Ido et al. Journal of Wood Science (2022) 68:55
https://doi.org/10.1186/s10086-022-02062-1

Journal of Wood Science

ORIGINAL ARTICLE

Open Access

Effects of the presence or absence and the position of glued edge joints in the lamina on the shear strength of glued laminated timber

Hirofumi Ido*, Atsushi Miyatake, Yasushi Hiramatsu and Kohta Miyamoto

Abstract

Four kinds of glued laminated timber were produced (i.e., one with a glued edge-joint and the other three with nonglued edge joints) in the lamina at different positions toward the depth direction. Shear tests using an asymmetric four-point bending method were then conducted for these glued laminated timber specimens. The results showed that although the glued edge-joint specimens had the highest shear strength in all groups, the shear strength decreased as the distance from the adjacent nonglued edge-joint plane decreased. Furthermore, the shear strength of all specimens exceeded the standard shear design strength value (2.1 N/mm^2) set by the Ministry of Land, Infrastructure, Transport and Tourism, Japan. Next, the shear strength of the nonglued edge-joint specimens was estimated based on that of the glued edge-joint specimens. Although the mean-estimated shear strength was lower than the mean-measured shear strength, the possibility of the shear strength changing based on the position of the nonglued edge-joint plane specimens from that of the glued edge-joint specimens was still estimated.

Keywords: Glued laminated timber, Glued edge-joint, Nonglued edge-joint, Shear strength, Japanese cedar

Introduction

Recent efforts have been made to convert nonresidential and mid-to-high-rise buildings into wooden structures in Japan [1]. Glued laminated timbers are used for these buildings, and the ratio of using domestic species, e.g., sugi (Japanese cedar, *Cryptomeria japonica*), is high. The lamina width used in large-dimension glued laminated timbers is 150 mm or more, which is larger than the usual lamina width of 105 or 120 mm. Therefore, large-dimension glued laminated timbers are often custom-made. Consequently, these glued laminated timbers with large dimensions using domestic species have low productivity and high manufacturing costs.

Sugi studs with a cross-section of approximately 45 mm × 105 mm are supplied stably in Japan. It is believed that productivity can be improved by using sugi studs and a flatbed press for cross-laminated timber (CLT) production to produce large panels, from which glued laminated timbers can be cut. Therefore, the authors proposed a glued laminated timber manufactured using sugi studs as lamina and CLT manufacturing equipment for production [2] (Fig. 1).

However, when a load was applied, as shown on the right figure in Fig. 1, shear forces were applied between the edge faces (short sides) of the laminae, and there is concern regarding whether the strength performance in this area is sufficient. Therefore, in this study, a model specimen was produced by extracting a portion of the glued laminated timber assumed in the right figure of Fig. 1 to examine the effects of the presence or absence

*Correspondence: ido@ffpri.affrc.go.jp

Forestry and Forest Products Research Institute, 1 Matsunosato, Tsukuba, Ibaraki 305-8687, Japan

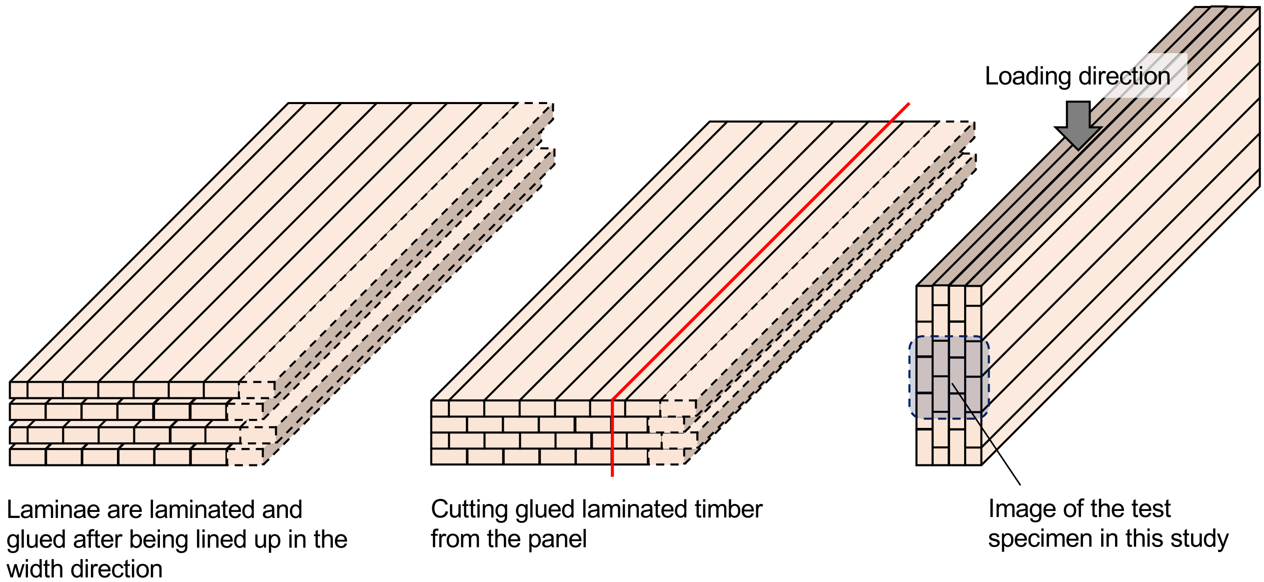

Fig. 1 Schematic image of the production of the glued laminated timber assumed in this study

and the position of glued edge joints on the shear strength of the glued laminated timber.

