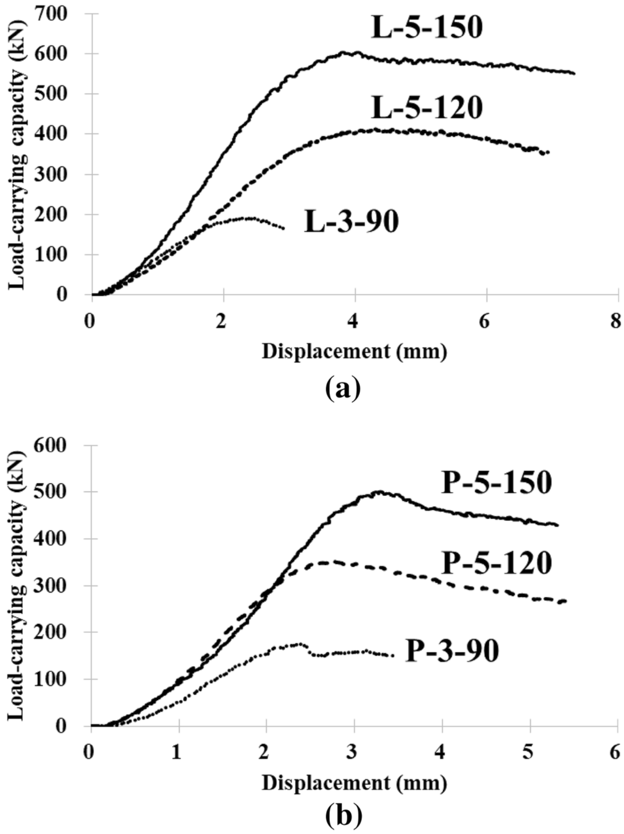

Fig. 6 Load-carrying capacity of CLT in major direction

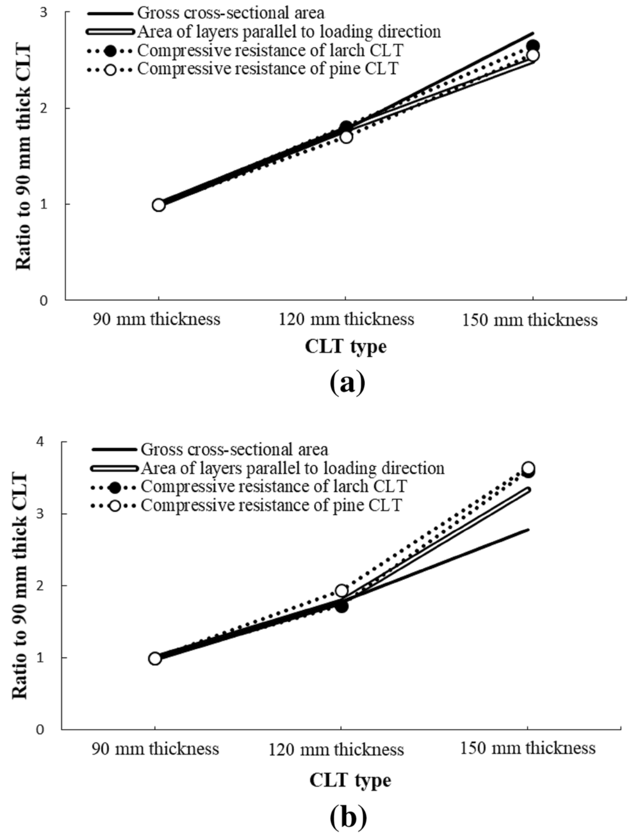

Fig. 7 Gross cross-sectional area, area of layers parallel to the loading direction, and the compressive resistance ratios (90, 120 and 150 mm thick CLT to 90 mm thick CLT)

if the resistance is predicted by multiplying the A_{gross} and a normalized strength. If the resistance is predicted by multiplying the $A_{parallel}$ and a normalized strength, the resistance of larger cross-sectional area CLT will be conservatively designed.

