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Strength properties of glued laminated timber made from edge-glued laminae II: bending, tensile, and compressive strength of glued laminated timber

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Abstract The purpose of this study was to investigate the strength properties of glued laminated timber composed of edge-glued laminae and to investigate the influence of edge gluing on the strength properties. Glued laminated timber composed of multiple-grade laminae (symmetrical composition, strength grade E95-F270, 10 laminations) was produced from karamatsu (*Larix kaempferi*) edge-glued laminae according to the Japanese Agricultural Standard. The bending, tensile, and compressive strengths of the glued laminated timber were measured. The average bending, tensile, and compressive strengths were 33.4, 24.5, and 35.9 MPa, respectively, and these values are almost equal to those of glued laminated timber composed of karamatsu single-piece laminae. It was determined that finger-joints and knots in the edge-glued laminae played a significant role in the failure of specimens. However, the use of glued edge-joints did not appear to affect the failure of specimens.

Key words Edge-gluing · Lamina · Glued laminated timber · Strength property · Modulus of elasticity

Introduction

Edge-gluing is a valid processing method for making effective use of small logs such as those produced from thinning operations. By using edge-glued laminae for structural glued laminated timber, a higher yield can be produced. However, few articles have been published on the strength of structural glued laminated timber composed of edge-glued laminae. Shibata et al.[1] made glued laminated timber composed of karamatsu (*Larix kaempferi*) finger-jointed single-grade laminae that had seven laminations. They sawed the glued laminated timber to the same thickness perpendicular to the lamination surface to produce laminae with six adhesive layers in the width direction and nonoverlapping finger-joints (FJs) in the lengthwise direction. They produced glued laminated timber composed of multiple-grade laminae with 13 laminations using those particular laminae for the outer layers, and conducted bending tests. They reported that nonoverlapping FJs in the lamina on the tension side of the glued laminated timber contributed to improved bending strength. Janowiak et al.[2] produced a wide glued laminated timber combination with laminations made from nominal 2 × 4- and 2 × 6-inch red maple (*Acer rubrum*) lumber placed edge-to-edge without edge-gluing (2 × 4/2 × 6 glulam beams). They showed that the modulus of elasticity (MOE) of the 2 × 4/2 × 6 glulam beams was almost the same regardless of the loading direction, parallel or perpendicular to the wide face of the laminations. In the bending test with loads applied parallel to the wide face of the laminations, the majority of failures involved a strength-reducing characteristic such as knots, slope of grain, or grain deviation. The use of the edge-to-edge laminations did not appear to affect the bending strength results.

Fujimoto et al.[3] produced two kinds of edge-glued laminae using karamatsu sawn lumber with various widths. One was produced by gluing lumber with similar MOE at the edge (uniform lamina) and the other was produced by gluing lumber regardless of the MOE at the edge (random lamina). They examined the strength properties and grading method of the edge-glued laminae, and showed that the average values of bending, tensile, and compressive strength parallel to the grain of the uniform laminae were equal to those of the random lamina, and that the strength properties of edge-glued laminae could be rated using one of the methods for rating a single-piece lamina, such as the longitudinal vibration technique, the dead weight method, or machine stress rating.

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To produce uniform laminae, the MOE of various-width sawn lumber must be measured before the edge-gluing process. On the other hand, for random laminae, the MOE is measured only after edge-gluing. Thus, it is easier and more practical to produce random laminae rather than uniform laminae. In this study, glued laminated timber was produced from random laminae and the strength properties were measured to investigate the influence of glued edge-joints.

Experimental

Production of edge-glued lumber

Edge-glued laminae were made from sawn lumber of karamatsu (*Larix kaempferi*) from Nagano Prefecture, Japan, that was 34 mm thick, 4000 mm long, and of various widths. First, the size, density, and the dynamic MOE (E_{fr}) determined by the longitudinal vibration technique, were measured for a total of 355 pieces of sawn lumber. The moisture content (MC) of the sawn lumber was also measured by using a dielectric-constant moisture meter HM-520 (Kett Electric Laboratory). For 62 of the 355 sawn lumber pieces, the static MOE (E_{dw}) was determined by the dead weight method.

