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Out-of-plane shear strength of cross-laminated timber made of Japanese Larch (*Larix kaempferi*) with various layups and spans

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Abstract

Cross-laminated timber (CLT) is a promising construction material. When CLT is used for horizontal applications, shear stress occurs in the out-of-plane direction and can fracture the transverse layers owing to the rolling shear. The out-of-plane shear strength of the CLT can be evaluated by an out-of-plane loading test and is affected by the CLT layups and/or span conditions. In this study, we conducted out-of-plane loading tests on 3-layer 4-ply, 5-layer 7-ply, 7-layer 7-ply, and 9-layer 9-ply CLT made of Japanese larch (*Larix kaempferi*) under various spans and investigated the effect of layups and spans on the out-of-shear strength. The fracture modes of the specimens were classified into three types: shear fracture, shear fracture accompanied by bending fracture, and bending fracture. The out-of-plane shear strength of the specimens except for the 9-layer 9-ply ones decreased as the span increased, and then converged to a constant value (1.0–1.5 kN/mm^2). In addition, the shear strength decreased exponentially as the number of laminae in the transverse layers increased and then converged to a constant value (1.0–1.5 kN/mm^2). The out-of-plane shear strength of the 9-layer 9-ply specimens decreased as the shear span increased; however, the converged value with a longer span could not be calculated because the tests were conducted under only three-span conditions. The shear strength of 3-layer 4-ply specimens was lower than that of the other layups. The results of the Monte Carlo simulation of the shear strength of the laminae in the transverse layers showed that a model, which assumed that the minimum shear strength of the laminae in the transverse layers determined the shear strength of a specimen, tended to correspond with the decreasing tendency of shear strength with longer spans. The results showed that the weakest link model for the out-of-plane shear fracture of the CLT would relate to a specimen with long span.

Keywords Transverse layer, Rolling shear, Number of laminae, Monte Carlo simulation

Introduction

Cross-laminated timber (CLT) is an engineered wood product developed in Europe during 1970–1980. After 10 years of research, standardization, and the expansion of production facilities from 2000 to 2009, CLT has become a structural material that has attracted attention not only in Europe but also globally. Recently, CLT has been used as a structural material in small and large buildings worldwide, opening new possibilities for the entire construction industry. CLT will continue to play an important role as an alternative to

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structural materials such as reinforced concrete and steel [1].

Japanese larch (*Larix kaempferi*) is a major softwood species planted in Japan. As it has high stiffness and strength when used as a CLT, it is expected to be applied to structural materials. When used for horizontal applications, such as a floors or roofs, CLT is subjected to out-of-plane loads, and rolling shear stress occurs in the transverse layers. As CLT has transverse layers with low shear strength in the rolling shear direction, it is important to confirm the out-of-plane shear strength of CLT using a structural material. The out-of-plane shear strength can be evaluated by an out-of-plane loading test; the center-point loading test for evaluating the out-of-plane shear strength is specified in the Japanese Agricultural Standards (JAS) for CLT [2], with a support span of five times the specimen thickness. However, CLT often exhibits bending fracture, which is a tensile failure of the bottom layer, in shear tests [3, 4]. In contrast, CLT can occasionally show shear fracture in a bending test, even though the support span is 18 times or more the specimen thickness [5, 6].

The out-of-plane shear strength on 5-layer 5-ply CLT made of Japanese larch or Sakhalin fir (*Abies sachalinensis*) decreases as the span increases, and the strength convergence values approach the rolling shear strength of the lamina [7]. In addition, the out-of-plane shear strength of the CLT decreases with an increase in lamination when the span-to-thickness ratio is the same [4, 8]. In a previous study [9], out-of-plane shear tests in 3-layer 3-ply CLT made of Japanese larch were conducted in which the support spans were 5.5–6.0 times the specimen thickness. In addition, the shear strength of each transverse layer lamina was generated using a Monte Carlo simulation based on the results of the rolling shear strength of the lamina. The simulation results were verified using the experimental values of the out-of-plane shear tests on the CLT specimens. The highest shear strength of the lamina generated by the simulation for each specimen tended to correspond to the experimental values. However, this result has limitations in terms of the layups and spans of the specimens. In this study, we conducted out-of-plane shear tests on 3-layer 4-ply, 5-layer 7-ply, 7-layer 7-ply, and 9-layer 9-ply CLT made of Japanese larch under center-point loading with various support spans. Based on the results, the effects of the layups and spans on the out-of-plane shear strength were evaluated. In addition, the out-of-plane shear strength of the CLT was simulated by Monte Carlo simulation and compared with the experimental values.

Monte Carlo simulation

In this study, the out-of-plane shear strength of CLT with various numbers of laminae in the transverse layers was simulated using a Monte Carlo simulation, according to a previous study [9]. The simulation procedure is as follows:

First, the shear strength of the transverse layer of laminae was assumed to have a normal distribution. As the rolling shear strength varied according to the cross-sectional dimensions of the laminae, the mean value of shear strength was derived from the regression line, which represented the rolling shear strength (f_R) of Japanese larch laminae, where the explanatory variable was the ratio of width to thickness [10] as follows:

$$f_R = 0.370\frac{w}{t} + 0.544, \tag{1}$$

where f_R is the rolling shear strength (N/mm^2); w is the lamina width (mm); t is the lamina thickness (mm).