In case of minor direction, the area of layers parallel to the loading direction ($A_{parallel}$) was 30×90, 40×120, and 60×150 mm^2 for 90, 120, and 150 mm thick CLT. The $A_{parallel}$ ratio was 1:1.78:3.33 for 90, 120, and 150 mm thick CLT (Fig. 7b). The average compressive resistance ratio of 120 mm thick CLT to 90 mm thick CLT was 1.72 for larch CLT and 1.94 for pine CLT, which were similar to the A_{gross} ratio and $A_{parallel}$ ratio. The compressive resistance ratio of 150 mm thick CLT to 90 mm thick CLT was 3.59 for larch CLT and 3.63 for pine CLT, which was higher than both A_{gross} ratio and $A_{parallel}$ ratio. The compressive resistance ratio was approximately 30% and 8% higher than the A_{gross} ratio and the $A_{parallel}$ ratio, respectively. Thus, it is more reasonable to predict the compressive resistance of CLT using the $A_{parallel}$ rather than the A_{gross}. These experimental results show that the laminas parallel to the loading direction supported the most of the compressive load.

Prediction of compressive resistance for cross-laminated timber using three different methods

Table 3 shows the predicted values from the three methods and the measured values from the experimental test. In method 1, the CLT compressive resistances were predicted by Eq. 6 and lamina compressive strengths. A thousand lamina compressive strengths, parallel to the loading direction, were generated using the Weibull distribution parameters of corresponding lamina grade in Table 1. The generated compressive strengths (MPa) were multiplied by the cross-sectional area of the corresponding laminas to predict the compressive resistance (kN) of the individual layer. The sum of the predicted values of the individual layers was regarded as the CLT compressive resistance. In major direction, the predicted average resistances and 5% WPEs were 13.7–34.7% and 13.6–43.4% higher than the actually measured values, respectively.

In the minor direction, the differences of average resistance between the predicted values and actual values were − 5.3–29.7%. The differences of 5% WPE of the predicted

Table 3 Predicted compressive resistance of cross laminated timber (kN)

Type	Loading direction	Actual compressive resistance of CLT		Predicted compressive resistance of CLT											
				Method 1				Method 2				Method 3			
		AVE[a]	5% WPE[b]	AVE	Diff. [c] (%)	5% WPE	Diff. (%)	AVE	Diff. (%)	5% WPE	Diff. (%)	AVE	Diff. (%)	5% WPE	Diff. (%)
L[d]-3[e]-90[f]	Major	234.4	198.6	315.7	34.7	250.8	26.3	315.7	34.7	250.8	26.3	291.9	24.5	209.5	5.4
	Minor	118.8	101.7	123.8	4.2	82.4	−19.0	123.8	4.2	82.4	−19.0	123.8	4.2	82.4	−19.0
L-5-120	Major	424.3	373.1	533.3	25.7	454.3	21.8	496.8	17.1	419.0	12.3	470.3	10.8	353.4	−5.3
	Minor	204.8	160.7	221.5	8.2	176.7	9.9	221.5	8.2	176.7	9.9	200.4	−2.2	144.9	−9.9
L-5-150	Major	620.7	511.0	733.0	18.1	634.3	24.1	665.1	7.2	577.6	13.0	646.9	4.2	514.5	0.7
	Minor	426.6	361.1	553.3	29.7	442.3	22.5	553.3	29.7	442.3	22.5	413.2	−3.1	310.3	−14.1
P-3-90	Major	189.3	136.8	243.6	28.7	189.9	38.8	243.6	28.7	189.9	38.8	222.0	17.3	151.6	10.8
	Minor	83.0	58.4	85.7	3.2	53.9	−7.7	85.7	3.2	53.9	−7.7	85.7	3.2	53.9	−7.7
P-5-120	Major	322.4	235.2	402.8	24.9	337.2	43.4	372.0	15.4	306.9	30.5	350.9	8.8	255.0	8.4
	Minor	160.7	128.4	152.3	−5.2	118.3	−7.8	152.3	−5.2	118.3	−7.8	138.8	−13.6	97.0	−24.5
P-5-150	Major	484.8	414.6	551.4	13.7	470.9	13.6	494.7	2.0	425.0	2.5	485.4	0.1	378.4	−8.7
	Minor	301.7	228.6	285.8	−5.3	231.0	1.1	285.8	−5.3	231.0	1.1	259.3	−14.1	192.4	−15.8

