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ORIGINAL ARTICLE

Prediction of compressive strength of cross-laminated timber panel

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Abstract Compressive strength of cross-laminated timber (CLT) is one of the important mechanical properties which should be considered especially in design of mid-rise CLT building because it works to resist a vertical bearing load from the upper storeys. The CLT panel can be manufactured in various combinations of the grade and dimension of lamina. This leads to the fact that an experimental approach to evaluate the strength of CLT would be expensive and time-demanding. In this paper, lamina property-based models for predicting the compressive strength of CLT panel was studied. A Monte Carlo simulation was applied for the model prediction. A set of experimental compression tests on CLT panel (short column) was conducted to validate the model and it shows good results. Using this model, the influence of the lamina's width on the CLT compressive strength was investigated. It reveals that the CLT compressive strength increases with the increase in the number of lamina. It was thought that repetitive member effect (or dispersion effect) is applicable for the CLT panel, which was explained by the decrease of the variation in strength. This dependency of the number of lamina needs further study in development of reference design values, CLT wall design and CLT manufacturing.

Keywords Cross-laminated timber · Lamina · Compressive strength · Monte Carlo simulation

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Introduction

Cross-laminated timber which is a European wood engineered product has a great lateral and vertical load resistance. As the interest of mid-rise wood frame buildings has increased, this product is recognized as a novel construction material which is appropriate for this tall building.

In low-rise wood frame building, the vertical load resistance of wall and column is not noticed as a critical performance in a structural design. However, in mid-rise buildings the walls and columns need to resist heavy vertical load of the upper storeys. Cross-laminated timber has shown a great possibility for the use in the mid-rise wood frame construction. The cross-laminated timber (CLT) walls in a mid-rise building need to resist much heavier vertical load than low-rise buildings.

The walls under vertical loads are designed based on the compressive strength and elasticity of CLT panel and slenderness ratio [1]. Out of the three factors governing the vertical resistance of wall, slenderness ratio and elasticity can be known without experimental tests up to failure. However, the compressive strength cannot be measured without failure test. Because CLT is being manufactured with various combinations of lamina in grade and dimension, the experimental tests for establishing the reference design value of CLT panel is quite demanding. Therefore, it is a common approach that the design of CLT panel is based on the performance of individual lamina grade as also true for designing glued-laminated timber. For such glued engineered wood products, many models have been developed to determine the reference design characteristics depending on the combinations. Foschi and Barrett [2] developed a model to predict bending strengths of glued-laminated timber. After that Bender et al. [3], Colling [4], Hernandez et al. [5], Renaudin [6], Serrano et al. [7] and

Lee et al. [8] studied flexural strength of glued-laminated beam with model verification. For compressive strength of glued-laminated timber, Frese et al. [9] predicted it by finite element analysis.

The CLT is made by gluing laminae crosswise; hence, the layers of CLT cross to a loading direction will be stressed in perpendicular to the grain direction under compression. The perpendicular to the grain compressive strength of wood is approximately 10 % of the parallel to grain compressive strength [10]. Therefore, the contribution of the cross layers in the global compressive strength of CLT panel is assumed to be null which makes a design conservative [1]. Glued-laminated products have a benefit of dispersion effect [11]. This effect works to make glued-laminated products more homogeneous material than solid wood by smearing out wood defects. Therefore, the variation of strength performance known from a single lamina grade could be averaged out within a final CLT panel.

The compressive resistance of CLT wall is calculated by multiplying cross-sectional areas of the involving parallel laminae by compressive strength based on 5th percentile strength of the lamina grade. However, the influence of homogenization on compressive strength was not considered. Therefore, in this study, based on the assumption of no contribution of cross layers to the global compressive strength of CLT panel, model predictions of the compressive strength of CLT panel were carried out. The prediction was verified by a set of experimental study. To recognize the influence of the homogenization on the strength statistically, a Monte Carlo simulation was used in the calculation of 5th percentile value.

