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ORIGINAL ARTICLE

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Strength properties of glued laminated timber made from edge-glued laminae I: strength properties of edge-glued karamatsu (*Larix kaempferi*) laminae

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Abstract The object of this study was to investigate the strength properties of edge-glued laminae and to propose a suitable grading method based on the lamina modulus of elasticity (MOE). Edge-glued laminae composed of lumber with similar MOEs (uniform laminae) and edge-glued laminae produced by randomly gluing lumber independent of MOE (random laminae) were made from karamatsu (*Larix kaempferi*) lumber having the same thickness and length, but various widths. For both the uniform and random laminae, there was a strong correlation between MOE values measured using the longitudinal vibration technique, the static bending test, and a grading machine. The average values of bending, tensile, and compressive strengths of the uniform laminae were similar to those of the random laminae. On the other hand, the average strength of laminae without end joints was significantly higher than that of finger-jointed laminae for both uniform and random laminae. Finger-joints and knots played a significant role in the failure of specimens, but the edge-gluing and the difference in MOE within an edge-glued lamina did not appear to affect the strength properties. The bending, tensile, and compressive strengths of edge-glued laminae were strongly correlated to the lamina MOE.

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

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Introduction

The edge-gluing process is useful for making wide structural lumber from narrow lumber or strips so that a high lumber yield can be obtained by fully utilizing narrow pieces of lumber from logs. Several articles have reported the strength properties of edge-glued lumber. The objective of these studies was mainly to improve the strength properties of dimension lumber or laminae for structural glued laminated timber.

Several studies have indicated that the following additional processing is required to improve the strength of edge-glued laminae: (a) use of a certain dimension, such as 2 × 4- and 2 × 6-inch dimension lumber,[1,2] (b) preparation of strips of clear wood or stronger species,[3–7] (c) measurement of the modulus of elasticity (MOE) before edge-gluing,[8,9] and (d) sawing glued laminated timber to produce edge-glued lamina with scattered knots or with randomized finger-joints.[9–11]

However, in order to practically use edge-glued lumber as laminae for structural glued laminated timber, the following are required: (1) edge-glued laminae need to be produced by a simple and efficient processing method to reduce production cost and increase productivity, (2) various-width lumber should be used to produce edge-glued laminae for high lumber yield from logs, (3) the strength properties of edge-glued lamina must be clarified for its strength reliability, and (4) a suitable grading method should be developed for estimating the strength properties of laminae.

In this study, edge-glued karamatsu laminae made from various-width lumber were produced by a practically continuous press. Their bending, tensile, and compressive strength properties with or without end joints were investigated. The mechanical properties of various-width lumber and the relationships with MOE for such lumber and edge-glued laminae were investigated, and a suitable grading method for edge-glued laminae was proposed.

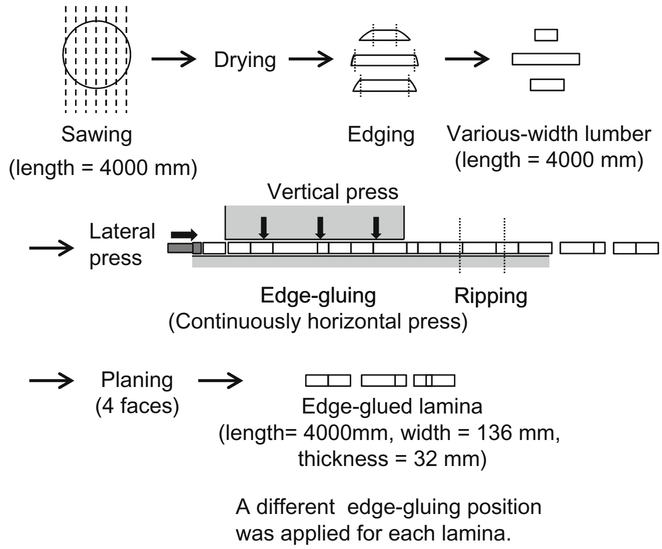

Fig. 1. Schematic of production of edge-glued lamina

Experiment

Materials

Karamatsu (*Larix kaempferi*) logs grown in Nagano Prefecture in Japan were sawn to the same thickness. After drying and edging, lumber of the same thickness (34 mm) and length (4000 mm), but of various widths was obtained (Fig. 1). A total of 493 specimens of various-width lumber were prepared.