[a] Average value

[b] Lower 5th percentile point estimate using Weibull distribution fit

[c] Difference between prediction and measured value: (predicted value−measured value)/measured value

[d] Species; *L* larch, *P* pine

[e] The number of layers

[f] Thickness of cross-laminated timber (mm)

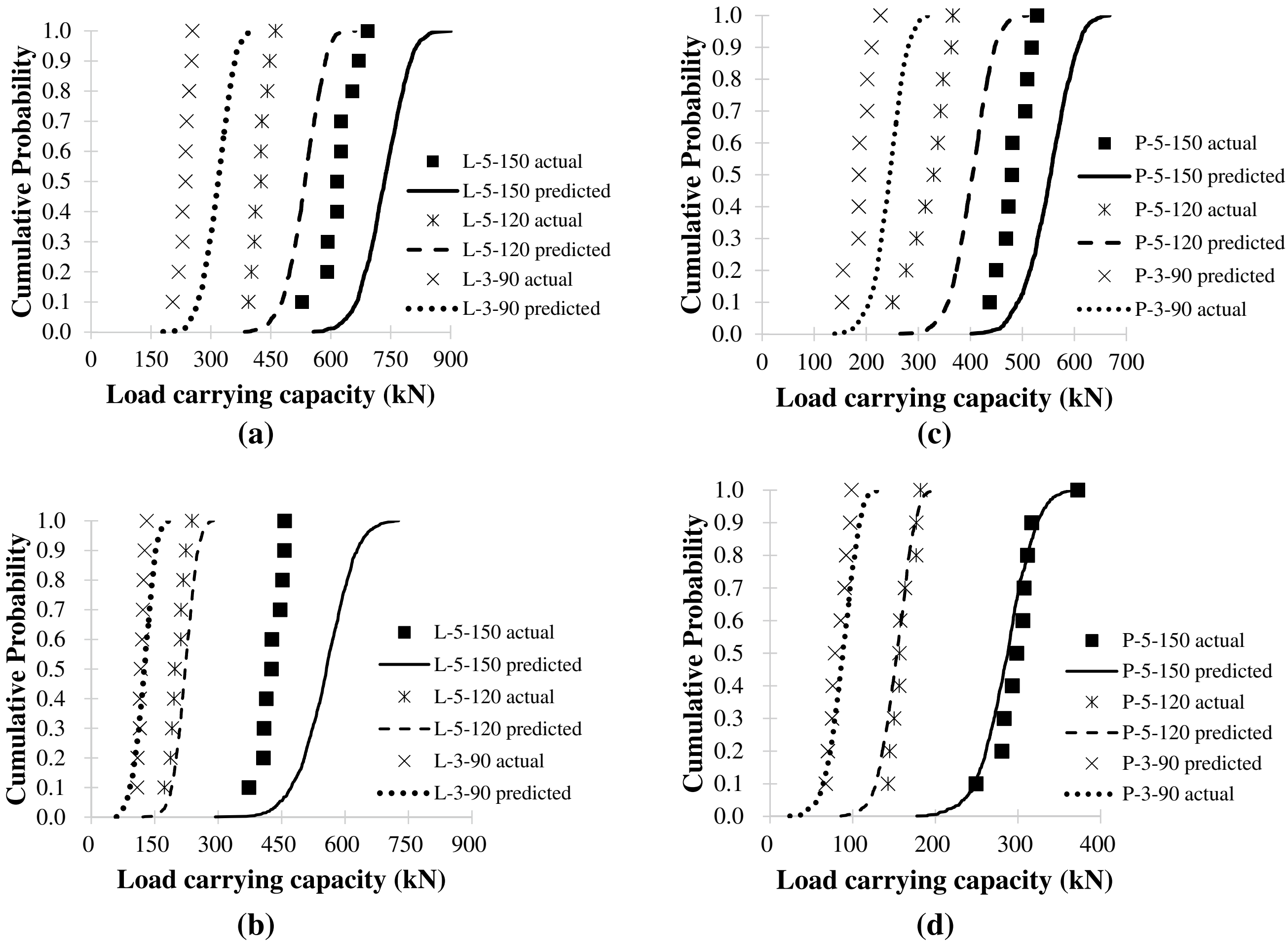

Fig. 8 Compressive resistance distributions of cross-laminated timber by Method 1

values and actual values were − 19.0–2.5%. The cumulative distributions clearly showed that the predicted distributions in the minor direction were closer to the measured values than those predictions in the major direction (Fig. 8). It would be caused by the lamina combination. In the major direction, two lamina grades were used for layers parallel to the loading direction. However, only one lamina grade was used for layers parallel to the loading direction in the minor direction. Thus, the prediction accuracy was better in the minor direction than in major direction. These results show that the Method 1 has a limitation to predict the CLT compressive resistance composed with different grades of lamina parallel to the loading direction.

In Method 2, the CLT compressive resistances were predicted by Eq. 7 and lamina compressive strengths. In the major direction, the predicted average resistances and 5% WPEs were 2.0–34.7% and 2.5–38.8% higher than the actually measured values, respectively. The differences between predicted values and actually measured values were slightly reduced comparing to Method 1. The cumulative distribution graphs by Method 2 (Fig. 9a, b) clearly showed that the predicted distributions became closer to the measured values rather than the graphs by Method 1 (Fig. 8a, c). The stiffness ratio of the two lamina grades used for layers parallel to the loading direction was reflected in Method 2, which led to these results. In the minor direction, the differences of average resistance and 5% WPE between the predicted values and actual values were same as Method 1, because only one lamina grade was used for layers parallel to the loading direction and in that case, the resulting stiffness ratio was equal to 1. Thus, the prediction accuracy was only improved in the major direction in this case.

In Method 3, the CLT compressive resistances were predicted by Eq. 13 using lamina compressive strengths of different grade laminas. In the major direction, the predicted average resistances and 5% WPEs were 0.1–24.5% and − 8.7–10.8%. The differences between predicted values and actually measured values were significantly reduced compared to Methods 1 and 2. The cumulative distribution graphs by Method 3 (Fig. 10) also showed