The developed glued laminated timber lamina was produced with glued edge joints, using a sugi stud and a resorcinol resin adhesive. Glued edge joints used extra adhesives and required an additional bonding step compared with nonglued edge joints. While, when producing a glued laminated timber with a nonglued edge-joint in the lamina, it is conceivable that the shear strength of the glued laminated timber decreases when a shear stress is applied to the plane of the nonglued edge joints. Additionally, the shear strength of the glued laminated timber differs depending on where the nonglued edge-joint exists in the glued laminated timber because the shear stress at the time of bending load varies according to the position in the depth direction of the test specimen [3].

Similar to this study, the specimen was grooved horizontally at the center of the depth of the test specimen to increase shear failure probability [4–8]. However, previous studies have reported that shear tests are rarely performed when grooves are formed at different positions in the depth direction of the specimen. For example, Martin et al. [9] conducted a shear test by providing nonglued edge joints to four central laminae of six constituting a glued laminated timber. They then set the interval between the nonglued edge joints and adjacent laminae to 38 mm. From that investigation, the shear strength of the test specimen with nonglued edge joints was 85–88% that of the test specimen with all solid laminae. However, tests in which the position of the nonglued edge joints would be changed to that in the depth direction of the specimen were not conducted.

This study conducted a shear test on the glued laminated timber using glued and nonglued edge joints in the lamina at different positions in the depth direction. The shear strength obtained from the shear test result of each glued laminated timber was then compared with the design shear strength set by the Ministry of Land, Infrastructure, Transport and Tourism, Japan [10]. Subsequently, the shear strength of the glued laminated timber with a nonglued edge-joint in its lamina was estimated from the position in the depth direction and then was compared with the measured value.

Materials and methods

Manufacturing of the glued laminated timber with glued and nonglued edge joints

Four different glued laminated timbers were produced: one that used a glued edge-joint in the lamina and three that used a nonglued edge-joint in the lamina (Figs. 2, 3, 4). A mixture of sugi L70 (according to the Japanese agricultural standard for glued laminated timber [11], with a standard of the Young's modulus in bending of ≥ 7.0 kN/mm^2) and L80 (similarly ≥ 8.0 kN/mm^2) laminae was used to produce the glued laminated timber and made to have almost the same-grade composition glued laminated timber.

The glued edge-joint lamina was manufactured as follows: First, two nonglued end joint sugi studs with a thickness, width, and length of 40, 107, and 1800 mm, respectively, were edge-jointed with an aqueous polymer

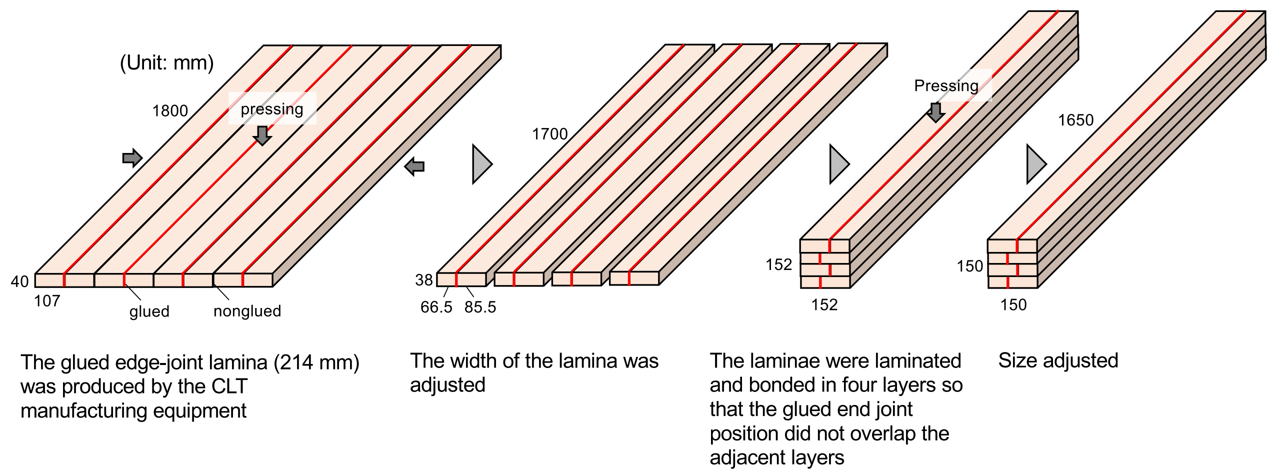

Fig. 2 Manufacturing procedure of the glued edge-joint glued laminated timber (GJ20)