Second, various-widths sawn lumber were glued at the edges irrespective of the MOE, and 329 edge-glued laminae were produced using the process described in Fujimoto et al.[3] Each edge-glued lamina was 125 mm wide, 32 mm thick, and 4000 mm long. A melamine resin-type adhesive (Oshika MG-100) was used for edge-gluing. Since various-width sawn lumber was edge-glued, the positions of the glued edge-joints in edge-glued laminae were different. Knots in the sawn lumber were not removed and the slope of the grain was not noted.

The MOE of all edge-glued laminae was measured using a grading machine (Iida Kogyo MGFE-251) capable of determining MOE during continuous feeding of lamina in the lengthwise direction (E_{gm}). Additionally, 60 of the 329 edge-glued laminae were randomly selected for measurement of E_{fr} and E_{dw}.

Production of glued laminated timber test specimens

Each specimen of edge-glued laminae was rated according to the grades provided by the Japanese Agricultural Standard (JAS) for glued laminated timber[4] using the minimum value of E_{gm} (E_{gm}-min). Based on the grading results, glued laminated timber composed of multiple-grade laminae (symmetrical composition, 10 laminations and strength grade of E95-F270) (Fig. 1) was produced according to JAS[4] from 250 of the 329 edge-glued laminae planed to a thickness of 30 mm. A resorcinol–phenol resin adhesive was used for finger-jointing (Oshika DF-2000) and laminating (Oshika D-90). The finger-joint (FJ) profile had a length of 20 mm, a pitch of 6.0 mm, a width of 1.0 mm at the tip, a width of 0.50 mm at the base, and a slope of 1/8.9.

Grade of lamina	MOE measured by grading machine (GPa)
L200	20.0
L180	18.0
L160	16.0
L140	14.0
L125	12.5
L110	11.0
L100	10.0
L90	9.0
L80	8.0
L70	7.0
L60	6.0
L50	5.0
L40	4.0
L30	3.0

L110
L100
L90
L70
L70
L70
L70
L90
L100
L110

Fig. 1. Relation between lamina grade and modulus of elasticity (*MOE*) in bending measured by grading machine according to Japanese Agricultural Standard (JAS) for glued laminated timber. The *right part* shows the grade composition of laminae of glued laminated timber E95-F270 (symmetrical composition, 10 laminations) composed of multiple-grade laminae according to JAS

Six specimens of glued laminated timber were provided for bending, tensile, and compressive strength tests. Specimens for bending tests were 120 × 300 mm in cross section and 6000 mm in length, for tension parallel to the grain they were 105 × 300 mm in cross section and 4000 mm in length, and for compression parallel to the grain they were 120 × 300 mm in cross section and 720 mm in length. The MOE of each grade of edge-glued lamina used for producing the glued laminated timber was similar among all specimens; in other words, all specimens were produced having a similar distribution of MOE of laminae. Since the positions of glued edge-joints in edge-glued laminae were different, the positions of glued edge-joints in the glued laminated timber were also different.

Each edge-glued lamina in the specimens was vertically finger-jointed at one place in the longitudinal direction. FJs were arranged at least 150 mm away from FJs in adjacent layers of a specimen. In the specimens for the bending test, all FJs were arranged between the loading points in the following test method. In specimens used for the tensile tests, all FJs were centered at intervals of 1000 mm in the direction of the specimen length. In specimens for the compressive tests, all FJs were centered at intervals of 480 mm in the direction of the specimen length.

Bending, tensile, and compressive test method

The density and E_{fr} of specimens were measured before conducting the tests. After the tests, samples for measuring MC were cut from the specimens near the failure position, and MC was measured by the oven-dry method.