Measurement of properties of various-width lumber

For each specimen of various-width lumber, the dimensions and weight were measured. The dynamic MOE (E_{fr}) and static MOE (E_{dw}) were measured. E_{fr} was determined by the longitudinal vibration technique and was calculated as follows:

$$E_{fr} = 4l^2\rho f^2$$

where l is the length of various-width lumber (4000 mm), ρ is the density of various-width lumber, and f is the fundamental frequency of various-width lumber.[12] E_{dw} was evaluated by dead weight method B, based on the Japanese Agricultural Standard (JAS) for glued laminated timber.[13] The difference between the deflection at the initial dead weight (49 N) and the maximum dead weight (98 N) was measured. The static MOE was calculated as follows:

$$E_{dw} = \frac{\Delta P l^3}{4bh^3\Delta y}$$

where ΔP is the difference between the initial load and the maximum load, l is the length of the span (3700 mm), b is the width of various-width lumber, h is the thickness of various-width lumber, and Δy is the deflection at the center of the span corresponding to ΔP. The moisture content of various-width lumber was measured by using a dielectric-constant moisture meter (Kett Electric Laboratory, HM-520).

Production of edge-glued laminae

A schematic of the production of edge-glued laminae is shown in Fig. 1. A total of 493 specimens of various-width lumber were divided into two groups having approximately equal distributions of E_{dw}. For one group (329 specimens), various-width lumber was glued according to the E_{dw} value to produce edge-glued laminae composed of lumber with similar MOE values (uniform lamina). For the other group (164 specimens), various-width lumber was randomly glued, producing edge-glued laminae composed of lumber with no regard to the MOE of the constituent pieces of various-width lumber (random lamina).

For the production of edge-glued laminae, we used a continuous horizontal press. A vertical press hardens the adhesive and prevents misalignment of lumber, and a lateral press pushes the various-width lumber pieces into the vertical press. The pressure of the lateral press was 1.0 MPa, and the temperature of the vertical press was 90°C. The press time was about 12 min. Melamine resin adhesive (Oshika, MG-100) was used for edge gluing. After the pressing operation, the lumber was ripped and planed. The finished dimensions of the laminae were 32 mm in thickness, 136 mm in width, and 4000 mm in length. The position and the number of edge-glued joints differed for each lamina (Fig. 1).

The number of produced edge-glued laminae was 285 for uniform lamina and 138 for random lamina. When producing edge-glued laminae from various-width lumber, the size of knots and the orientation of the grain were ignored.

Measurement of properties of edge-glued laminae

For both uniform and random laminae, the density, E_{fr} by the longitudinal vibration technique, E_{dw} by the dead weight method, and MOE (E_{gm}) by grading machine (Iida Kogyo, MGFE-251) were determined. We used a grading machine capable of determining the MOE of sawn lumber during continuous feeding in the lengthwise direction, and the average value (E_{gm}-avg) was obtained. The relationship between the MOE of various-width lumber and that of the edge-glued laminae and the relationship between the MOE values measured by each method were investigated. The moisture content of edge-glued laminae was measured by using a dielectric-constant moisture meter (Kett Electric Laboratory, HM-520).

Estimation of MOE of edge-glued laminae

The MOE of edge-glued laminae was estimated using the MOE and the width of the various-width lumber pieces within the edge-glued lamina. The estimated MOE was calculated as follows:

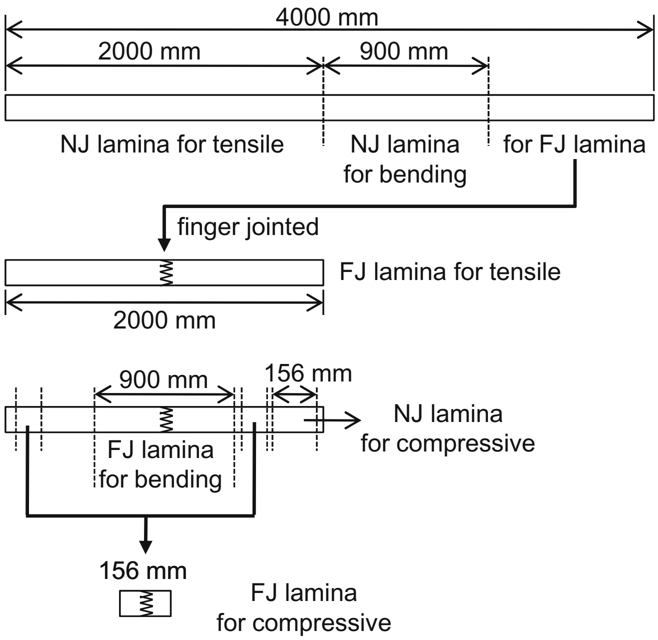

Fig. 2. Schematic of fabrication of specimens for strength property tests. *FJ*, finger-jointed; *NJ*, nonjointed