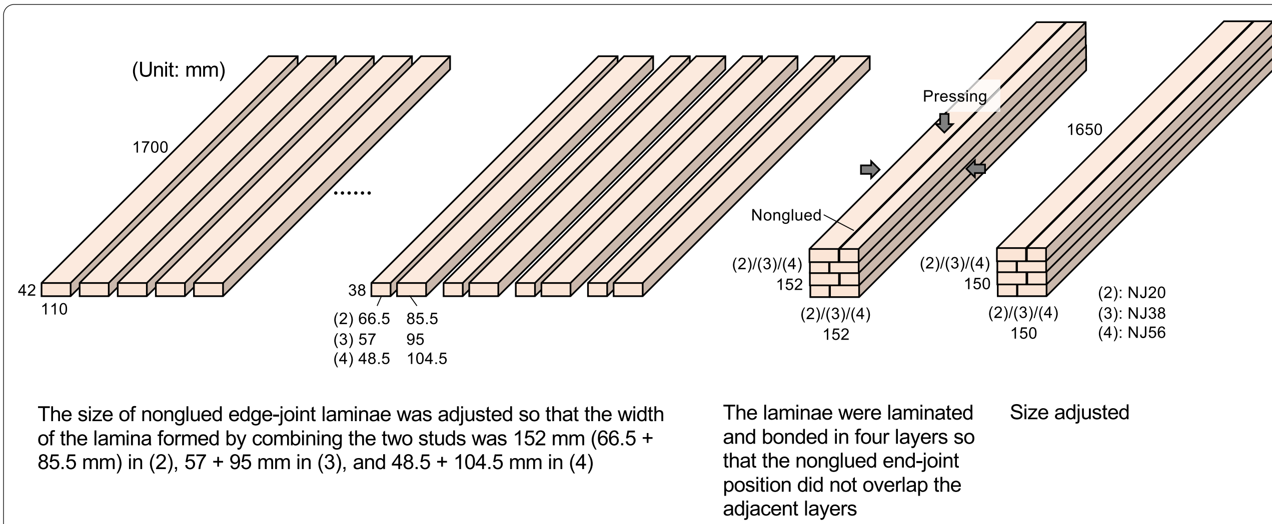

Fig. 3 Manufacturing procedure of the nonglued edge-joint glued laminated timber (NJ20, NJ38 and NJ56)

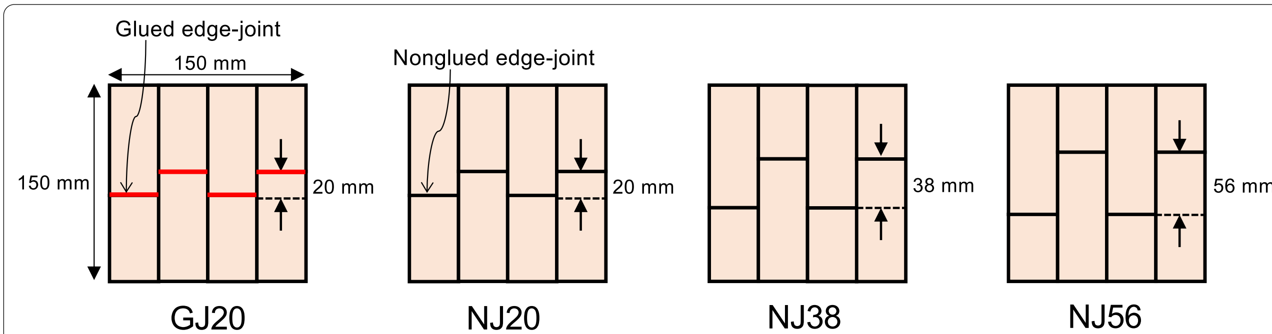

Fig. 4 Cross-sectional view of the manufactured glued laminated timbers

isocyanate adhesive (5340S, Oshika Corporation). The amount of adhesive applied was approximately 200 g/m^2. The glued edge-joint lamina (214 mm width) was then produced using the CLT manufacturing equipment of the Forestry and Forest Products Research Institute, with a pressing pressure of 0.14 N/mm^2 due to equipment availability. The pressing time was set at 50 min. The width of the lamina was adjusted so that the width of one stud of the glued edge-joint lamina became 66.5 mm and the width of the other stud became 85.5 mm, producing a (1) glued edge-joint lamina with a thickness, width, and length of 38, 152, and 1700 mm, respectively. Subsequently, for the nonglued edge-joint lamina, the nonglued end joint sugi stud with a thickness, width, and length of 42, 110, and 1700 mm, respectively, was adjusted so that the width of the lamina formed by combining the two studs was 152 mm (66.5 + 85.5 mm) in (2), 57 + 95 mm in (3), and 48.5 + 104.5 mm in (4). As a result, 20 sets of laminae of (1)–(4) were produced.

Glued laminated timber was then produced using these laminae. The lamina of (1) was bonded in four layers so that the glued end joint position did not overlap the adjacent layers. An aqueous polymer isocyanate adhesive (5340S, Oshika Corporation) was used for laminating with a spread amount, pressing pressure, and pressing time of 200 g/m^2 per adhesive layer, 0.8 N/mm^2, and 60 min, respectively. The pressing time was changed from that of edge-joint because of differences in temperature at different production times. Similarly, laminae (2)–(4) were laminated and bonded using a similar procedure. Subsequently, the size of the glued laminated timbers was adjusted to a thickness, width, and length of 150, 150, and 1650 mm, respectively, using a planer. The glued laminated timbers from laminae (1)–(4) were then called GJ20, NJ20, NJ38, and NJ56, respectively. GJ means the glued edge-joint, and NJ means the nonglued edge-joint. Additionally, the number after the symbol denotes the distance between the glued or nonglued edge-joint plane and the adjacent layers of the glued or nonglued edge-joint plane in millimeters. Consequently, five pieces of each of the four kinds of glued laminated timbers were produced.

Nondestructive and shear tests

All glued laminated timber specimens were subjected to the nondestructive test. For these investigations, the density, Young's modulus using the longitudinal vibration method, Young's modulus and shear modulus using the Timoshenko–Goens–Hearmon flexural vibration (TGH) method [12, 13] were calculated. For the Young's modulus and shear modulus using the TGH method, the specimen was installed so that the plane of the glued or nonglued edge joints was horizontal.

The longitudinal vibration method was used calculating the Young's modulus from the primary resonance frequency obtained by attaching an acceleration pickup to one end of the specimen and striking the other end with a hammer to measure vibration. The Young's modulus and shear modulus measurements, using the TGH method, were calculated from the first to the fourth resonance frequencies obtained by attaching an acceleration pickup to the top end of the specimen and striking the vicinity with a hammer.