In this study, the laminae were 125 mm wide and 30 mm thick, and the mean value of the shear strength was calculated as 2.08 N/mm^2 using Eq. (1). The standard deviation of the shear strength was determined as 0.42 N/mm^2, which was calculated using the mean value of 2.08 N/mm^2 described above and coefficient of variation of the rolling shear strength of Japanese larch laminae that were 120 mm wide and 30 mm thick (20.4%) [10]. The number of laminae generated in the simulation ranged from 3 to 100. The actual number of laminae in the transverse layers of the specimens in this study was multiples of two, three, and four. Then, the generated number was limited to those values. Finally, the two models that determine the out-of-plane shear strength of a specimen were assumed as follows:

In the first model, the fracture of the specimen occurred when a lamina with minimum shear strength in the transverse layers broke. In the other model, the fracture of the specimen occurred when all the laminae in the transverse layers broke. In other words, the minimum and maximum values of the generated shear strength determined the out-of-plane shear strength. The results based on these models were verified by comparing them with experimental values. The number of simulation cycles was 1000 for each number of generated laminae.

Materials and methods

Specimens

The test specimens were cut from CLT panels composed of 125-mm-wide and 30-mm-thick Japanese larch laminae that were adhered using a phenol–resorcinol–formaldehyde resin. Edge gluing was not performed between laminae. The stress grade of the CLT

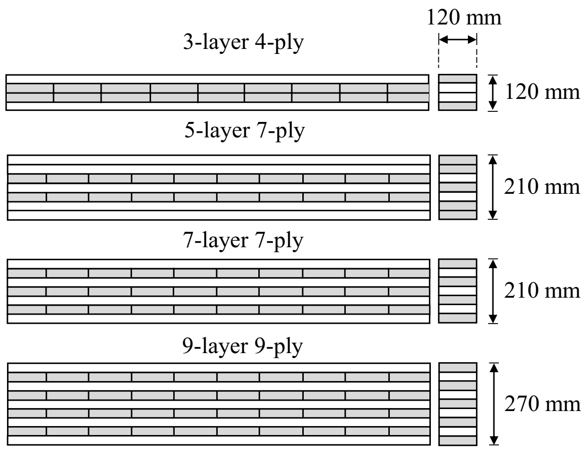

Fig. 1 Layups of specimens

panels was Mx120 as specified in JAS [2]. The layups of the specimens were 3-layer 4-ply, 5-layer 7-ply, 7-layer 7-ply, and 9-layer 9-ply as shown in Fig. 1. The width of each specimen was 120 mm. The grain direction of the outermost layers was parallel to the length of the specimens.

Out-of-plane shear tests

The out-of-plane shear test was conducted by the center-point loading test with a testing machine (TOKYO KOKI TESTING MACHINE Co. LTD; maximum bending load capacity of 200 kN), as shown in Fig. 2. The support spans were in the range of 5–16 times the specimen thickness, as listed in Table 1. When the support span was less than 2100 mm, the tests were conducted by reversing the loading and support points because of the restriction of the minimum support span. A constant monotonic loading speed of 3–6 mm/min was applied to equalize the test duration from the start to the maximum load for each specimen, and the test was terminated at 80% of the maximum load. The tests were conducted in an unconditioned environment. Displacement was measured at the bottom surface of the specimen at the loading points in the specimens with support spans of less than 2100 mm using displacement transducers, and the mean value of both values was recorded as the displacement of the specimen. In the specimens with support spans greater than 2100 mm, the displacement was measured at the bottom surface at the span center. The lengths of the plates of the loading and support points were 120 mm for 3-layer 4-ply specimens and 200 mm for the other specimens. The moisture content of the specimens was measured after the tests using the oven-dried weights of the specimen pieces.

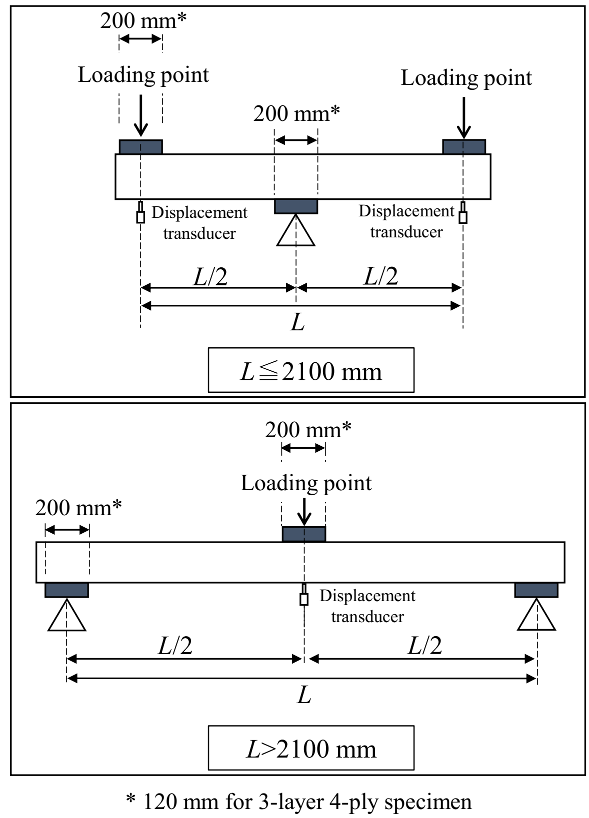

Fig. 2 Diagram of the shear test. *L* is the support span length

Calculation of the out-of-plane shear strength

The shear stress was calculated considering its internal distribution. The shear strength was calculated as follows [7]:

$$\tau_{\max} = \beta \times \frac{P_{\max}}{2bh}, \tag{2}$$

where $\tau_{\max}$ is the out-of-plane shear strength (N/mm2); β is the shear stress distribution coefficient; $P_{\max}$ is the maximum load (N); b is the specimen width (mm); and h is the specimen thickness (mm).