Materials and methods

Experiments

Compressive strength of lamina

Korean Larch (*Larix kaempferi*) was used to produce 100 mm (width) × 30 mm (thickness) × 2400 mm (length) laminating stock which was graded according to Korean Standard F 3021-structural glued-laminated timber [12]. This standard dictates that, after being passed visual quality checking, laminae should be classified by modulus of elasticity (MOE) measured by an MOE-rating machine, then each lamina is given a grade which specifies a corresponding minimum MOE to satisfy. For example, Grade E11 of lamina should have the MOE of 11GPa or higher.

Thirty-nine pieces of Grade E11 laminae were prepared for evaluating the compressive strength of lamina. The length of laminae was 2600 mm with a cross section of 30 mm by 100 mm. Maximum strength reducing defect (MSRD) was identified for the full length. To prevent buckling during the compressive test, the lamina specimens were cut into 180 mm length (slenderness ratio, L/r, <17) (short column, ASTM D198 [13]) including an identified MSRD as Fig. 1 shows.

The 180 mm length specimens were tested by a universal testing machine in wood fiber direction. The maximum load was recorded and compressive strengths were calculated by dividing the maximum load by the cross-sectional area. The final dimension was 29.4 × 98.9 mm. From the compressive strength, 5th percentile strength was calculated by 2-parameter Weibull distribution (Eq. 1). The parameters of the best fit Weibull distribution was estimated by a program written in Matlab 2013a (MathWorks). From the best fit Weibull distribution, 5th percentile point estimate was calculated as 5th percentile compressive strength.

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (1)$$

where, $F(t)$ is Weibull cumulative density function. β and η are shape and scale parameters of Weibull distribution, respectively.

Compressive strength of CLT panel

To verify the prediction model of compressive strength for CLT panel, 34 pieces of CLT specimens were tested. E8 and E11 grade laminae of 30 mm by 100 mm by 2600 mm were prepared to make the CLT specimen. By assembling E8 grade laminae at inner cross layer and E11 grade laminae at outer layer, 34 pieces of 3-layer CLT panels were manufactured with one-component Poly Urethane adhesive (OTTO COLL P84, Hermann OTTO GmbH, Germany). The laminae were not glued edgewise. After curing, the panels were trimmed into 1200 mm (width) × 90 mm (thickness) × 2400 mm (length). The CLT panels were cut into four strip panel specimens [approximately 200 mm (width) × 90 mm (thickness) × 2400 mm (length)], then the 400 mm length test specimens were cut from the strip panel to prevent buckling at compression test (slenderness ratio, L/r, <17). Average final dimension was 197.7 mm (width) × 88.4 mm (thickness) × 400.5 mm (length).

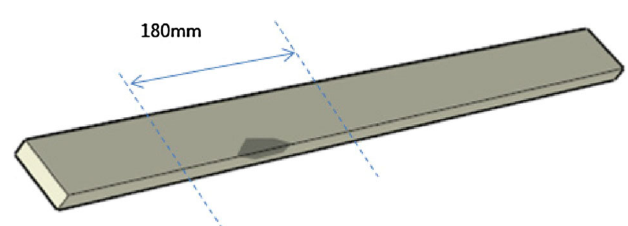

Fig. 1 Preparation of lamina test specimen containing MSRD (maximum strength reducing defect)

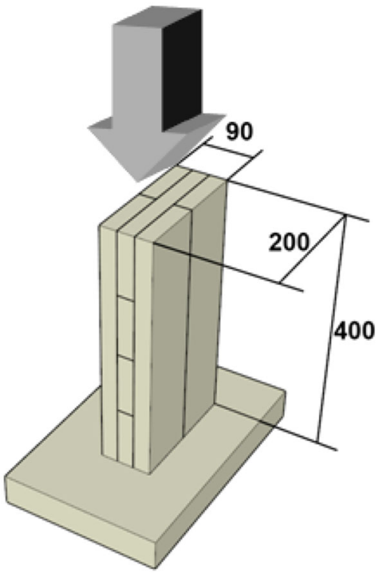

Fig. 2 Compression test specimen for CLT (cross-laminated timber) panel (unit: mm)

Unlike the lamina specimens containing MSRD, the location of MSRD in a CLT panel was not considered in preparing the specimens; hence, the CLT specimens were randomly cut along the length. Figure 2 shows a CLT specimen which has four E11 laminae parallel to the loading direction at the outer layers and, four or five E8 cross laminae in the middle layer. Average contact cross-sectional area for compression was 88.4 mm by 197.7 mm.