After the nondestructive tests, a shear test was conducted using the asymmetric four-point bending method (Fig. 5). The distance between the nearest loading and reaction points was 450 mm or three times the specimen depth. Furthermore, in many cases, the load was temporarily decreased by shear failure, followed by a subsequent increase in the load again. Finally, a rapid load decrease by bending failure was observed. The shear failure result was when the load decreased and shear failure was confirmed. Shear strength was then calculated using the load at which the first shear failure occurred. However, in the case of bending failure without shear failure, shear strength was calculated using the load during bending failure as the apparent shear failure. Shear strength was finally calculated using the following equation:

$$\tau = \frac{3aF}{2A(a+S)}, \quad (1)$$

where τ is shear strength (in Newton per square millimeters), a is the distance between the reaction point and the nearest loading point at both ends (in millimeters), F is the load at the shear failure or ultimate load when specimens failed in bending (in Newton), A is the cross-section of the specimen (in square millimeters), and S is the distance between the central reaction point and loading point (in millimeters).

After the shear test, a test specimen, approximately 20 mm in length, for the moisture content measurement was cut out from the vicinity of the failed part. The moisture content was then calculated using the oven-dry method.

Next, one or two block shear test specimens with a shear plane of 28 mm × 25 mm, following the Japanese agricultural standard for glued laminated timber, were collected from the glued edge-joint position of all lamina layers in each test specimen for GJ20. The exact number of block shear test specimens with a shear plane of 25 mm × 25 mm based on JIS Z 2101 [14] was also obtained from the solid wood positions in the vicinity where the block shear test specimens for the glued edge-joint positions were collected. The number of test specimens was 34 for both types. Subsequently,

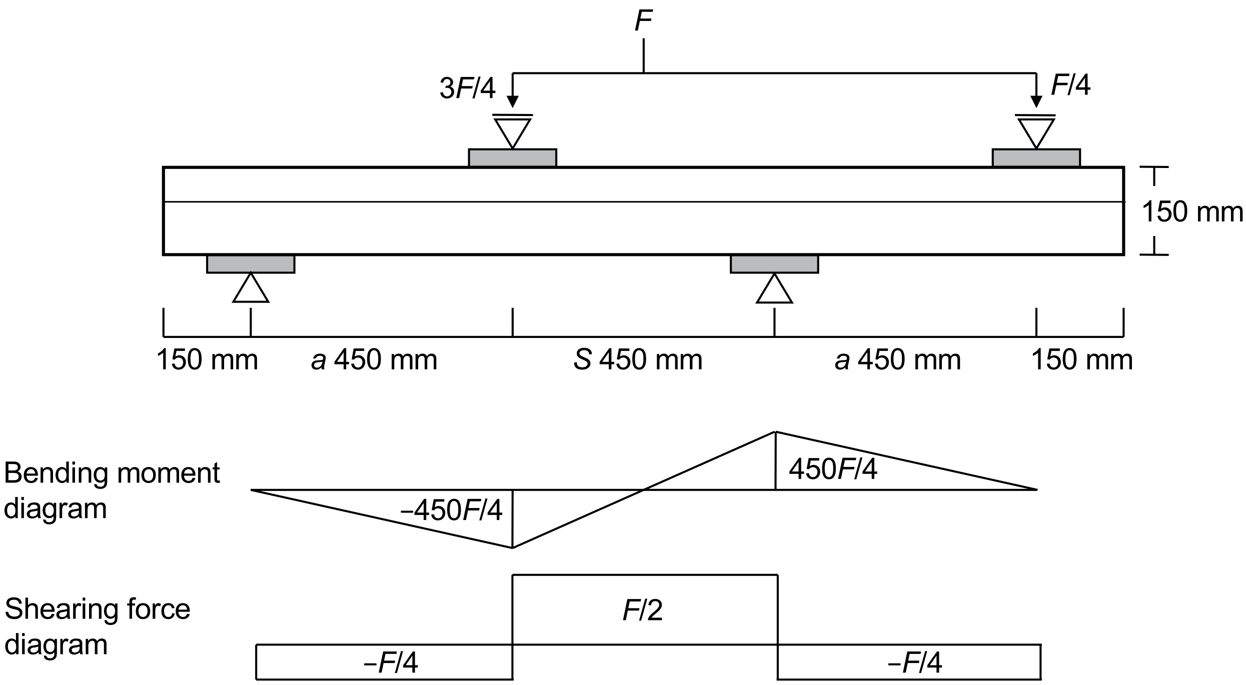

Fig. 5 Loading configuration of the asymmetric four-point bending method

the block shear test was conducted according to the Japanese agricultural standard for glued laminated timber and JIS Z 2101. Moisture content was also calculated using the oven-dry method after the block shear test.

Results and discussion

Results of the nondestructive tests

Table 1 lists the mean and coefficient of variation (CV) of the nondestructive tests. The Tukey–Kramer's honestly significant difference (HSD) test for density, moisture content, and Young's modulus using the longitudinal vibration method did not show significant difference in the mean values of each group at a 5% significance level. However, the Tukey–Kramer's HSD test showed significant mean differences in Young's modulus and shear modulus using the TGH method at a 5% significance level.

Regarding the shear modulus calculated based on the TGH method, the mean ratios of the nonglued edge-joint specimen (NJ20, NJ38, and NJ56) to the glued edge-joint specimen (GJ20) were significantly different, with the ratio of GJ20 being 1 and the others ranging from 0.63 to 0.69. Therefore, glued or nonglued edge joints had a significant effect. Although this finding was not the direct purpose of the study, the results suggested that the measurements of the shear modulus using the TGH method effectively detect internal cracking in the timber, which is the current problem [15].

Results of the shear test by the asymmetric four-point bending method and block shear test

Tables 1 and 2 list the mean and CV results of the shear tests using the asymmetric four-point bending method and block shear tests, respectively.