The stress distribution coefficient β was calculated as follows (Fig. 3):

$$\beta = \frac{bh\{E_i\left(x_{\mathrm{i}}^2 - x^2\right) + \sum_{j=i+1}^{m} E_{\mathrm{j}}(x_{\mathrm{i}}^2 - x_{\mathrm{i}-1}^2)\}}{2EI}, \tag{3}$$

where x is the distance in which shear stress is calculated from the neutral axis (mm); i is the lamina order where x is counted from the neutral axis; x_{i} is the distance in the outer surface of the i-th lamina to the neutral axis (mm); E_{i} is the Young's modulus of the i-th lamina (kN/mm^2); m is the order of the outermost lamina counted from the neutral axis in the x located direction; E is the apparent

Table 1 Results of the shear tests

Specimens	Support span [mm]	Span-to-thickness ratio	*n*	Out-of-plane shear strength [N/mm²]			CV [%]	Number of laminae in transverse layers	Failure type		
				Min	Mean	Max			S	SB	B
3-layer 4-ply (MC: 10.8%) (Density: 512 kg/m³)	600	5	4	2.37	2.66	2.98	10.5	10	4	0	0
	720	6	4	2.06	2.22	2.32	5.5	12	4	0	0
	960	8	4	1.64	1.66	1.67	0.9	16	3	1	0
	1200	10	4	1.33	1.38	1.45	3.6	20	4	0	0
	1440	12	4	1.20	1.27	1.33	4.6	24	4	0	0
	1680	14	4	1.03	1.07	1.12	3.4	28	3	0	1
	1920	16	4	0.81	1.04	1.24	17.7	32	2	0	2
5-layer 7-ply (MC: 11.2%) (Density: 523 kg/m³)	1050	5	4	2.56	2.77	2.94	6.4	18	3	1	0
	1260	6	6	1.92	2.11	2.33	6.9	22	3	3	0
	1680	8	4	1.57	1.63	1.72	4.1	28	3	1	0
	2100	10	4	1.72	1.76	1.79	1.6	34	4	0	0
	2520	12	4	1.21	1.44	1.58	11.2	42	3	0	1
	2940	14	4	0.76	1.27	1.59	29.9	48	1	1	2
7-layer 7-ply (MC: 11.2%) (Density: 514 kg/m³)	1050	5	4	2.15	2.21	2.29	2.9	27	4	0	0
	1260	6	4	1.49	1.78	1.91	11.0	33	2	1	1
	1680	8	4	1.28	1.47	1.55	9.0	42	4	0	0
	2100	10	4	1.38	1.60	1.73	9.3	51	1	1	2
	2520	12	4	1.17	1.31	1.58	14.7	63	1	0	3
	2940	14	4	1.01	1.18	1.45	16.0	72	2	0	2
	3360	16	4	0.63	0.79	0.88	14.6	81	0	0	4
9-layer 9-ply (MC: 11.6%) (Density: 501 kg/m³)	1260	6	4	1.67	1.74	1.77	2.8	52	3	0	1
	2160	8	4	1.46	1.56	1.64	4.8	72	3	0	1
	2700	10	4	1.20	1.34	1.50	9.3	88	3	0	1

n is the number of specimens, CV is coefficient of variation, MC is moisture content, S is the number of specimens showing shear fracture, SB is the number of specimens showing shear fracture accompanied by bending fracture, and B is the number of specimens showing bending fracture. MC and density are mean values

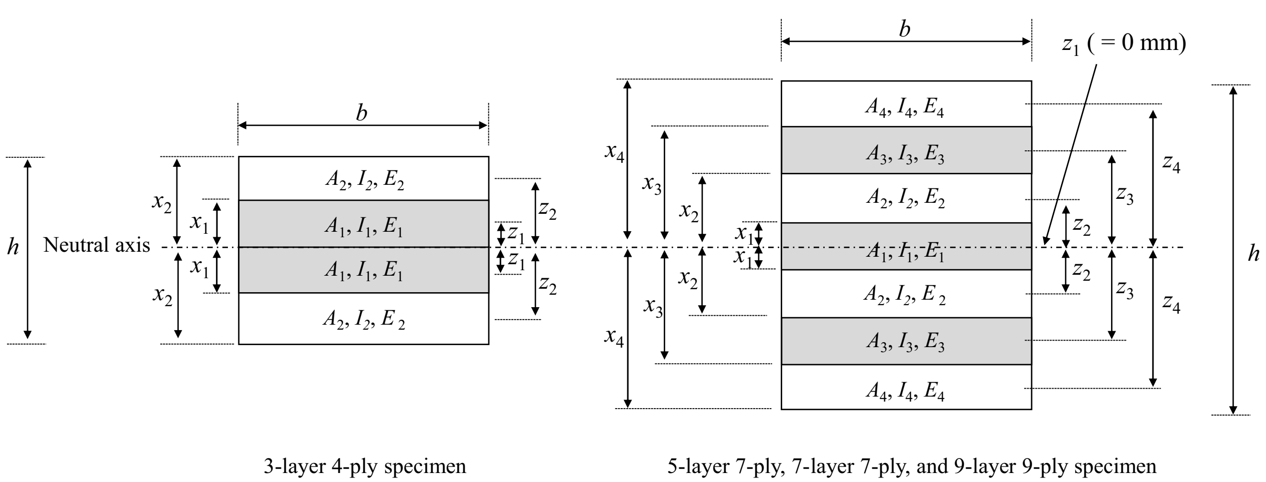

Fig. 3 Definition of lamina configuration. b is the specimen width, h is the specimen thickness, i is the i-th layer, x_i is the distance from the top outer surface of the i-th lamina to the neutral axis, A_i is the cross-sectional area of the i-th lamina, I_i is the moment of inertia of the area of the i-th lamina, E_i is the Young's modulus of the i-th lamina, and z_i is the distance in the center of the i-th lamina from neutral axis (mm)

Young's modulus of the specimen (kN/mm^2); and I is the moment of inertia of the area of the specimen (mm^4).