The specimens were loaded by a universal testing machine in the fiber direction of outer layer. The maximum load was recorded and the compressive strength was calculated by dividing by apparent area of cross section. Also 5 % point estimate was calculated as a 5th percentile strength by the same procedure as the lamina test.

Prediction of compressive strength for CLT panel

Under compressive loading, the cross layers of the CLT panel are loaded in perpendicular to the grain direction. Note that the resistance of compression in perpendicular to the grain direction is only 10 % of the parallel to the grain direction. The compressive resistance of CLT (F_{CLT} - $A_{apparent}$) was calculated by Eq. 2.

$$F_{CLT}A_{apparent} = \sum F_i A_i \quad (2)$$

where,
F_{CLT} is the compressive strength of CLT panel (MPa)
F_i is the compressive strength of ith lamina (MPa) ($F_i = 0$ if ith lamina is in a cross layer)
A_i is the cross-sectional area of ith lamina (mm^2)
$A_{apparent}$ is the cross-sectional area of CLT (mm^2)

Before comparing the prediction with the as-measured load resistance of CLT, an adjustment of size effect was made for the CLT. Since the cutting location of 180 mm-long lamina specimen was selected to contain MSRD of each laminae, the measured strength of lamina is the full-length property. However, the location of 400 mm-long CLT specimens was randomly cut out from 2600 mm full-length CLT. Therefore, the probability for this 400 mm-long short CLT specimen to contain MSRD would be lower than for the full-length CLT specimen. To adjust this disagreement, the compressive test results of the CLT specimens were modified by a size factor. The compressive load resistance of CLT was adjusted based on Weibull weakest link theory in which 0.1 was used as k factor in Eq. 3 [14].

$$\frac{\sigma_{adjusted}}{\sigma_{measured}} = \left(\frac{L_{measured}}{L_{adjusted}}\right)^k \quad (3)$$

where,
$\sigma_{measured}$ is the measured CLT compressive strength (MPa)
$\sigma_{adjusted}$ is the adjusted CLT compressive strength (MPa)
$L_{measured}$ is the length of specimen (400 mm) (mm)
$L_{adjusted}$ is the length of specimen to be adjusted into (2600 mm) (mm)
k is the length effect parameter (0.1)

For calculation of the 5th percentile strength of the CLT panel, two methods were used in this study: deterministic method (DM) and Monte Carlo simulation (MCS). When DM was used, the 5th percentile strength of the CLT panel was calculated with the 5th percentile value of the lamina used, and the average load resistance of the CLT panel can also be done by the corresponding value of the lamina. When MCS was used, the distribution of compressive strength for Grade E11 was input. The compressive strengths of four Grade E11 laminae were generated based on the best fit Weibull distribution. With the generated compressive strength, the compressive strength of CLT was calculated by Eq. 2. This procedure was repeated until 3000 CLT panel calculations. Out of 3000 compressive strength results, 5th percentile value was obtained by non-parametric approach.

Results and discussions

For the E11 lamina test, compressive strength was measured and 5th percentile strength was calculated by 2-parameter Weibull distribution analysis. The test results are shown in Fig. 3 and Table 1. Also, the compressive strength of the CLT specimens measured is shown in Fig. 4 and Table 2.

By the DM, the 5th percentile value and average compressive load resistance of CLT panel were predicted as

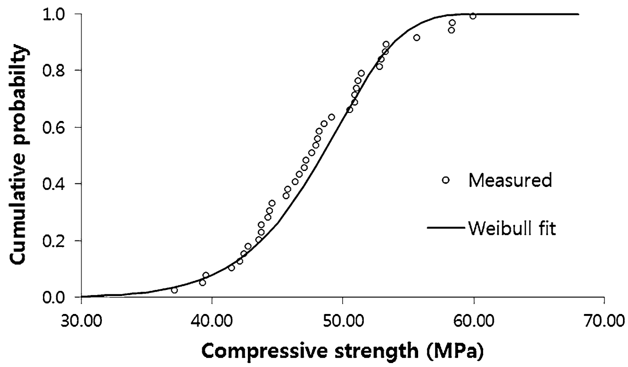

Fig. 3 Cumulative probability of compressive strength for Grade E11 laminae

Table 1 Statistics of compressive strength for grade E11 lamina

	Statistics
Repetition	39
Average compressive strength (MPa)	47.93
Standard deviation (MPa)	5.34
Coefficient of variation (%)	11.14
Minimum compressive strength (MPa)	37.19
Maximum compressive strength (MPa)	59.96
5th percentile strength (MPa)	38.36
Weibull distribution parameter	
Scale (η)	50.03
Shape (β)	11.18

