Research paper

Evaluation of the Shear Performance of Structural Glulam Member Joints with Embedded Metal Connectors[1)]

Min-Chyuan Yeh,[2,3)] Yu-Li Lin,[2)] Yung-Chin Huang[2)]

【Summary】

A symmetrical mixed-grade composition glulam was fabricated using Japanese cedar plantation timber in the study. The sizes of the beam and column members were 120×304×1500 and 120×152×900 mm, respectively. A beam-column structure was constructed with 2 different types of developed metal connectors with different numbers of bolts to examine the shear resistance performance of the joints. The results indicated that the maximum shear capacity, yield strength, and energy absorption of a glulam joint using a 5-mm-thick flat-type connector were 34, 48, and 111% higher than those using a T-type connector. The structural characteristic factor also showed adequate ductility. The initial stiffness levels of glulam joints fixed with 3 and 5 bolts, respectively, were 2.8-and 4.0-times that with 2 bolts, while the energy absorption was reduced to 44 and 15%. Furthermore, joints fixed with 2 or 3 bolts had higher ductility factors and adequate structural characteristic factors for resisting a shear load.

Key words: joint, glulam, shear strength, Japanese cedar.

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2) Department of Wood Science and Design, National Pingtung Univ. of Science and Technology, 1 Shuehfu Rd., Neipu, Pingtung 91201, Taiwan. 國立屏東科技大學木材科學與設計系，91201屏東縣內埔鄉學府路1號。

3) Corresponding author, e-mail:yehmc@mail.npust.edu.tw 通訊作者。

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研究報告

埋入式金屬連結件接合結構用集成材之剪斷性能評估[1)]

葉民權[2,3)] 林玉麗[2)] 黃永欽[2)]

摘 要

本研究利用國產柳杉造林木組成對稱異等級集成材，梁尺寸為120×304 mm，柱尺寸為120×120 mm，並開發兩種金屬連結件，以不同數量螺栓組合梁柱結構，探討接合之剪斷抵抗性能。結果顯示，以平板型5 mm厚金屬連結件之接合，在最大剪斷承載力、降伏強度及能量吸收較T型連結件之接合條件分別高34、48及111%，同時結構特性因素也顯示有適當之延展性。集成梁兩端分別以3或5支螺栓接合之初始剛性為以2支接合條件之2.8及4.0倍，而能量吸收則分別降為2支接合條件的44及15%。柳杉結構用集成材在接合時以2或3支螺栓固定者，在剪力載重下有較高之延展性因素，及適當之結構特性因素。

關鍵詞：接合、集成材、剪斷強度、柳杉。

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INTRODUCTION

Joint performance is a major consideration for designing a glulam framework. Many studies dealt with the bending moment resistance of a cantilevered glulam member connected to a column using bolts or dowels while being subjected to a bending load. Yeh et al. (2008) reported that improvements of 67.4 and 53.0% in the bending moment capacity of glulam joints were found for a steel plate connection joined with 6 bolts of 18- and 15-mm diameters, respectively compared to values with 4 bolts. The structural behavior of bolted or pinned joints of glulam members in tension or compression was also tested and simulated from different aspects. Yeh et al. (2007) indicated the long-term allowable shear strengths of 15- and 18-mm bolts were 18.3 and 23.5%, respectively, of the measured yield bearing strength for a Japanese cedar glulam. In most cases, glulam members failed by shearing or splitting at the member ends where the joint received bolts or pins. The shearing characteristics of members would then play a critical role in the joint failure mechanism. Furthermore, the shear force becomes profound on a deep beam member subjected to a transverse load or for a design application with a short span. ASTM (2002) suggests that the span length of beams with a rectangular cross-section primarily for evaluating the shear properties should have a ratio of span to beam depth of < 5. This ratio category will provide a high percentage of shear failure. Hayashi et al. (2002) found 3 failure modes in girder-beam and post-beam structures assembled with a standard metal connector for Japanese conventional post and beam structures. This was reduced to 1 major failure mode when assembled with Haratec connectors. They suggested that the strength properties of the joints were influenced by the depth of the glulam, the type of connector, and the type of joint. Therefore, it is important to further examine the shear resistance of a glulam connection in relation to the mechanical fastener efficiency.

Glulam members are usually used in the large wooden building construction, and are often joined using metal connectors in addition to bolt fasteners. For construction convenience, these mechanical fasteners are mounted on the member faces. But in many cases, exposure of the connection hardware on the glulam framing may have a negative impact on the appearance for interior design. For fire concerns, certain protections to prevent the heating of mechanical fasteners which could cause a loss of strength are required. Some suggestions on the fire design were made for connections and supports of beams to columns, beams to beams, and columns to foundations to ensure necessary fastener protection (JSCA 2004). In this study, metal connectors inserted into wooden members and fastened with different numbers of bolts were developed to investigate the structural adequacy of a glulam joint based on the shear resistance performance.