E and I were calculated as follows:

$$E = \frac{\Sigma_{\text{all laminae}}\left(E_i I_i + E_i A_i z_i^2\right)}{I}, \tag{4}$$

$$I = \frac{bh^3}{12}, \tag{5}$$

where I_i is the moment of inertia of the area of the i-th lamina (mm^4); A_i is the cross-sectional area of the i-th lamina (mm^2); and z_i is the distance in the center of the i-th lamina from the neutral axis (mm).

The Young's modulus of the parallel layer laminae was assumed to be 12.0 kN/mm^2 and 6.0 kN/mm^2 for outer and inner laminae, respectively. The Young's modulus of the transverse layer laminae was assumed to be 0 kN/mm^2 according to previous studies [7, 11]. Consequently, β in the neutral axis was 1.286 for 3-layer 4-ply, 1.344 for 5-layer 7-ply, 1.273 for 7-layer 7-ply, and 1.255 for 9-layer 9-ply specimens. β in a transverse layer can be used when the shear strength is calculated because the out-of-plane shear strength of the CLT is usually determined by a fracture in the transverse layers [7]. However, the neutral axis of 5-layer 7-ply and 9-layer 9-ply specimens lies in the parallel layer. β in the transverse layer nearest to the neutral axis was calculated as 1.327 and 1.240 for 5-layer 7-ply and 9-layer 9-ply specimens, respectively (Fig. 4). The difference between these values and β on the neutral axis was 1.2%, which can be considered adequately small. Therefore, the shear strength was calculated using β in the neutral axis in this study. In addition, the values calculated using Eq. (2) were regarded as the out-of-plane shear strength, even though the specimen showed a bending fracture.

Results and discussion

Out-of-plane shear behavior obtained from experiments

Table 1 lists the results of the out-of-plane shear test, and Fig. 5 shows the typical fracture modes. Three types of fractures were observed in the specimens: shear fracture of the transverse layer laminae due to rolling shear (*S*), shear fracture of the transverse laminae accompanied by bending fracture of the tensile parallel layer (SB), and bending fracture of the tensile parallel layer (B). Specimens with shorter spans tended to show shear fractures (S). The 3-layer 4-ply, 5-layer 7-ply, 7-layer 7-ply, and 9-layer 9-ply specimens with spans less than 1440 mm (12 h), 2520 mm (12 h), 1680 mm (8 h), and 2700 mm (10 h), respectively, often showed shear fracture (S). In contrast, bending fracture (B) often occurred when the span was long. The 5-layer 7-ply specimens with 2940 mm (14 h) span and 7-layer 7-ply specimens with a span greater than 2100 mm (10 h) often showed bending fracture (B).

The shear stress–strain curves of all the specimens are shown in Fig. 6. The shear stress was calculated using Eq. (2), where P_{max} is replaced by each load. The shear strain was calculated as follows:

$$\gamma = \frac{2\delta}{L}, \tag{5}$$

where γ is the shear strain (rad);δ is the displacement (mm); and L is the support span length (mm).

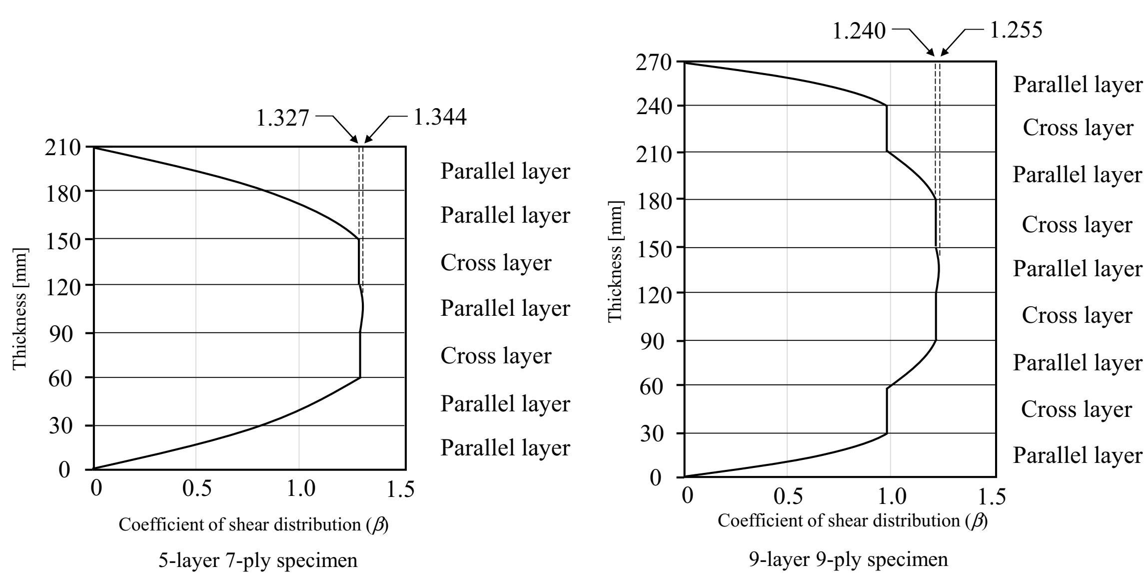

Fig. 4 Coefficient of shear stress distribution in 5-layer 7-ply and 9-layer 9-ply cross sections