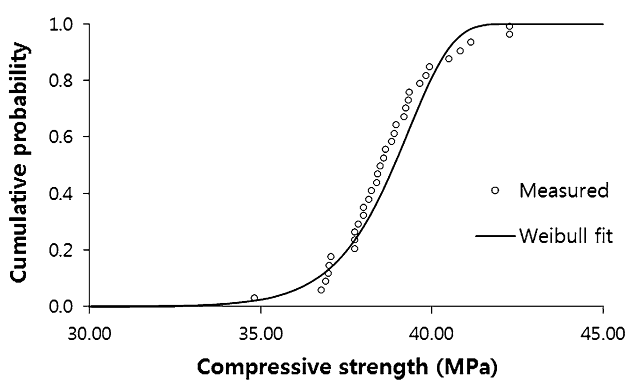

Fig. 4 Cumulative probability of compressive strength for CLT (cross-laminated timber) panel

shown in Table 3. Average compressive load resistance of CLT panel was 558.1 kN and 5th percentile value was 446.7 kN. In this case, the difference in the 5th percentile load resistance between the measured and predicted values (−17.36 %) was larger than in the average (−0.57 %).

In DM prediction, the 5th percentile value of the lamina specimen was used for the calculation of the 5th percentile compressive load resistance of CLT panel based on an assumption that all parallel laminae have the 5th percentile compressive strength (38.36 MPa) simultaneously in the CLT panel. However, the probability of being lower than the 5th percentile strength predicted by DM, in which all laminae have the 5th percentile strength, might not be 5 %. This difference between the 5th percentile strength to determine and predicted value by DM method may increase as the number of laminae increases. To determine more accurate 5th percentile value, a MCS was used. The MCS was expected to be more likely to reflect the real manufacturing situation in terms of probability calculation. The compressive strengths of all the parallel laminae were randomly generated based on the best fit distribution of Grade E11 lamina grade. All laminae are independently generated. With the generated compressive strengths, the compressive load resistance of CLT panel was predicted by Eq. 2. 5th percentile strength was calculated from the simulated results by the non-parametric approach. As shown in Table 3, the MCS provided a more accurate 5th percentile value than the DM. The simulated compressive load resistance fits well to the measured result (see Fig. 5). Based on this comparison between the MCS model and the measured result, it was concluded that the MCS models used in this study can predict 5th percentile compressive strength of CLT panel more successfully than the DM method. The two methods (MCS and DM) used the same prediction formula but a difference was found in the 5th percentile calculation because of MCS's better reflection of actual CLT panel assembly.

Table 2 Statistics of compressive strength for CLT panel

	Statistics
Repetition	34
Average compressive strength (MPa)	38.71
Standard deviation (MPa)	1.56
Coefficient of variation (%)	4.03
Minimum compressive strength (MPa)	34.83
Maximum compressive strength (MPa)	42.29
5th percentile strength (MPa)	35.82
Weibull distribution parameter	
Scale (η)	39.36
Shape (β)	31.48

However, MCS still underestimate the CLT compressive strength (−6.57 % in Table 3). It should be noted that the resistance of cross laminae was not considered at the prediction of compressive strength. Even if the cross laminae have relatively low properties in strength and Young's modulus, they appears to make a positive contribution to the compressive resistance of CLT panel to some extent.