For the block shear tests, the mean moisture content of the solid wood specimens was 1.4% higher than that of the glued edge-joint specimens. Therefore, the mean density of the solid wood specimens was also higher. Nevertheless, the shear strength could also be affected by moisture content, even though the mean shear strength of the solid wood specimens and that of the glued edge-joint specimens were similar. According to Markwardt et al. [16], the shear strength of wood changed by 3% per 1% change in moisture content. However, the adjustment factor of the glued edge-joint was unknown. In this study, the mean values of the glued edge-joint specimens and the solid wood specimens were 7.65 and 7.97 N/mm^2, respectively, when all shear strengths were adjusted to a 15% moisture content using this ratio. Nevertheless, from the Tukey–Kramer HSD test, specimens with and without moisture content adjustments did not show significant differences in the mean shear strength between the glued edge-joint and solid wood specimens at a 5% significance level. Therefore, the shear strength of the glued

Table 1 Mean and CV results from the nondestructive and shear tests obtained using the asymmetric four-point bending method

Group	Density (kg/m^3)	MC (%)	$E_{fr\text{-}L}$ (kN/mm^2)	$E_{TGH(V)}$ (kN/mm^2)	$G_{TGH(V)}$ (kN/mm^2)	Shear strength (N/mm^2)
GJ20 (N = 5)	402 (2.77)	11.4 (1.06)	8.11 (3.15)	7.75 (3.62)	0.823 (6.68)	5.70 (9.94)
NJ20 (N = 5)	402 (5.98)	11.7 (2.17)	8.18 (6.10)	7.86 (8.05)	0.564 (12.1)	3.40 (13.0)
NJ38 (N = 5)	392 (3.28)	11.8 (2.91)	8.54 (3.22)	8.19 (2.18)	0.517 (7.11)	3.66 (14.2)
NJ56 (N = 5)	392 (2.30)	11.6 (2.05)	8.56 (3.38)	8.67 (4.03)	0.560 (6.38)	4.11 (5.20)

The left and right values in the cell are the mean value and CV (in percentage). In the case of bending failure, shear strength was calculated using the load during bending failure as the apparent shear failure

N, number of specimens; MC, moisture content; $E_{fr\text{-}L}$, Young's modulus by the longitudinal vibration method; $E_{TGH(V)}$, Young's modulus by the Timoshenko–Goens–Hearmon flexural vibration method (TGH method); $G_{TGH(V)}$, shear modulus by the TGH method

Table 2 Mean and CV of the block shear tests

Group	Density (kg/m^3)	MC (%)	Shear strength (N/mm^2)
Glued edge-joint (N = 34)	335 (7.15)	11.4 (3.27)	8.57 (15.7)
Solid wood (N = 34)	383 (9.49)	12.8 (5.28)	8.52 (10.1)

The left and right values in the cell are the mean value and CV (in percentage)

N, number of specimens; MC, moisture content

edge-joint specimens was considered equivalent to that of the solid wood specimens.

Figure 6 provides examples of the failure modes by the asymmetric four-point bending method. GJ20 shows that three of five specimens failed to bend. Although shear failure occurred between the central loading point and the support of both specimens, one of the specimens failed at the glued edge-joint plane and the other failed near the neutral axis of solid wood. In particular, the