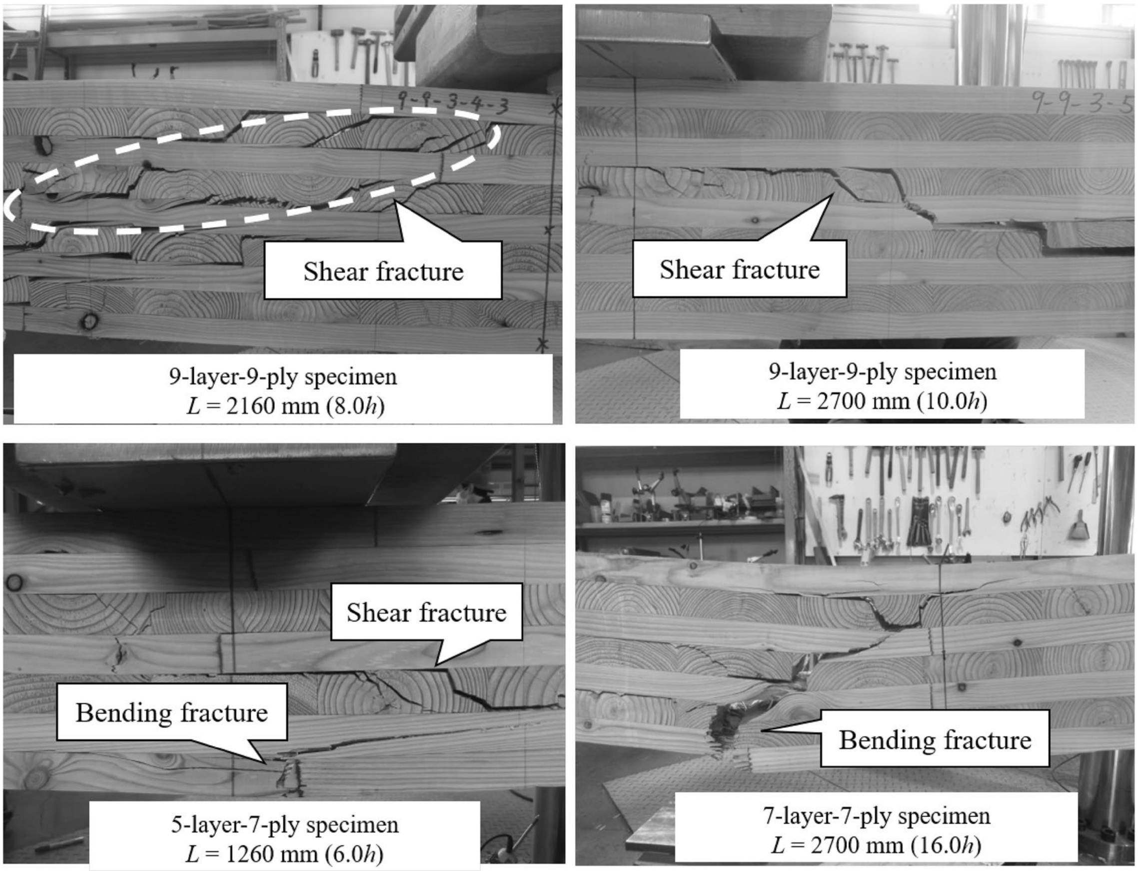

Fig. 5 Typical examples of fracture modes. *L* is the support span length

The appearance of the shear stress–strain curves of the specimens with shear fracture accompanied by bending fracture (SB) was similar to that of the specimens with shear fracture (S). Specimens with shorter spans exhibited a temporary decrease in shear stress. The load reached its maximum value after its behavior was repeated. Specimens with longer spans showed a monotonic shear stress increase and did not exhibit a temporary decrease in shear stress until reaching the maximum stress, even though they showed shear fracture (S). The appearance of the shear stress–strain curves of these specimens was similar to that of the specimens that showed a bending fracture.

Figure 7 shows the relationship between the shear span ($L/2$), in which a constant shear force occurs, and the out-of-plane shear strength. The strength of the specimens that showed shear fracture accompanied by bending fracture (SB) was nearly equal to that of the specimens that showed only shear fracture (S) except for one 5-layer 7-ply specimen. Therefore, in this study, the following discussion on the out-of-plane shear strength refers to that of the specimens that showed shear fracture and shear fracture accompanied by bending fracture. The experimental formulas in Fig. 7 of 3-layer 4-ply, 5-layer 7-ply, and 7-layer 7-ply specimens were calculated using the results of specimens that showed shear fracture or shear fracture accompanied by bending fracture by the non-linear least squares method using the statistical analysis software R version 4.2.3 [12]. These models assume that the out-of-plane shear strength follows a power law and converges to a constant value. The converged values for the longer span ranged from 1.0 N/mm^2 to 1.5 N/mm^2. This model fitted the experimental values relatively well, in agreement with a previous study [7]. In addition, the out-of-plane shear strength of the specimens that exhibited bending fracture tended to be lower than that of the specimens that exhibited shear fracture or shear fracture accompanied by bending fracture. The 9-layer 9-ply specimens also showed a decreasing tendency as the shear span increased; however, the converged value with a longer span could not be calculated because only three-span conditions were considered.