$$E_{\mathrm{est}} = \frac{\sum_{i=1}^{n}(b_i \cdot E_i)}{b}$$

where E_{est} is the estimated MOE, E_i is the MOE of the various-width lumber used to make the edge-glued lamina, b_i is the width of the lumber used to make the edge-glued lamina, b is the width of the edge-glued lamina, and n is the number of specimens of various-width lumber used to make the edge-glued lamina. The relationship between the E_{est} calculated from the E_{dw} of lumber and the measured E_{dw} of edge-glued laminae was investigated.

Prepare specimens for testing

The specimens for strength property tests were fabricated from 4000-mm lengths of edge-glued laminae. The procedure was as follows (see Fig. 2). First, a lamina without end joints [nonjointed (NJ) lamina, 2000 mm long] for the tensile test and a NJ lamina (900 mm long) for the bending test were cut from a 4000-mm-long edge-glued lamina. Second, vertically finger-jointed (FJ) laminae, 2000 mm long, were fabricated using the rest of the edge-glued laminae. The fabrication of the finger-jointed laminae is described in the following section. Some of the FJ laminae were used for tensile tests; others were used to fabricate 900-mm-long FJ laminae for bending tests, 156-mm NJ laminae for compressive tests, and 156-mm FJ laminae for compressive tests (Fig. 2). Specimen dimensions for bending, tensile, and compressive tests were 30 mm (thickness) × 130 mm (width) × 900 mm (length), 30 mm (t) × 130 mm (w) × 2000 mm (l), and 26 mm (t) × 120 mm (w) × 156 mm (l), respectively. FJ laminae and NJ laminae made from both uniform and random laminae were tested for bending, tension, and compression.

Fabrication of finger-jointed laminae

In the production of FJ lamina, edge-glued laminae of similar MOE were glued together. The finger-joint was placed in the longitudinal center of the edge-glued laminae. The finger-joint profile had a length of 20 mm, a pitch of 6 mm, a width of 1.0 mm at the tip, and a width of 0.5 mm at the base with a slope of 1/8.9. Resorcinol–phenol resin adhesive (Oshika, DF-2000) was applied for finger-jointing. The end pressure employed was 0.6 MPa.

Bending, tensile, and compressive tests

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

The static bending test for NJ and FJ laminae was conducted by flatwise four-pointed loading using a universal testing machine (Shimadzu, Autograph AG-5000B) by bending test C based on JAS.[13] The total span was 630 mm and the distance between the loading point and the support was 210 mm. The loading speed was 5 mm/min. For FJ laminae, the specimen was set so that the finger-joint was at the midspan position between the loading points. The bending strength (σ) was calculated as follows:

$$\sigma = \frac{P_{\max} l}{bh^2}$$

where $P_{\max}$ is the maximum load (N), l is the length of span (630 mm), b is the width of the edge-glued lamina (130 mm), and h is the thickness of edge-glued lamina (30 mm).

Tensile testing parallel to the grain was conducted using a tensile testing machine (Iida Kogyo, NET-40) according to JAS.[13] The distance between grips was 600 mm. For FJ laminae, the specimen was set so that the finger-joint was at the midspan position between the grips. All specimens were broken in approximately 1–4 min.

Compressive testing parallel to the grain was conducted using a compressive testing machine (Maekawa Testing Machine Mfg., A-300-B4) according to BS EN 408.[14] The finger-joint was placed in the middle of the specimen. All specimens were broken in approximately 2–4 min.