Four-point bending tests were conducted using a universal testing machine (Tokyo Koki Seizosho) according to

JAS.[4] The span was 5400 mm and the distance between the loading point and support was 2100 mm. Loading perpendicular to the adhesion layer was continued until final failure of the specimen. Deflection of the midspan was measured using two displacement transducers over a distance of 100 mm (Tokyo Sokki Kenkyujo CDP-100).

Tests to determine the tension parallel to the grain were conducted using a tensile testing machine (Maekawa Testing Machine Mfg. A, No. 100/100 RCT) according to BS EN 408.[5] The specimens were set between 500-mm-long grips so that FJs were at the midspan position of the 3000-mm free span. Loading was continued until final failure of the specimen. Displacement was measured over a distance of 1000 mm using two laser displacement sensors (Keyence LC-2320) at the center of the specimen.

Tests to determine the compression parallel to the grain were conducted using a compression testing machine (Maekawa Testing Machine Mfg. A-300-B4) according to BS EN 408.[5] Loading was continued until final failure of the specimen. Strain was measured using ten strain gauges placed on both sides (five on each) of the specimen at the center. The length of the strain gauges was 120 mm (Tokyo Sokki Kenkyujo PL-120).

Results and discussion

MOE of edge-glued laminae

The average values and coefficients of variation of width, density, E_{fr}, and E_{dw} of various-width sawn lumber was 120 mm and 23.3%, 527 kg/m^3 and 9.32%, 11.7 GPa and 16.9%, and 10.6 GPa and 14.8%, respectively. These values are similar to the values measured by Fujimoto et al.[3] The average value and coefficient of variation of MC was 12.2% and 24.8%, respectively.

The distribution of E_{fr}, E_{dw}, the average value of E_{gm} (E_{gm}-avg), and E_{gm}-min of the edge-glued laminae are shown in Fig. 2. The average value of E_{gm}-min was about 1 GPa lower than that of the others. The averages and coefficients of variation of E_{fr}, E_{dw}, and E_{gm}-avg were similar to the values measured by Fujmoto et al.[3] In addition, Hashizume et al.[6] showed that the average value and coefficient of variation of E_{dw} (n = 1642) and E_{gm}-avg (n = 65653) of karamatsu single-piece laminae was 10.9 GPa and 18.0% and 10.6 GPa and 21.5%, respectively. E_{fr}, E_{dw}, and E_{gm}-avg of edge-glued laminae were distributed mainly in the range 10–13 GPa (80% of the samples). E_{gm}-min of edge-glued laminae were distributed mainly in the range 9–12 GPa (70% of the samples). These results indicated that there were a lot of edge-glued laminae that could be used for the outer layers of glued laminated timber E95-F270.

The relationship between the MOE values of the 60 specimens of edge-glued laminae obtained by each method is shown in Fig. 3. There was a strong correlation between MOE values obtained by different methods, and these results are similar to the results of Fujimoto et al.[3] For measuring the MOE and rating the edge-glued laminae, the longitudinal vibration technique, the dead weight method, and grading machines can all be applied. In this study, the edge-glued lamina was rated using E_{gm}-min because the knot diameter ratio of the edge-glued laminae according to JAS[4] was not measured. The average E_{gm}-min values of the edge-glued laminae making up the test specimens are shown