The relationship between the number of laminae in the transverse layers in the shear section and the out-of-plane

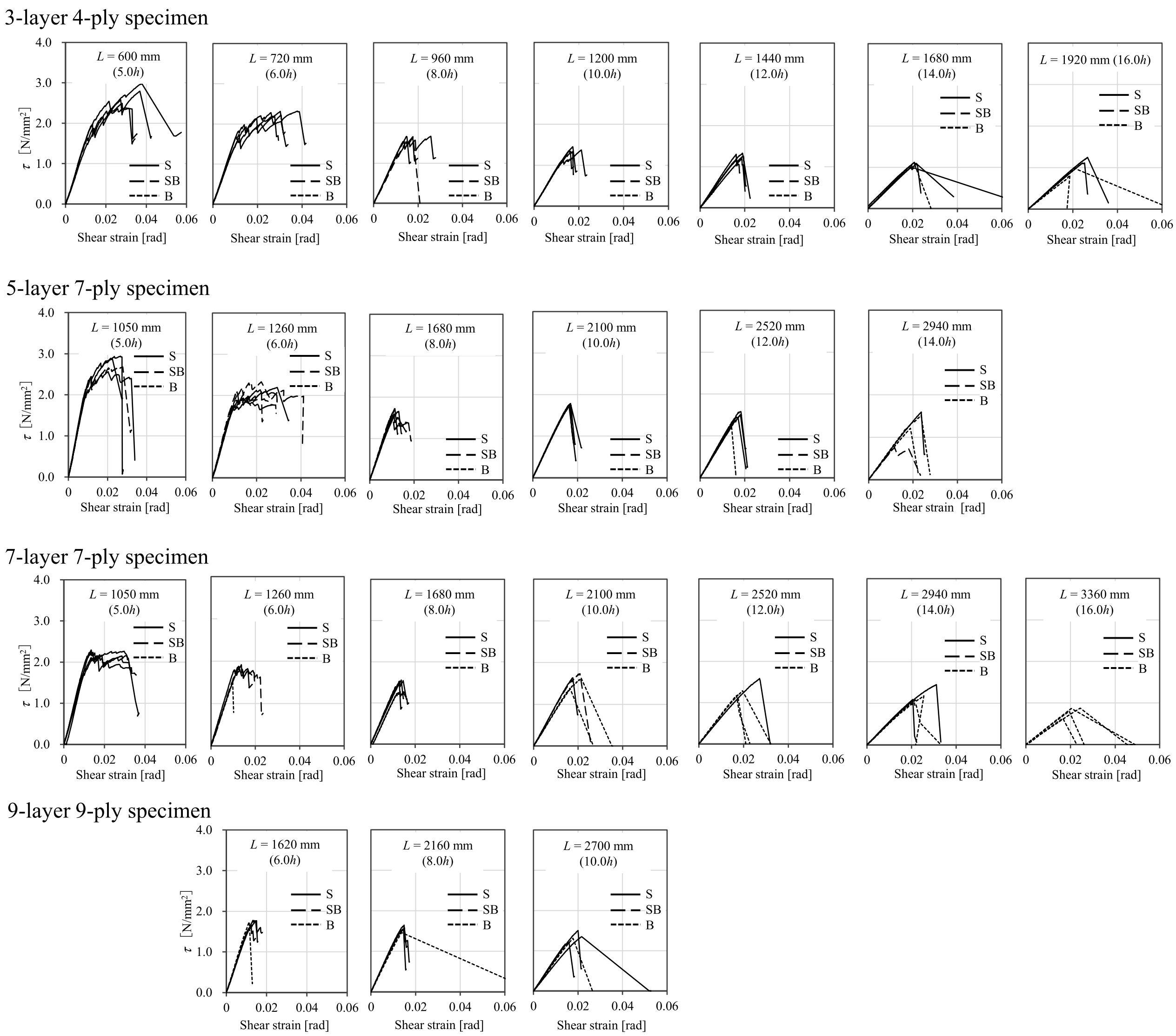

Fig. 6 Shear stress–strain curves. τ is the shear stress, L is the support span length, h is the specimen thickness, S is the specimen showing a shear fracture, SB is the specimen showing a shear fracture accompanied by a bending fracture, and B is the specimen showing a bending fracture

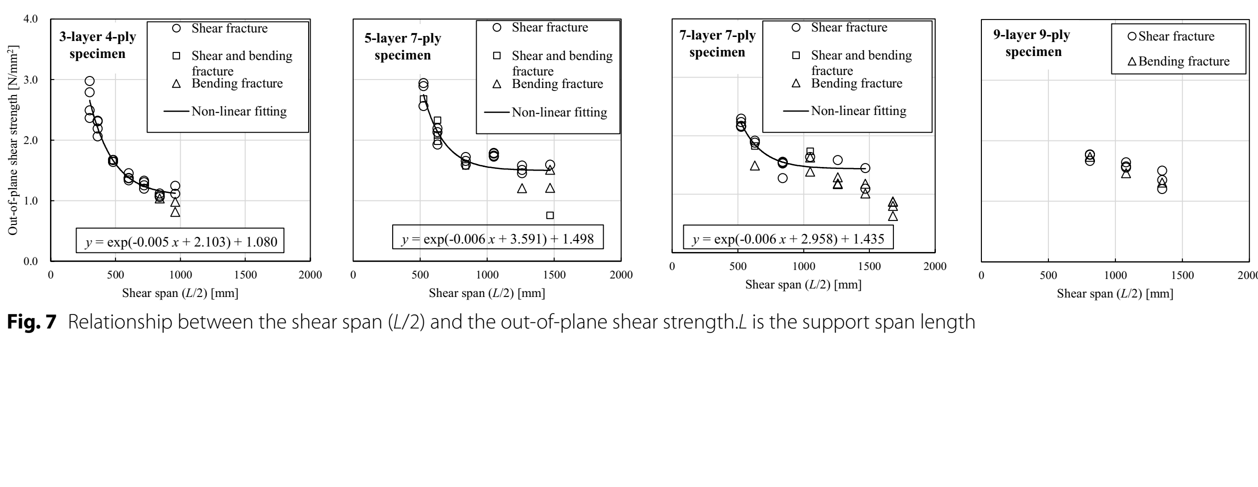

Fig. 7 Relationship between the shear span (L/2) and the out-of-plane shear strength.L is the support span length