Results and discussion

Properties of various-width lumber

The width, density, E_{fr}, and E_{dw} of various-width karamatsu lumber are shown in Fig. 3. The width of lumber ranged from 45.1 to 169 mm, and the average was 123 mm. E_{dw} of various-width lumber ranged from 6.47 to 19.5 GPa, and the

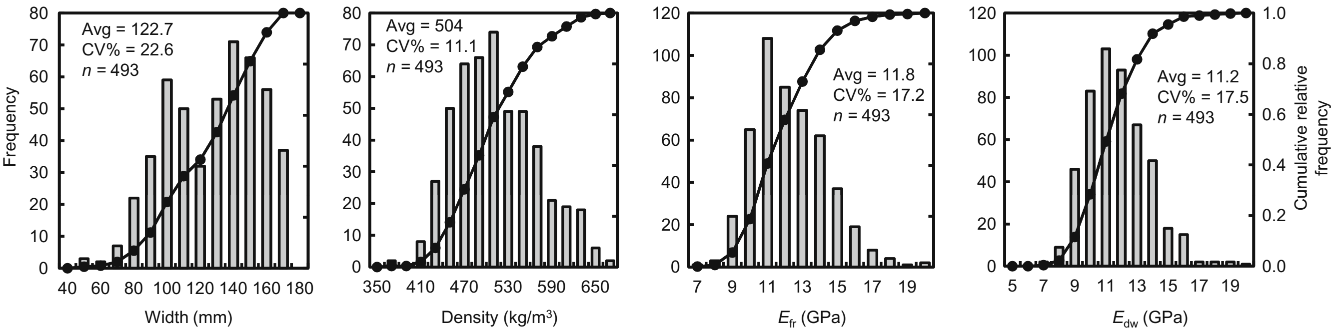

Fig. 3. Distribution of properties of various-width lumber. *Avg*, average; *CV%*, coefficient of variation (%); *n*, number of specimens; E_{fr}, modulus of elasticity measured by longitudinal vibration method; E_{dw}, modulus of elasticity measured by dead weight method

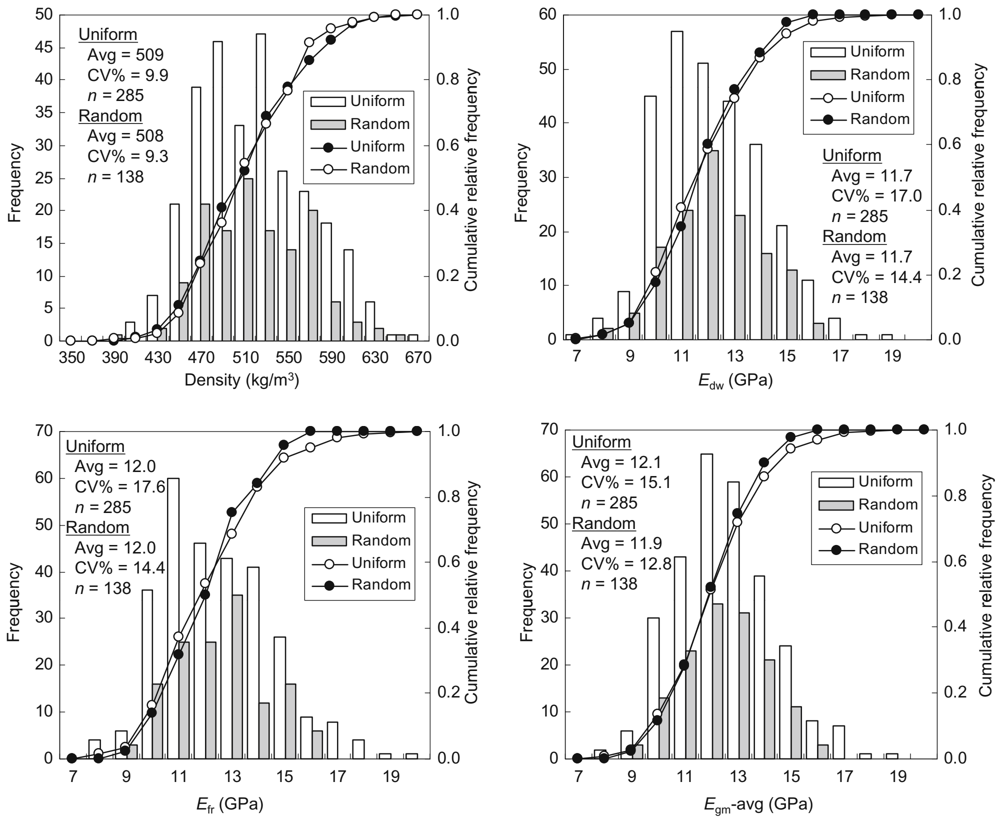

Fig. 4. Distributions of properties of edge-glued lamina. E_{gm}-avg, modulus of elasticity measured using a grading machine