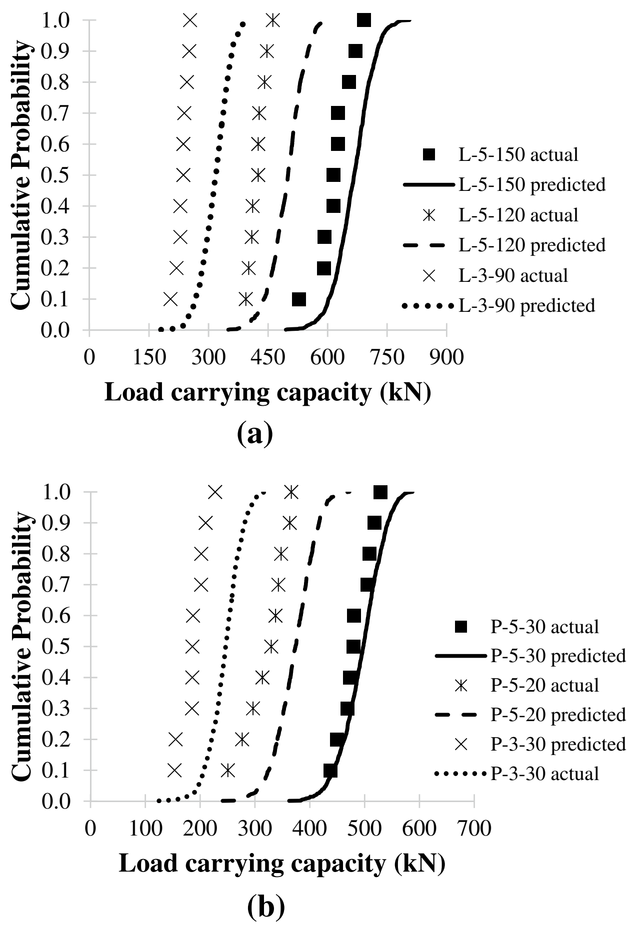

Fig. 9 Compressive resistance distributions of cross-laminated timber by Method 2

that the predicted distributions became closer to the measured values rather than the graphs by method 1 (Fig. 8) and Method 2 (Fig. 9). The small differences between the predicted values and the measured values were achieved by accounting for the load sharing effect and the weakest lamina effect in the prediction. The load sharing effect indicates that the higher load was applied to the higher grade lamina in the CLT. The weakest lamina effect indicates that the load-carrying capacity of the CLT decreased when the weakest lamina parallel to the loading direction failed. The Method 2 reflected the combination of the different lamina grades in the CLT by just changing the width of a specific layer based on the stiffness ratio [22, 23]. Therefore, in this case, the Method 2 could not reflect the load sharing effect.

Although only one lamina grade was used in the minor direction of different thickness of the CLT specimens, different compressive resistances were predicted by Method 3 due to the weakest lamina effect. The predicted average resistances and 5% WPEs by Method 3 were −14.1–4.2% and −24.5–7.7%. Especially, the predicted 5% WPEs for the compressive resistance of different thickness CLT became lower than the measured values, which meant that the CLT compressive resistance could be predicted more safely when Method 3 was employed.

Overall, when different grade laminas were used for the layers parallel to the loading direction, the CLT compressive resistance could be predicted more accurately using Method 3. For this reason, the load sharing and weakest lamina effect should be considered in the prediction of compressive load-carrying capacity of the CLT consist of different grade laminas.

Conclusion

In this study, a new approach (Method 3) for predicting the CLT compressive resistance was developed and compared with the existing two methods (Methods 1 and 2). Method 1 was useful when one lamina grade was used for all layers parallel to the loading direction, but the predicted 5% WPE result showed an overestimation noted up to 43.4% when two different grade laminas were used parallel to the loading direction.

In Method 2, compressive resistances of each lamina were predicted in the same way as Method 1, in addition to Method 1, a stiffness ratio between lamina grades was reflected. When two different grade laminas were used for layers parallel to the loading direction, the overestimated values by Method 1 became closer to being an accurate measurement, as compared to the measured values. However, the predicted 5% WPE values were still overestimated by 38.8%.

In the new approach (Method 3), a load shearing effect and weakest lamina effect were accounted for the prediction of compressive resistance of the CLT. As a result, when two different grade laminas were used for layers parallel to the loading direction, the differences between the predicted 5% WPE values and the measured values were reduced as −8.7–10.8%.

Overall, the Method 3 showed the best prediction accuracy for results in this experiment. Especially, when CLT was composed of different lamina grades parallel to the loading direction, the prediction accuracy of compressive resistance of the CLT in-plane could be improved by considering the load sharing and weakest lamina effect.