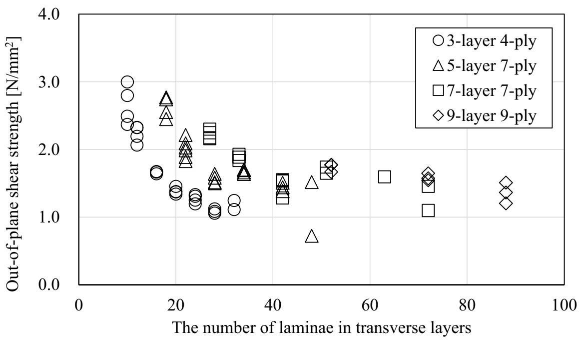

Fig. 8 Relationship between the number of laminae in transverse layers and the out-of-plane shear strength. Plots represent the experimental values of specimens that exhibited shear fracture or shear fracture accompanied by bending fracture

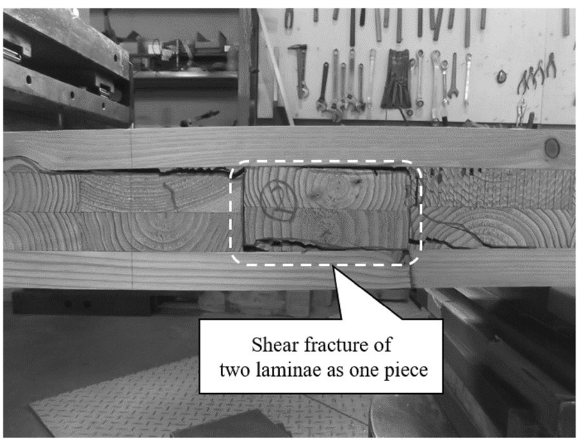

Fig. 9 The fracture of transverse layer laminae of a 3-layer 4-ply specimen

shear strength of the specimens that exhibited shear fracture or shear fracture accompanied by a bending fracture is shown in Fig. 8. Hayashi et al. [13] reported that the number of laminae in the transverse layers of the shear section can affect the out-of-plane shear strength. In this study, the out-of-plane shear strength decreased exponentially as the number of laminae in the transverse layers increased, and then converged to a constant value (1.0–1.5 kN/mm^2), as well as the results of non-linear fitting (Fig. 7). The out-of-plane shear strength of 3-layer 4-ply specimens was lower than that of the other layups with the same number of laminae in the transverse layers. The shear fracture of 3-layer 4-ply specimens appeared to be fracture in the unified neighboring transverse layer laminae, as shown in Fig. 9. In previous studies [3, 8, 14–17], the rolling shear strength of a lamina and the out-of-plane shear strength of a CLT were affected by the cross-sectional dimensions of the transverse lamina, which decreased as the width of the laminae decreased or their thickness increased. The adjacent transverse layers of 3-layer 4-ply specimens in this study probably behaved like unified 60-mm-thick laminae and affected the out-of-plane shear strength.

Estimation of the out-of-plane shear strength using Monte Carlo simulation

The results obtained from the simulation are shown in Fig. 10, where the experimental values of the specimens indicated shear fracture or shear fracture accompanied by bending fracture. The experimental values of 3-layer 4-ply are not shown in this figure because the cross-sectional dimensions of the transverse lamina differ from those of the other layups (Fig. 9). Expected values in Fig. 10 are calculated using empirical distribution functions of the simulation results. The maximum model assumed that specimen fracture occurred when all laminae in the transverse layers broke. This means that the shear fracture of the transverse layer laminae occurred in order from the lowest to the highest shear strength until the ultimate fracture of a specimen. In the maximum model (parallel model), the expected value of the failure load was generally predicted to increase with an increase in the number of elements, and this trend was also confirmed by the simulation results (Fig. 10, right). However, the shear test results did not exhibit this trend. This model was fitted to the results of a previous study in which six laminae were used [9]. This behavior can be explained by the shear stress–strain curves obtained from the shear tests (Fig. 6). A temporary decrease in the shear stress was observed in the specimens with shorter spans. This suggests that the shear fracture in a transverse layer lamina with minimum strength did not determine the specimen fracture when the span was short. Fracture in a transverse layer lamina with maximum strength may determine specimen fracture only when the number of laminae in the transverse layers in the shear section is extremely low (18 or less in this study).

The minimum model assumes that specimen fracture occurs when a lamina with minimum shear strength in the transverse layers breaks. Expectation values of the failure load predicted by this model decreased as the number of laminae increased. The shear test results exhibited this trend (Fig. 10, left), and the shear stress–strain curves represented this tendency (Fig. 6). The frequency of the temporary decrease in the shear stress decreased, and some specimens did not show this until the specimen fractured as the span increased. When the span exceeded a certain value (5-layer 7-ply with a 2100 mm span, 7-layer 7-ply with a 2100 mm span, and 9-layer 9-ply with a 2160 mm span), no temporary decrease in shear stress was observed. Fracture in these specimens was determined by the lamina with the