average was 11.2 GPa. These results are comparable to the E_{dw} of 10.9 GPa for simple karamatsu laminae without edge jointing[15] (single-piece laminae). E_{fr} of various-width lumber ranged from 6.74 to 19.5 GPa, and the average was 11.8 GPa. The coefficient of correlation between E_{dw} and E_{fr} of various-width lumber was 0.992. The average moisture content and density of lumber was 8.1% and 504 kg/m^3, respectively. The average value of E_{dw} of various-width lumber for production of uniform laminae was 11.2 GPa and that for production of random laminae was also 11.2 GPa.

Properties of edge-glued laminae

An edge-glued lamina consisted of a single piece or multiple pieces of lumber. The number of pieces within each edge-glued lamina was from one to four. For uniform laminae (285 specimens), the number of edge-glued laminae consisting of one, two, three, and four pieces was 4 (1.4%), 220 (77.2%), 61 (21.4%), and 0 (0%), respectively. For random laminae (141 specimens), the number of edge-glued laminae consisting of one, two, three, and four pieces was 1 (0.7%), 95 (67.4%), 44 (31.2%), and 1 (0.7%), respectively. For uniform laminae, the average difference in E_{dw} of the constituent various-width lumber was 0.0393 GPa, with differences ranging from 0.000128 to 1.23 GPa. For random laminae, the average difference in E_{dw} of the constituent various-width lumber was 2.21 GPa, with differences ranging from 0.0295 to 9.16 GPa.

Figure 4 shows the density, E_{fr}, E_{dw}, and E_{gm}-avg of edge-glued laminae. For both uniform and random laminae, the average E_{dw} of edge-glued lamina was 11.7 GPa, which is

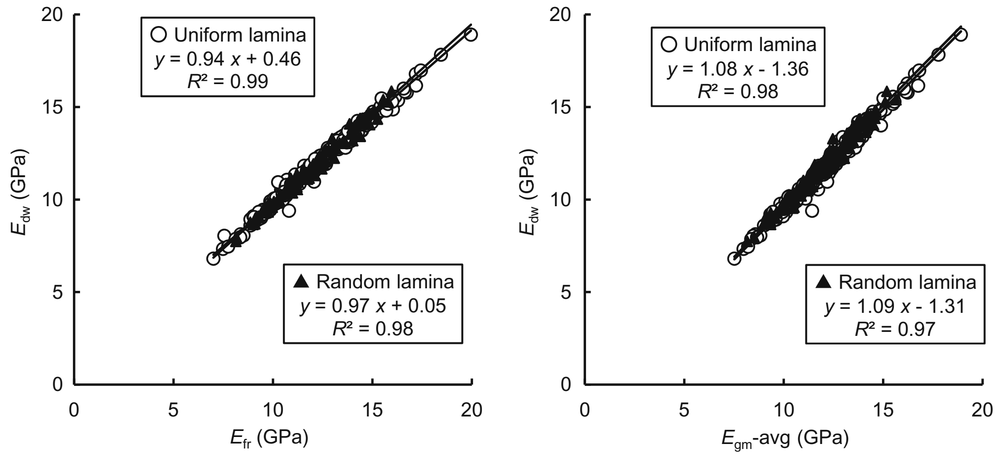

Fig. 5. Relationship among E_{fr}, E_{gm}-avg, and E_{dw} of edge-glued lamina

slightly higher than the average E_{dw} (11.2 GPa) of the constituent various-width lumber. There was a significant difference between the average E_{dw} of edge-glued laminae and that of various-width lumber (at the 5% level). For uniform laminae, the coefficient of variation (CV) of E_{dw} of edge-glued laminae was 17.0%, almost the same as that of the various-width lumber, while for random lamina, CV was 14.4%, lower than that of both the various-width lumber and uniform laminae, but there was no significant difference among the values. In previous reports,[3,5,8,9] CV was lower for edge-glued samples; however, a decline in CV was not observed in this study. Hashizume et al.[15] showed that the average value and CV of E_{dw} (n = 1642) of single-piece laminae was 10.9 GPa and 18.0%, respectively.