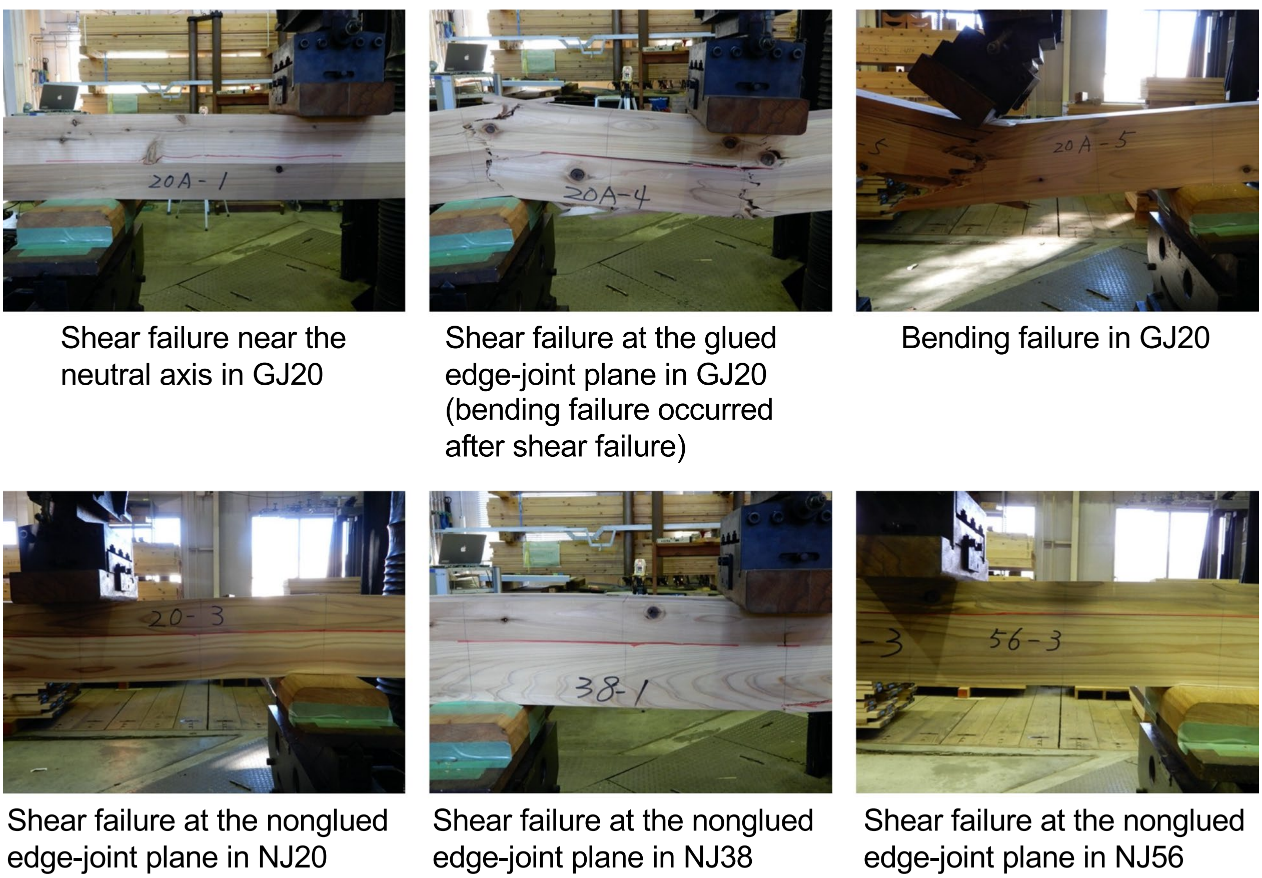

Fig. 6 Examples of the failure modes using the asymmetric four-point bending method

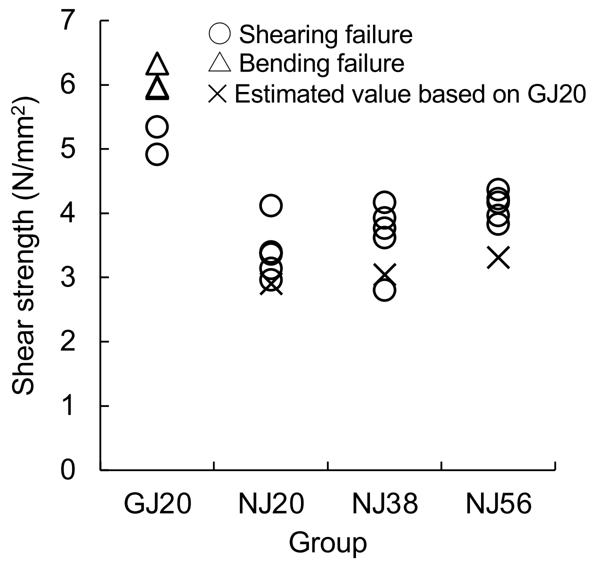

Fig. 7 Shear strength of each specimen using the asymmetric four-point bending method

NJ20, NJ38, and NJ56 specimens failed to shear at the nonglued edge-joint plane.

Figure 7 shows the shear strength of each specimen by the asymmetric four-point bending method. The shear and bending failures are indicated as an empty circles and triangles, respectively. GJ20 had the highest shear strength value in all groups. In particular, the shear strength in the nonglued edge-joint specimens decreased as the distance from the adjacent nonglued edge-joint plane decreased (from NJ56 to NJ20).

Comparing this result with the design strength set by the Ministry of Land, Infrastructure, Transport and Tourism, Japan, all specimens exceeded the shear design strength of 2.1 N/mm^2, which was in the laminated direction of the sugi glued laminated timber [10]. Note that in this design strength notification, the shear design strength of 2.1 N/mm^2 was multiplied by 0.6 for the unevaluated laminae of the glued edge-joint. Therefore, the original shear design strength was reduced further.

Shear strength estimation

The shear strengths of NJ20, NJ38, and NJ56 were estimated based on the assumption that the shear strength of GJ20 was 1. The following two factors affect the shear strength of glued laminated timber: the presence or absence of glued edge joints and the position of shear failure in the cross-section.

First, on the basis of the presence or absence of a glued edge-joint, the shear strength of the nonglued edge-joint plane in NJ20, NJ38, and NJ56 was zero. NJ20, NJ38, and NJ56 failed in the solid wood adjacent to the nonglued edge-joint plane. Therefore, when the shear strength of the nonglued edge-joint plane was 0, the effective specimen in the laminated direction width under shear was 1/2 of the total laminated direction width of the specimen because the laminated direction width of the nonglued edge-joint plane was similar to the laminated direction width of the adjacent solid wood (Fig. 4).

Although the shear stress was at the maximum at the neutral axis, its value decreased from that point to the upper or lower edges (Fig. 8). The position of shear failure in the cross-section of NJ20, NJ38, and NJ56 was the solid wood position adjacent to the nonglued edge-joint plane, which was 10, 19, and 28 mm away from the neutral axis, respectively. Moreover, of the two GJ20 specimens that failed in shear, one specimen failed at the neutral axis and the other failed at the glued edge-joint. The specimen that failed at the neutral axis is represented here. Furthermore, assuming that the shear stress at the neutral axis was 1, the shear stress values at positions 10, 19, and 28 mm away from the neutral axis were 0.982, 0.936, and 0.861, respectively. Hence, the stress applied to this position was doubled because the effective laminated direction width result of NJ20, NJ38, and NJ56 at these portions was 1/2. When this result was multiplied by the previous value, the shear stress at NJ20, NJ38, and NJ56 at the shear failure position became 1.964, 1.872, and 1.722, respectively. Alternatively, when the shear strength of GJ20, which was the standard, was 1, NJ20, NJ38, and NJ56 took the reciprocal of the shear stress, becoming 0.509, 0.534, and 0.581, respectively. Similarly, when the mean shear strength of GJ20 was 5.70 N/mm^2, including the value of the specimens that failed to bend, the estimated shear strengths of NJ20, NJ38, and NJ56 became 2.90, 3.04, and 3.31 N/mm^2, respectively. This value is indicated by x in Fig. 7.