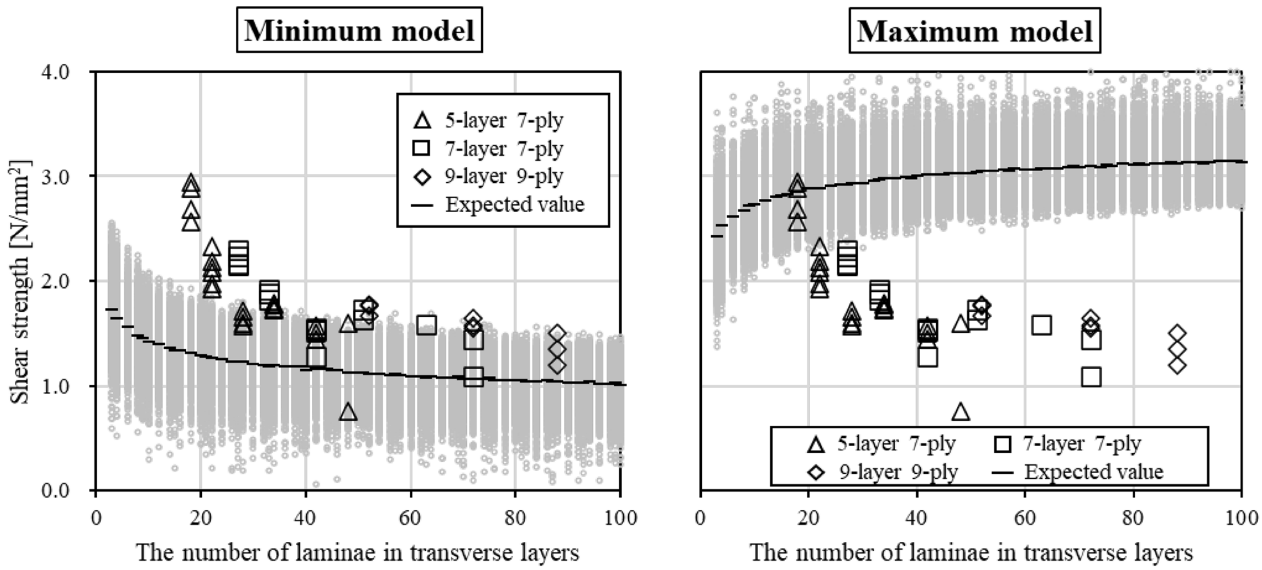

Fig. 10 Results of the Monte Carlo simulation for the out-of-plane shear strength. Plots represent experimental values of specimens showing shear fracture or shear fracture accompanied by bending fracture

minimum strength. Therefore, an out-of-plane shear fracture under a long-span condition, in which the first decrease in shear stress determines the specimen fracture, is related to the weakest link model.

This study has some limitations. The fracture models suggested in this study assumed that all laminae in the transverse layers in the shear section had an equal probability of fracture, even though the shear fracture tended to concentrate in the transverse layer laminae on the diagonal line connecting the loading and supporting plates in the shear tests (Fig. 5). Although the rolling shear strength of multiple adjacent laminae tends to be greater than that of a single lamina [10], the simulation was conducted based on the rolling shear strength of a single lamina. This is one of the reasons why the simulated value is lower than the experimental value (Fig. 10, left). Furthermore, these discussions are based on the results of what is assumed to be composite beam theory which neglects any shear deformation. Detailed analyses, such as those incorporating the effects of shear deformation and stress concentration by compressive strain at the loading and/or supporting points, may improve the comparison of different layup specimens and simulation accuracy in future studies.

Conclusions

Out-of-plane shear tests were carried out for the 3-layer 4-ply, 5-layer 7-ply, 7-layer 7-ply, and 9-layer 9-ply CLT made of Japanese larch to evaluate the effects of layups and spans on the out-of-plane shear strength. The fracture modes of the specimens were classified into three types: shear fracture, shear fracture accompanied by bending fracture, and bending fracture. The strength of 3-layer 4-ply, 5-layer 7-ply, and 7-layer 7-ply CLT decreased exponentially and then converged to a constant value (1.0–1.5 kN/mm^2) as the shear span increased. The 9-layer 9-ply CLT showed a decreasing tendency as the shear span increased; however, the converged value with a longer span could not be calculated because only three-span conditions were considered. The strength of 3-layer 4-ply CLT was lower than that of the other layups. In addition, the strength decreased exponentially as the number of laminae in the transverse layers increased and then converged to a constant value. This tendency was represented by the results obtained from Monte Carlo simulations. The minimum model, which assumed that the minimum shear strength of the laminae in the transverse layers determined the shear strength of a specimen, tended to correspond with the decreasing tendency of shear strength with longer spans. Therefore, out-of-plane shear fracture of a specimen with long span would relate to the weakest link model.

Abbreviations

CLT	Cross-laminated timber
JAS	Japanese Agricultural Standards
f_R	Rolling shear strength
w	Lamina width
t	Lamina thickness
τ_{max}	Out-of-plane shear strength
β	The shear stress distribution coefficient
P_{max}	Maximum load
b	Specimen width
h	Specimen thickness

x Distance in which shear stress is calculated from the neutral axis (mm)
i The lamina order where x is counted from the neutral axis
x_i Distance in the outer surface of the i-th lamina to the neutral axis
E_i The Young's modulus of the i-th lamina
m The order of the outermost lamina counted from the neutral axis
E The apparent Young's modulus of the specimen
I The moment of inertia of the area of the specimen
I_i The moment of inertia of the area of the i-th lamina
A_i The cross-sectional area of the i-th lamina
z_i Distance in the center of the i-th lamina from the neutral axis
γ Shear strain
δ Displacement
L Support span length

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Author contributions
YK was responsible for data collection and wrote the manuscript. WI and RT helped collect the samples and data. YK and RT analyzed the data. YO, Sawa, and TS contributed to improving this manuscript. All the authors have read and approved the final manuscript.

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Availability of data and materials
The samples, test methods, and data are described in this manuscript. A detailed explanation of the test methods and data is available from the corresponding author upon request.

Declarations

Competing interests
The authors declare that they have no competing interests regarding the publication of this manuscript.

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