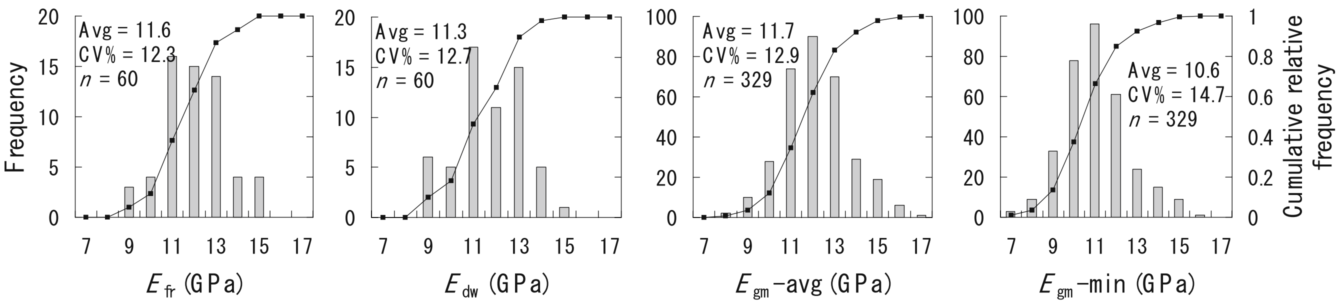

Fig. 2. Distribution of modulus of elasticity of edge-glued laminae. *Avg*, average; *CV%*, coefficient of variation (%); *n*, number of specimens; E_{fr}, modulus of elasticity measured by longitudinal vibration method; E_{dw}, modulus of elasticity measured by dead weight method; E_{gm}-*avg*, the average value of modulus of elasticity measured using a grading machine; E_{gm}-*min*, the minimum value of modulus of elasticity measured using a grading machine

Fig. 3. Relationships between modulus of elasticity values of edge-glued laminae measured by the dead weight method and by other methods

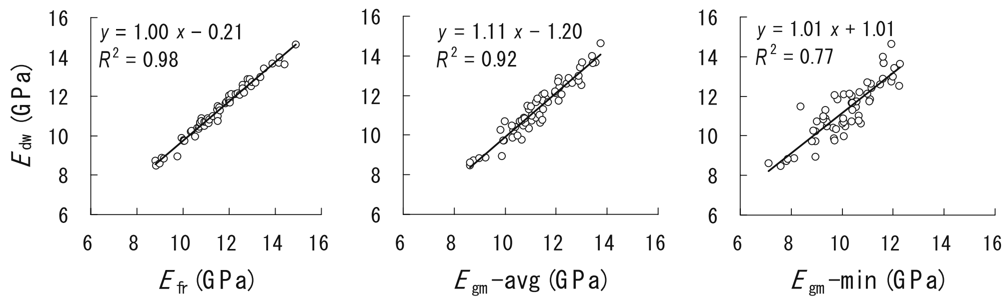

Fig. 4. Average minimum modulus of elasticity values (Gpa) [as measured using a grading machine] of edge-glued laminae used to produce the glued laminated timber specimens (n = 6)

Lamination	Avg	CV%	Avg	CV%	Avg	CV%
1	12.3	(2.39)	12.3	(3.25)	12.3	(2.96)
2	10.8	(1.35)	10.6	(1.33)	10.6	(1.29)
3	10.4	(0.767)	10.3	(0.688)	10.3	(0.590)
4	9.43	(1.30)	9.39	(1.19)	9.41	(1.29)
5	9.01	(1.16)	8.97	(1.92)	9.00	(1.90)
6	8.17	(5.98)	8.25	(4.34)	8.26	(4.74)
7	9.80	(1.04)	9.77	(1.13)	9.79	(1.00)
8	10.1	(0.760)	10.1	(0.860)	10.1	(1.00)
9	11.2	(1.62)	11.1	(1.72)	11.1	(1.54)
10	11.7	(0.972)	11.6	(1.23)	11.7	(1.38)
	Specimen for bending test		Specimen for tensile test		Specimen for compressive test	

Table 1. Results of bending tests on glued laminated timber

	MC (%)	Density (kg/m^3)	E_{fr} (GPa)	MOE (GPa)	MOR (MPa)
n	6	6	6	6	6
Avg	12.0	529	11.5	10.9	33.4
Max	12.1	542	11.8	11.2	36.4
Min	11.8	508	11.2	10.7	29.0
CV%	1.05	1.96	2.13	1.97	7.73

CV%, coefficient of variation; MC, moisture content; E_{fr}, modulus of elasticity by longitudinal vibration method; MOE, modulus of elasticity in bending; MOR, bending strength

Table 2. Results of tests on tension parallel to the grain in glued laminated timber