The relationship between the MOE values measured using each method is shown in Fig. 5; there was a strong correlation between all the MOEs. These results imply that the MOE of edge-glued laminae can be determined by the longitudinal vibration technique, the dead weight method, and with a grading machine, the same as for single-piece laminae.

The average moisture contents of uniform and random laminae were 9.9% and 9.4%, respectively.

Relationship between estimated and measured MOE

Figure 6 shows the relationship between the measured MOE (E_{dw}) and the estimated MOE (E_{est}) of edge-glued lamina calculated from the E_{dw} of the constituent various-width lumber. The measured MOE was almost the same as the estimated MOE. Therefore, the MOE of edge-glued lamina can be estimated from the MOE and the width of the pieces of various-width lumber within an edge-glued lamina.

Strength of edge-glued laminae

Figure 7 shows the relationship between E_{fr} and bending strength of NJ and FJ laminae. The average value of bending strength for NJ laminae was 59.3 MPa for uniform laminae and 62.2 MPa for random laminae. The average value of bending strength for FJ laminae was 49.4 MPa for uniform laminae and 49.4 MPa for random laminae. The average moisture content of specimens was 10.4%. Hashizume et al.[16] reported that the bending strength of single-piece laminae was 60.3 MPa for NJ laminae and 46.6 MPa for FJ laminae. These results are similar to our results and imply that edge-gluing did not influence the bending strength of laminae.

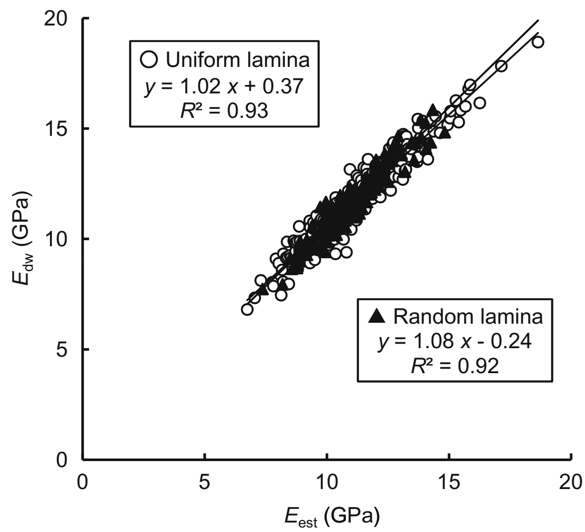

Fig. 6. Relationship between estimated MOE (E_{est}) and measured MOE (E_{dw}) by the dead weight method for edge-glued lamina

In the tensile test, the relationship between E_{fr} and tensile strength of NJ laminae and FJ laminae is shown in Fig. 8. The average value of tensile strength of NJ laminae was 35.1 MPa for uniform laminae and 33.9 MPa for random laminae. The average value of tensile strength of FJ laminae was 29.6 MPa for uniform laminae and 28.2 MPa for random laminae. The average moisture content of specimens was 11.5%. These results are also similar to those obtained by Hashizume et al.[16] for single-piece laminae.

Figure 9 shows the relationship between E_{fr} and compressive strength of NJ and FJ laminae. The average value of compressive strength of NJ laminae was 46.4 MPa for