Table 3 Results of compressive load resistance for CLT (cross-laminated timber) (kN)

	Measured		Predicted			
			DM		MCS	
	Value	Length adjusted	Value	Difference	Value	Difference
Average	676.8	561.3	558.1	−3.2 (−0.57 %)	557.3	−4.0 (−0.71 %)
5th percentile	653.8	542.2	446.7	−95.5 (−17.6 %)	506.5	−35.6 (−6.57 %)

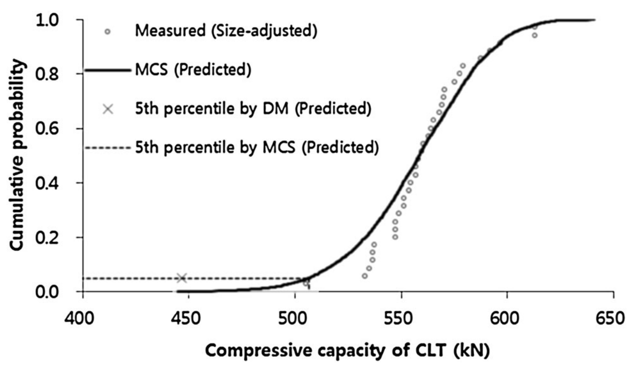

Fig. 5 Comparison of measured CLT (cross-laminated timber) compressive load resistance with the predicted values by DM (deterministic method) and MCS (Monte Carlo simulation)

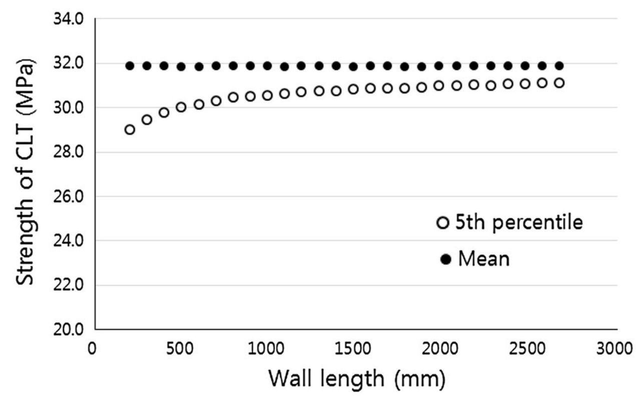

Fig. 6 Change of CLT (cross-laminated timber) compressive strength according to the width of parallel lamina used in a CLT, where CLT panels were made of 98.45 mm width lamina

Steiger et al. [15] reported that the homogeneity of CLT increases as the number of lamina increases. Therefore, the 5th percentile strength expected to be influenced by the number of laminae due to the homogenization. Using the MCS, the influence of the number of laminae in a CLT on the compressive strength of CLT wall was investigated. If the lamina width is consistent, the number of lamina would increase with the increase in the length of CLT wall. Figure 6 shows that the 5th percentile compressive strength of CLT panel has a tendency to increase as the number of laminae in CLT increases. When testing for establishment of the reference design strength, this dependency on the lamina's width needs to be considered. This implies that the strengths of CLT panel also might be able to be adjusted by a factor like the repetitive member effect of beam (or system effect), which explains that the load carrying capacity of individual member is increased by load sharing with adjacent members. It is thought that feasibility of this effect factor on CLT panel needs further study.

In manufacturing CLT, the lamina dimension needs to be decided in advance and it can make an effect on the performance of resulting CLT. Therefore, in this study, the influence of lamina width on CLT compressive strength was investigated by the MCS analysis as well. If the volume of CLT is consistent, the number of the parallel lamina will increase as the width of the lamina decreases. The decrease in the width of lamina would increase the compressive strength of the lamina, which is known as width effect (or size effect). Therefore, before predicting compressive strength of CLT, the compressive strength of lamina was adjusted by the weakest link theory (Eq. 4), in which as a k factor 0.11 was used (Barrett and Lau [10]).

$$\frac{\sigma_{\text{adjusted}}}{\sigma_{\text{measured}}} = \left(\frac{W_{\text{measured}}}{W_{\text{adjusted}}}\right)^{k} \quad (4)$$

where,

σ_{measured} is the measured CLT compressive strength (MPa)
σ_{adjusted} is the adjusted CLT compressive strength (MPa)
W_{measured} is the width of specimen (98.45 mm) (mm)
W_{adjusted} is the width of specimen to be adjusted (mm)
k is the width effect parameter (0.11)