On the basis of the results of the current study, although the mean shear strengths of NJ20, NJ38, and NJ56 were 3.40, 3.66, and 4.11 N/mm^2, respectively, the estimated values were smaller than the measured mean values. This reduction was because the measured mean value of GJ20 included three of the five specimens that failed to bend. Furthermore, although these three specimens failed in bending before they failed in shearing, the actual shear strength was considered to be greater than the apparent shear strength. In other words, the true shear strength of the specimen that failed in the bending before shear failure would have been greater than the apparent shear strength determined from the load at bending failure because the load would have continued to increase without bending failure. Another factor was the difference in the size of the shear area. Studies have shown that although the shear strength

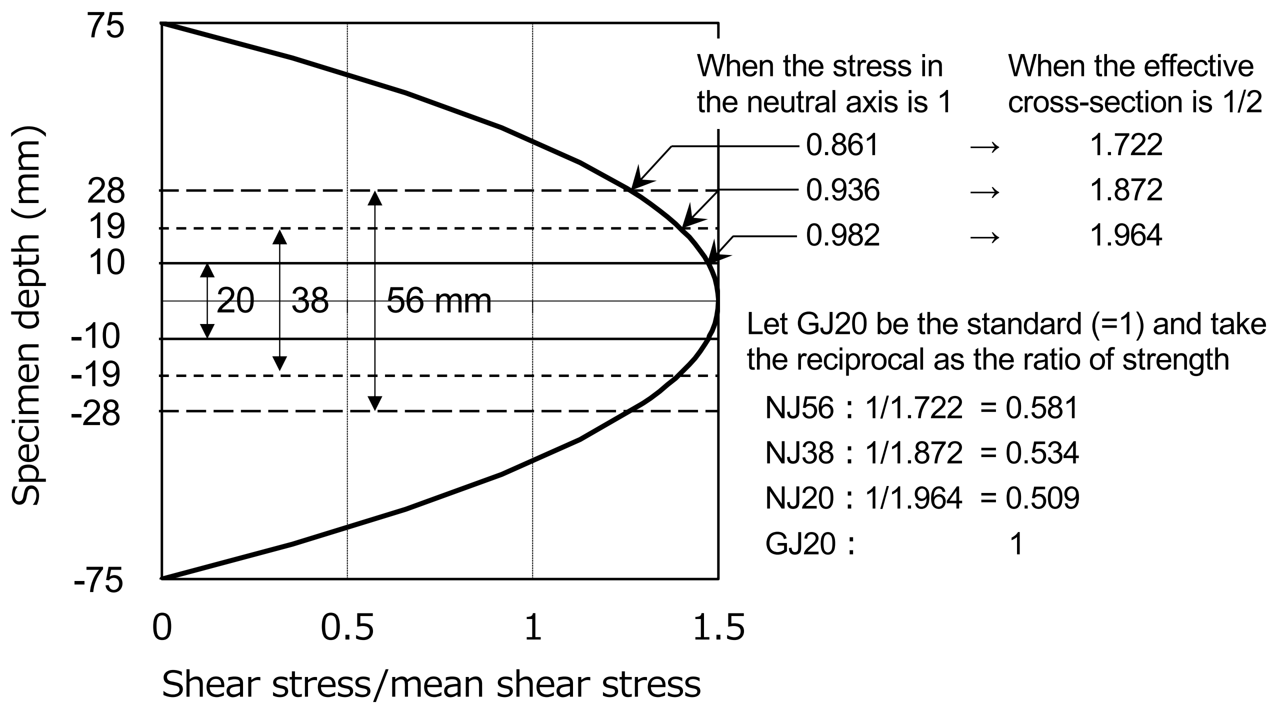

Fig. 8 Shear stress at each position in the cross-section

decreases with increasing shear area [17–23], the shear areas of NJ20, NJ38, and NJ56 were half as large as that of GJ20. Consequently, the shear strength may have increased. Alternatively, when the mean shear strength of NJ20 was 1, the measured and estimated mean ratios of NJ20, NJ38, and NJ56 were 1:1.08:1.21 and 1:1.05:1.14, respectively. Hence, although both NJ38 and NJ56 showed a slightly lower estimated value ratio, estimating the tendency for a gradual increase in shear strength was possible because the position of the non-glued edge-joint deviated from the neutral axis.

Conclusions

Four kinds of glued laminated timber were produced: one with a glued edge-joint in the lamina and the other three with nonglued edge joints in their laminae at different positions in the depth direction.

Nondestructive tests were conducted for the glued laminated timbers. With the shear modulus using the TGH method, the ratio of the mean nonglued edge-joint specimens (NJ20, NJ38, and NJ56) to the glued edge-joint specimen (GJ20) was significantly different. Therefore, glued or nonglued edge joints was significantly affected the shear modulus.

Subsequently, block shear tests were conducted for the specimens collected from the glued laminated timbers. In specimens with and without moisture content adjustment, the mean shear strength between the glued edge-joint and solid wood specimens did not show significant differences at the 5% significance level. Therefore, the shear strength of the glued edge-joint specimens was considered equivalent to that of the solid wood specimens.

Shear tests using the asymmetric four-point bending method were conducted for glued laminated timbers. The shear strength decreased as the distance from the adjacent nonglued edge-joint plane decreased although the glued edge-joint specimens had the highest shear strength value in all groups. The shear strength of all specimens exceeded the shear design strength of 2.1 N/mm^2 by the Ministry of Land, Infrastructure, Transport and Tourism, Japan.

Finally, the shear strength of the nonglued edge-joint specimens was estimated based on the shear strength of the glued edge-joint specimens. Consequently, the mean-estimated shear strength was lower than the mean-measured shear strength. This result was considered because the actual shear strengths of the glued edge-joint specimens that failed in bending were assumed to be higher. However, the size effect was considered because the shear area of the glued edge-joint specimens was larger than that of the nonglued edge-joint specimens. Furthermore, although the aforementioned factors should be investigated in the future, this study successfully estimated the tendency of the shear strength to change depending on the positions of the nonglued edge-joint specimen from the shear strength of the glued edge-joint specimens, which was the primary goal of this study.