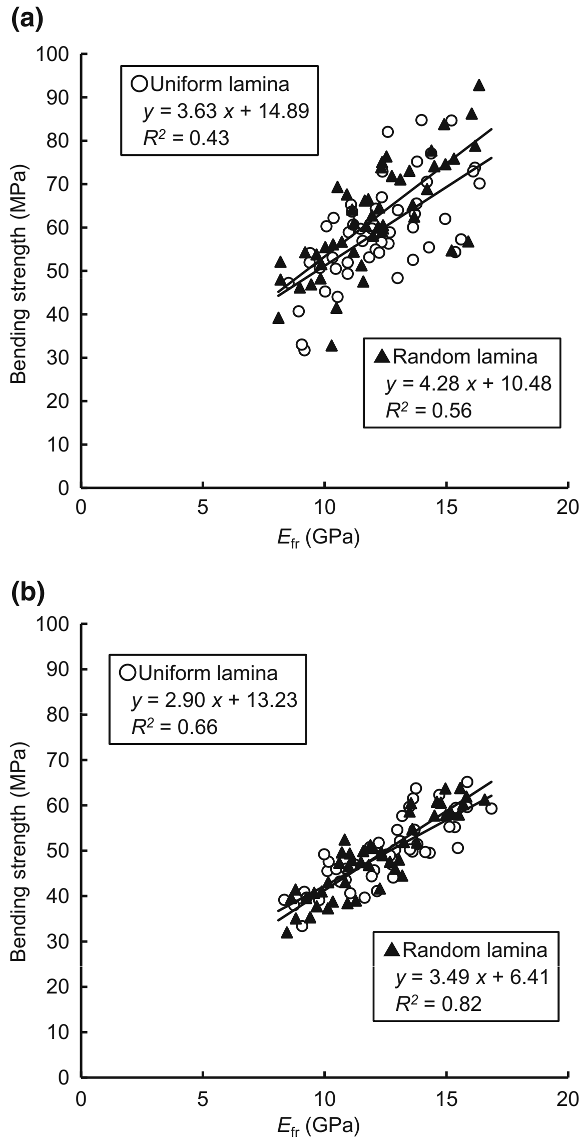

Fig. 7. Relationship between E_{fr} and bending strength for **a** nonjointed lamina and **b** finger-jointed lamina

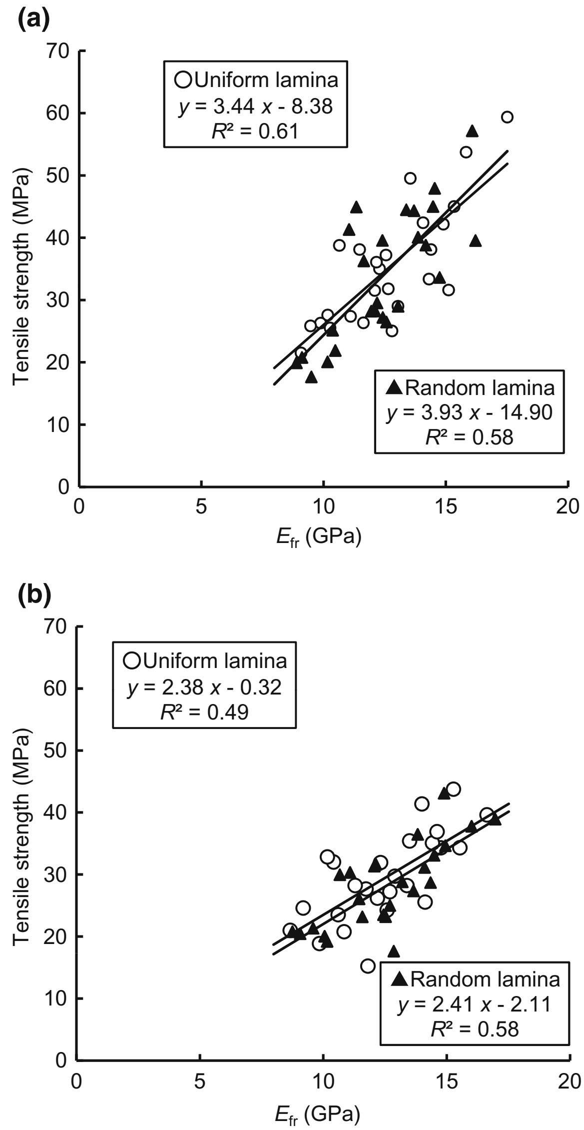

Fig. 8. Relationship between E_{fr} and tensile strength for **a** nonjointed lamina and **b** finger-jointed lamina

uniform lamina and 49.0 MPa for random lamina. The mean value of compressive strength of FJ laminae was 41.5 MPa for uniform lamina and 43.7 MPa for random lamina. The average moisture content of specimens was 11.0%.

For the bending, tensile, and compressive strengths, there was no significant difference between uniform and random lamina (at the 5% level), while the strength properties of NJ laminae were significantly higher than those of FJ laminae (at the 5% level). Finger-joints and knots played a significant role in the failure of specimens, and the difference in MOE of the various-width lumber within an edge-glued lamina and the edge-gluing itself did not appear to affect the strength properties. There was a high correlation between E_{fr} of edge-glued lamina and the bending, tensile, and compressive strength properties. These findings imply that MOE need not be measured before edge-gluing and needs to be carried out only after edge-gluing of the lamina. Furthermore, our findings indicate that the strength properties of edge-glued laminae can be estimated from the lamina MOE.