For analysis on influence of lamina width on CLT performance, the dimension of CLT wall was assumed to be 1200 mm (wall length) by 2600 (height) by 88.4 mm (thickness). The width of lamina was determined by the number of parallel laminae. The compressive strength of CLT was predicted by the MCS analysis with change in the number and size of parallel laminae. The Fig. 7a shows the compressive strength of CLT according to the lamina width. As it shows, with the decrease of lamina width, the compressive strength of CLT increased. Especially, the variation in strength decreased as the width of lamina decreases (Fig. 7b). Steiger et al. [15] described that the homogeneity of CLT increases as the number of lamina

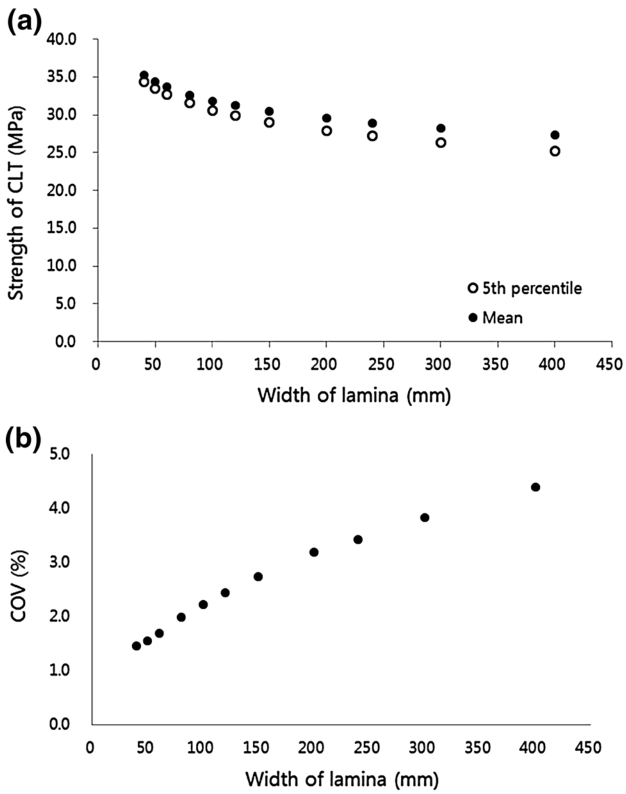

Fig. 7 Change of CLT (cross-laminated timber) compressive strength according to the width of lamina used in CLT manufacturing, where the CLT panel length was consistent (1200 mm). **a** Compressive strength, **b** covariance of compressive strength

increases and as a result, the bending stiffness was affected by the width of lamina. In compressive strength, the same tendency was found as bending stiffness. As well as decrease in variation, Fig. 7a also shows the increase of mean compressive strength, which was caused by width effect. When the width of lamina decreases in a given volume, the width effect and the increased homogeneity lead to the increase in the 5th percentile compressive strength. As an example, the CLT made of 40 mm width lamina showed 15.0 % higher compressive strength than 120 mm width lamina.

In CLT manufacturing, the dimension of lamina needs to be determined to maximize the efficiency. For the structural material, the strength is a key property to increase in terms of efficiency. The result of this study indicates that the increase of compressive strength of CLT wall element can be achieved by just reducing the width of lamina. This finding can provide a good chance to increase the efficiency in manufacturing structural CLT walls. But much care is necessary to reduce the width of lamina because making narrower laminae can also increase the cost as it requires more processing.

Conclusions

The compressive strength of CLT panel was predicted by the corresponding lamina property. In 5th percentile strength calculation, the DM method has a tendency to underestimate the 5th percentile strength. For more accurate calculation, a Monte Carlo simulation was applied in this study. A set of experimental study on CLT panel (short column) indicated that the MCS method showed better fit to the experimental result than DM method.

Using this model, the influence of wall length and lamina's width on the compressive strength of CLT panel was investigated. Then it showed that the compressive strength increases with the increase in the wall length (the number of parallel lamina used in a CLT panel). Also the compressive strength increased as width of the lamina decreases. This dependency needs to be considered in test for determination of allowable strength and CLT wall design and in CLT manufacturing.

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