Abbreviations
CLT: cross-laminated timber; CV: coefficient of variation; HSD: honestly significant difference; *N*: Number of specimens; MC: Moisture content; $E_{fr\text{-}L}$: Young's modulus by the longitudinal vibration method; $E_{TGH(V)}$: Young's modulus by the Timoshenko–Goens–Hearmon flexural vibration method (TGH method); $G_{TGH(V)}$: Shear modulus by the TGH method.

Acknowledgements
The authors would like to thank Dr. Hiroto Suesada of Shinshu University, Dr. Kazushige Murayama of the Forestry and Forest Products Research Institute, Mr. Kai Ito of Aomori Prefectural Industrial Technology Research Center, and Tomomichi Iguchi of Okinawa Prefecture for their contributions to manufacturing the glued laminated timber. This study's findings were partly presented at the 71st Annual Meeting of the Japan Wood Research Society in March 2021.

Author contributions
HI tested and analyzed the glued laminated timber and contributed mainly to writing the manuscript. AM planned the composition and manufactured the glued laminated timber. YH planned the production method of glued laminated timber and manufactured the glued laminated timber. KM planned and manufactured the glued edge joints and conducted the block shear test. All authors have read and approved the final manuscript.

Funding
Grants from the Bio-oriented Technology Research Advancement Institution, NARO project (the special scheme project on advanced research and development for next-generation technology), were used to support this research.

Availability of data and materials
The datasets analyzed during this study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare no competing interests.

Received: 6 June 2022 Accepted: 29 August 2022
Published online: 22 September 2022

References
1. Forestry Agency (2020) Annual report on forest and forestry in Japan fiscal year 2019, p 2. https://www.maff.go.jp/e/data/publish/attach/pdf/index-182.pdf. Accessed 29 Aug 2022.
2. Ido H, Nagao H, Harada M, Miyatake A, Noda Y, Yoshida S, Shimizu K (2021) Development of large dimension glued laminated timber using studs (Part 1) Manufacturing and material performances. Mokuzai Kogyo 76(4):129–134 (**in Japanese**)
3. Timoshenko S (1958) Strength of materials. Part I Elementary theory and problems, 3rd edn. Van Nostrand Reinhold Company, New York, pp 113–120
4. Radcliffe BM, Suddarth SK (1955) The notched beam shear test for wood. Forest Prod J 5(4):131–135
5. Suzuki N, Okohira Y (1982) On the measurement of shearing strength of wood by bending test. Bull Fac Agr, Mie Univ 66:21–27 (**in Japanese**)
6. Nagao H, Kato H (1998) Preliminary examination on the shear strength of sugi lumber. In: Abstracts of the 48th annual meeting of the Japan wood research society, Shizuoka, 3-5 April 1998, 3E14 (**in Japanese**)
7. Korin U (1988) Shear strength in bending of timber. In: proceedings of the international council for building research studies and documentation. Vancouver, September, CIB-W18A/21-6-3
8. Yoshihara H, Furushima T (2003) Shear strengths of wood measured by various short beam shear test methods. Wood Sci Technol 37(3–4):189–197
9. Martin ZA (2005) Full-scale shear and bending tests on glulams with non-glued edge joints. APA Report T2005-84, Engineered Wood Association
10. Notification No. 1024 of the Ministry of Land, Infrastructure, Transport and Tourism, June 12 (2001) Establishment of special allowable unit stress and special material strength, Ministry of Land, Infrastructure, Transport and Tourism, Tokyo (**in Japanese**)
11. Notification No. 1152 of the Ministry of Agriculture, Forestry and Fisheries, September 25 (2007) Japanese agricultural standard for glued laminated timber, Ministry of Agriculture, Forestry and Fisheries, Tokyo (**in Japanese**)
12. Kubojima Y, Yoshihara H, Ohta M, Okano T (1996) Examination of the method of measuring the shear modulus of wood based on the Timoshenko theory of bending. Mokuzai Gakkaishi 42(12):1170–1176
13. Kubojima Y, Tonosaki M (2012) Young's and shear moduli of glued laminated timber composed of different species obtained by a flexural vibration test. Holzforschung 66(7):871–875
14. JIS Z 2101 (2009) Methods of test for woods (in Japanese). Japanese Standards Association, Tokyo
15. Kawasaki Y (2020) History of wood drying. In: Shida S, Kawasaki Y (eds) Wood drying. Kaiseisha Press, Otsu, pp 29–30 (**in Japanese**)
16. Markwardt LJ, Wilson TRC (1935) Strength and related properties of woods grown in the United States. Tech Bull No.479, USDA, Washington, DC.
17. Keenan FJ (1974) Shear strength of wood beams. Forest Prod J 24(9):63–70
18. Longworth J (1977) Longitudinal shear strength of timber beams. Forest Prod J 27(8):19–23
19. Quaile AT, Keenan FJ (1978) Shear strength of small composite wood beams. Wood Sci 11(1):1–9
20. Soltis LA, Rammer DR (1994) Shear strength of unchecked glued-laminated beams. Forest Prod J 44(1):51–57
21. Rammer DR, McLean DI (1996) Recent research on the shear strength of wood beams. In: Proceedings of the international wood engineering conference, New Orleans, 28-31 October, 2-96-2-103
22. Rammer DR, Soltis LA, Lebow PK (1996) Experimental shear strength of unchecked solid-sawn Douglas-fir. Res Pep FPL-RP-553, US Department of Agriculture, Forest Products Laboratory, Madison.
23. Ido H, Nagao H, Kato H (2006) Evaluation of the shear strength of lumber by different test methods. Mokuzai Gakkaishi 52(5):293–302 (**in Japanese**)

Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.