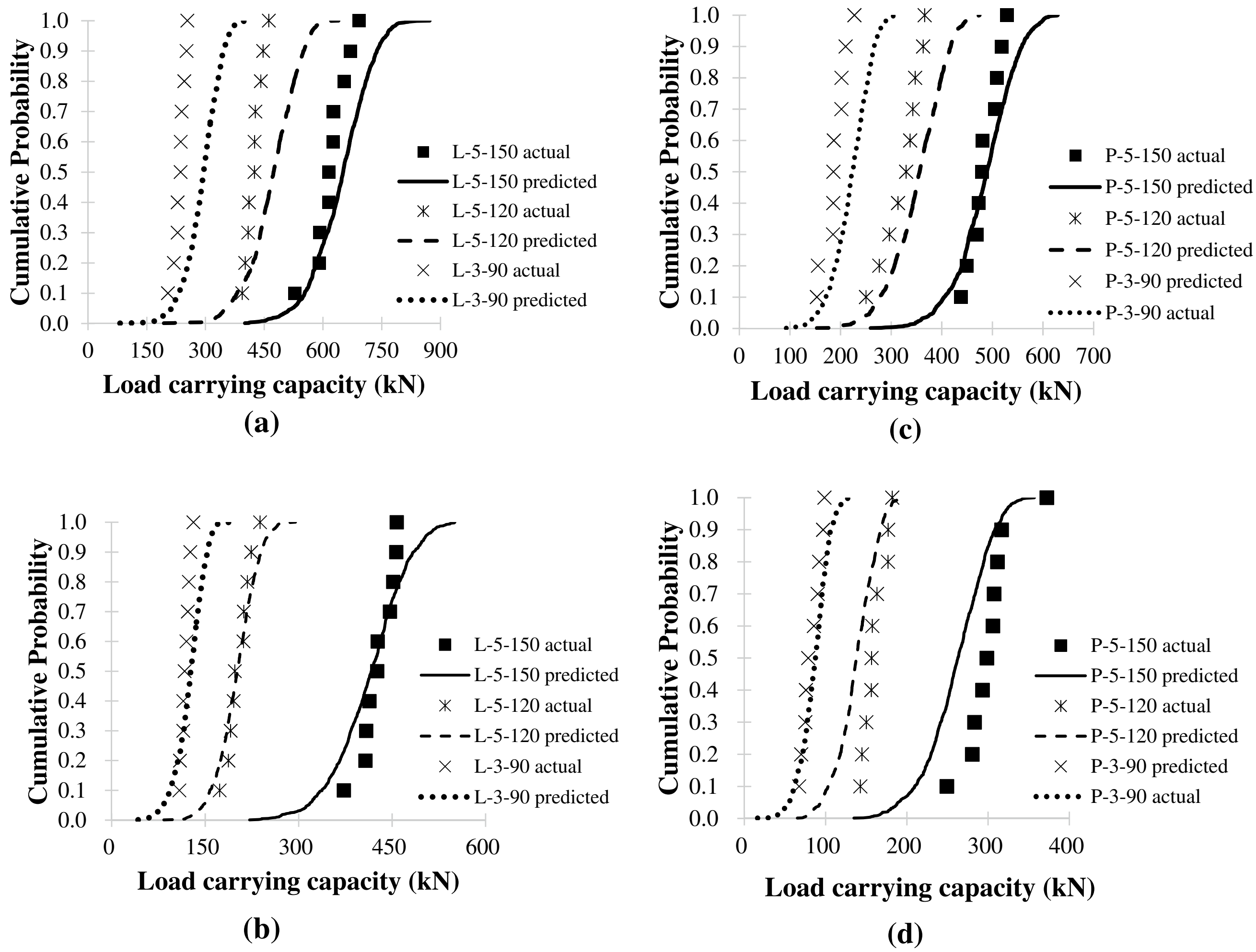

Fig. 10 Compressive resistance distributions of cross-laminated timber by Method 3

Acknowledgements This study was carried out with the support of 'Forest Science & Technology Projects (Project No. 2017051B101719BB02)' provided by Korea Forest Service.