	MC (%)	Density (kg/m^3)	E_{fr} (GPa)	$E_{t,0}$ (GPa)	$f_{t,0}$ (MPa)
n	6	6	6	6	6
Avg	12.6	530	11.9	11.5	24.5
Max	12.9	535	12.2	12.2	27.4
Min	12.4	527	11.6	10.9	20.1
CV%	1.26	0.641	2.00	3.89	11.2

$E_{t,0}$, modulus of elasticity in tension parallel to the grain; $f_{t,0}$, tensile strength parallel to the grain

Table 3. Results of tests on compression parallel to the grain in glued laminated timber

	MC (%)	Density (kg/m^3)	E_{fr} (GPa)	$E_{c,0}$ (GPa)	$f_{c,0}$ (MPa)
n	6	6	–	6	6
Avg	12.7	529	–	10.4	35.9
Max	12.9	540	–	10.8	36.9
Min	12.5	521	–	9.62	34.9
CV%	1.18	1.37	–	4.15	1.86

$E_{c,0}$, modulus of elasticity in compression parallel to the grain; $f_{c,0}$, compressive strength parallel to the grain

in Fig. 4. MOE values ranged from 9 to 12.5 GPa in 76.3% of the laminae, whereas they ranged from 7 to 8 GPa in only 0.6% of the laminae. Usually, laminae having MOE values of 7–8 GPa are used for the inner lamination of E95-F270-grade glued laminated timber (Fig. 1). In this study, however, laminae having MOE of 8–10 GPa were mainly used for inner lamination.

Bending, tensile, and compressive test results

The results of the tests on bending, tension parallel to the grain, and compression parallel to the grain are shown in Tables 1–3. In the bending tests, FJs and knots in the edge-glued laminae on the tension side between the loading points played a significant role in the failure of specimens.

In the tensile tests, two of the six specimens broke at FJs and knots in the span length, and the other four specimens broke at knots in the grips. Especially, knots at the edge of the laminae appeared to affect the failure of specimens. In the compressive tests, failure was seen near the bottom of FJs and knots. In all specimens, fatal failure along the glued edge-joints was not seen. Hence, it is considered that glued edge-joints are not a strength-reducing characteristic.

Hashizume et al.[7] produced glued laminated timber (symmetrical composition, 10 laminations and a strength grade of E95-F270) composed of multiple-grade karamatsu single-piece laminae which were rated using E_{gm}-min. They reported that the average bending strength and tensile strength were 35.9 and 17.0 MPa, respectively. The bending strength was equal to that of glued laminated timber composed of edge-glued laminae, and the tensile strength of glued laminated timber composed of edge-glued laminae was slightly higher than that of glued laminated timber composed of single-piece laminae. Thus, it was considered that there was no difference in strength properties between glued laminated timber composed of edge-glued laminae and that composed of single-piece laminae. Furthermore, it was considered that structural glued laminated timber could be produced from edge-glued laminae using a similar process to that used for single-piece laminae.

In this study, the loading direction in the bending test was perpendicular to the adhesion layer of lamination, so shear force did not occur at the adhesion layer of edge-gluing. Consequently, the use of glued edge-joints did not appear to affect the strength properties. To clarify the strength properties of glued laminated timber composed of edge-glued laminae, tests should be conducted with the loading parallel to the adhesion layer of lamination (perpendicular to the adhesion layer of edge-gluing) in which shear force would occur at the adhesion layer of edge-gluing. The influence of knot size on strength properties should also be examined.

Conclusions

Glued laminated timber made from karamatsu edge-glued laminae by gluing various-width sawn lumber at the edge independent of MOE demonstrated bending, tensile, and compressive strengths nearly equal to those of glued laminated timber composed of single-piece laminae. In all specimens, the use of glued edge-joints did not appear to affect the strength results. FJs and knots in the edge-glued laminae played a significant role in the failure of specimens. These results showed that glued laminated timber could be produced from edge-glued laminae using a similar process to that used for single-piece laminae.

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