Conclusions

In order to use edge-glued lumber as laminae for structural glued laminated timber, we produced edge-glued laminae from various-width karamatsu (*Larix kaempferi*) lumber using a continuous horizontal press. Both edge-glued laminae composed of lumber with a similar MOE and edge-glued lamina composed of randomly glued lumber with no regard to the MOE of the constituent lumber were fabricated and their strength properties were investigated. In addition, grading methods for edge-glued laminae using the

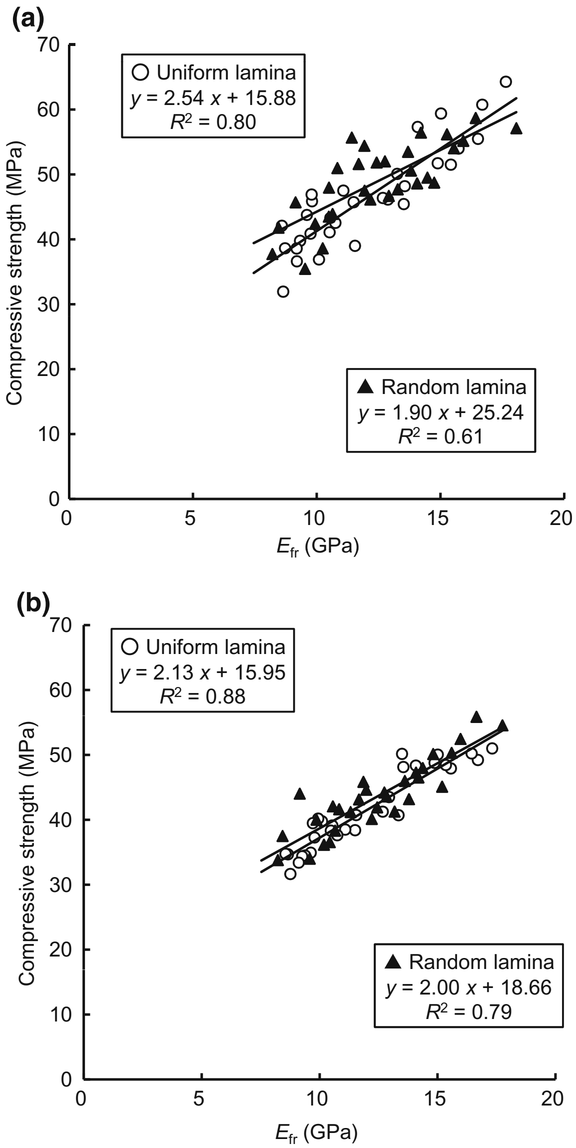

Fig. 9. Relationship between E_{fr} and compressive strength for **a** non-jointed lamina and **b** finger-jointed lamina

longitudinal vibration technique, the dead weight method, and a grading machine were investigated. The following conclusions were drawn from this study:

1. For edge-glued laminae composed of lumber with similar MOE (uniform laminae) and edge-glued laminae randomly composed of lumber independent of MOE (random laminae), there was a strong correlation between MOE values measured using the longitudinal vibration technique, the dead weight method, and a grading machine. The MOE of edge-glued laminae can be determined using the longitudinal vibration technique, the dead weight method, or a grading machine, the same as for single-piece laminae.
2. The measured MOE of edge-glued laminae was almost the same as the MOE of edge-glued laminae calculated by using the MOE and the width of the constituent various-width lumber within edge-glued laminae. Therefore, the MOE of edge-glued laminae can be estimated from the MOE and width of the constituent various-width lumber.
3. The bending, tensile, and compressive strengths of uniform laminae were similar to those of random laminae. However, the strength properties of laminae without end joints (NJ laminae) were significantly higher than those of finger-jointed laminae (FJ laminae) for both uniform and random lamina (at the 5% level). Finger-joints and knots played a significant role in the failure of specimens, but the difference in MOE of the constituent various-width lumber within an edge-glued lamina and the edge-gluing itself did not appear to affect the strength properties of NJ or FJ laminae.
4. The bending, tensile, and compressive strengths of edge-glued laminae were strongly correlated to the MOE of edge-glued laminae for both NJ and FJ laminae. Consequently, MOE should be measured only after edge-gluing of the laminae, and the strength properties of the edge-glued laminae can be estimated from the lamina MOE.

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