References

1. CTBUH (2017) Tall buildings in numbers, tall timber: a global audit. Council on tall buildings and urban habitat. http://www.ctbuh.org. Accessed 29 Jan 2018
2. Brandner R, Flatscher G, Ringhofer A, Schickhofer G, Thiel A (2016) Cross laminated timber (CLT): overview and development. Eur J Wood Prod 74:331–351
3. Serrano E, Enquist B (2010) Compression strength perpendicular to grain in cross-laminated timber (CLT). In: 11th World Conference on Timber Engineering (WCTE 2010), Riva del Garda
4. Bogensperger T, Augustin M, Schickhofer G (2011) Properties of CLT-panels exposed to compression perpendicular to their plane. In: 44th CIB-W18 Meeting, Alghero
5. Brandner R, Schickhofer G (2014) Properties of cross laminated timber (CLT) in compression perpendicular to grain. In: 1st INTER-Meeting, Bath
6. Barrett JD, Lau W (1994) Canadian lumber properties. Canadian Wood Council, Ottawa
7. Karacabeyli E, Douglas B (2013) Chapter 3 structural. In: CLT handbook: cross-laminated timber US edition. FPInnovations, Pointe-Claire, p5
8. Oh JK, Lee JJ, Hong JP (2015) Prediction of compressive strength of cross-laminated timber panel. J Wood Sci 61:28–34
9. Wallner-Novak M, Koppelhuber J, Pock K (2014) Cross-laminated timber structural design—basic design and engineering principles according to Eurocode. proHolzAustria, Vienna
10. APA (2012) Standard for performance-rated cross-laminated timber. ANSI/APA PRG 320–2012. APA—The Engineered Wood Association. Tacoma, WA, USA
11. MAFF Notification No. 3079 of 20 December (2013) Japanese Agricultural Standard for cross laminated timber. Ministry of Agriculture, Forestry and Fisheries (MAFF), Tokyo
12. KS F 3021:2013 (2013) Structural glued laminated timber. Korean agency for technology and standards, Chungcheongbuk-do
13. ASTM D143-14 (2014) Standard test methods for small clear specimens of timber. American society for testing and materials, West Conshohocken

14. ASTM D198-14 (2014) Standard methods of static tests of lumber in structural sizes. American society for testing and materials, West Conshohocken
15. Lee JJ, Kim GC, Kim KM, Oh JK (2003) Distribution characteristics of bending properties for visual graded lumber of Japanese larch. J Korean Wood Sci Technol 31:72–79
16. Park CY, Pang SJ, Park JS, Kim KM, Park MJ, Lee JJ (2010) Study of the distribution properties and LRFD code conversion in Japanese larch. J Korean Wood Sci Technol 38:94–100
17. Pang SJ, Oh JK, Park CY, Park JS, Park MJ, Lee JJ (2011) Characteristics evaluation of bending strength distributions on revised Korean visual grading rule. J Korean Wood Sci Technol 39:1–6
18. Pang SJ, Park JS, Hwang KH, Jeong GY, Park MJ, Lee JJ (2011) Bending strength of Korean softwood species for 120 × 180 mm structural members. J Korean Wood Sci Technol 39:444–450
19. Pang SJ, Oh JK, Hong JP, Lee SJ, Lee JJ (2018) Stochastic model for predicting the bending strength of glued-laminated timber based on the knot area ratio and localized MOE in lamina. J Wood Sci 64:126–137
20. Cramer SM, Wolfe RW (1989) Load-distribution model for light-frame wood roof assemblies. J Struct Eng 115:2603–2616
21. Green DW, Kretschmann DE (2007) Lumber property relationships for engineering design standards. Wood Fiber Sci 23:436–456
22. Kassimali A, Craddock JN, Matinrad M (1986) Bending and transverse shear stresses in fiber-composite beams by the transformed-section method. Compos Struct 5:33–49
23. Kassimali A, Craddock JN, Wigell GA, Abbasnia R (1986) Transformed-section model for composite beams based on axial stiffness. J Struct Eng 112:2235–2350