MATERIALS AND METHODS

Materials

Japanese cedar (*Cryptomeria japonica*) logs were harvested at the age of 35 yr old from a plantation forest located in the Hsinchu Forest District. The size of laminae was 38×120 mm after being sawn, kiln-dried, and planed. The moisture content of the sawn lumber was 11.9±0.6%. The dynamic modulus of elasticity (DMOE) of the laminae was first measured along the longitudinal fiber direction using a tap-tone approach. Each lamina was then assigned a grade based on DMOE values for the subsequent layout process of lamina combination. A resorcinol phenol formaldehyde adhesive (RPF) and hardener of paraformaldehyde mixed in a ratio of 15: 100 were used for the glulam lamination. The adhesive was applied at a rate of 250 $g \cdot m^{-2}$ with an application pressure of 0.98 MPa for 6 h during glulam fabrication. An E95-F270 grade symmetrical mixed-grade composition glulam with a size of 304×120×1500 mm was assembled for beam members and E65-F225 with a size of 152×120×900 mm for column members. The layout of the laminae with assigned grades for both beam and column members in this study are shown in Figs. 1 and 2. An inserted connection between the beam and column members was developed. Two types of steel connectors were designed, i.e., flat- and T-types (T), using a 5-mm-thick steel plate for the connection (Figs. 3, 4). The determination of the sizes of SS400 steel connectors and the layout for the fastener locations followed spacing requirements for bolt application specified in the building code (Minstry of the Interior 2011).

Methods

Several basic tests were carried out to provide information related to shear or split properties of Japanese cedar. A shear test on solid wood was performed using the CNS 455 method, and a wood block cleavage test was also conducted using the CNS 6716 method. Both grain orientations, radial and tangential, were considered, and each test condition had 24 replicates. Further, a wood block shear test for adhesion was also carried out on glulam specimens using the CNS 11031 method with 100 replicates.

For full-size shear evaluation, each specimen was constructed with 2 column members on both sides and 1 short beam member in the center forming an H-shaped structure. Bolts with either 2, 3, or 5 fasteners were used for beam-column connections for both flat- and T-type steel plates. The diameter of the SS400 bolts was 15.9±0.1 mm, and the size of SS400 washers was 50×50×5 mm. The mechanical fasteners at both ends of glulam beam members were laid out following code requirements of spacing as shown in

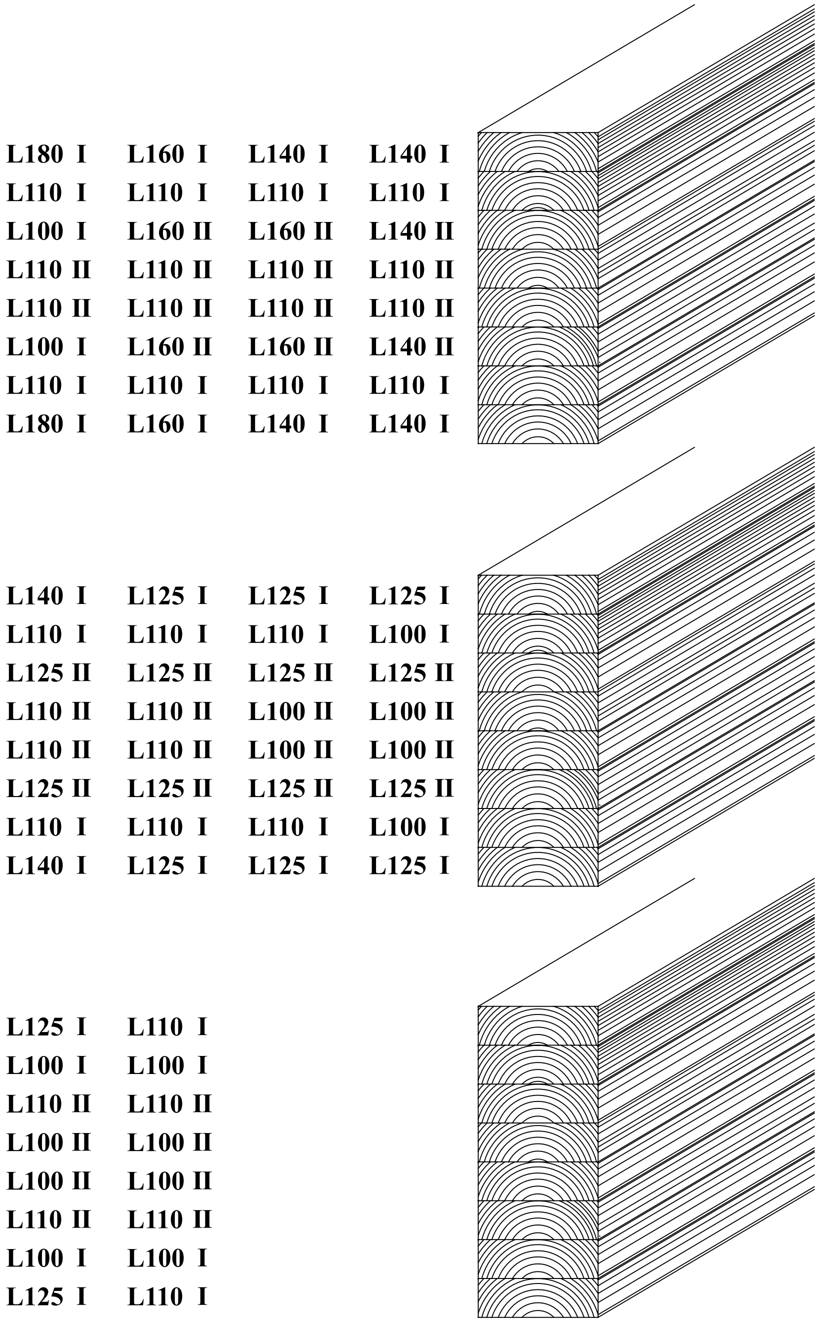

Fig. 1. Layout of Japanese cedar laminae with different grades for balanced symmetrical structural glulam beams (I, knot ratio ≤ 17%; II, ≤ 25%).

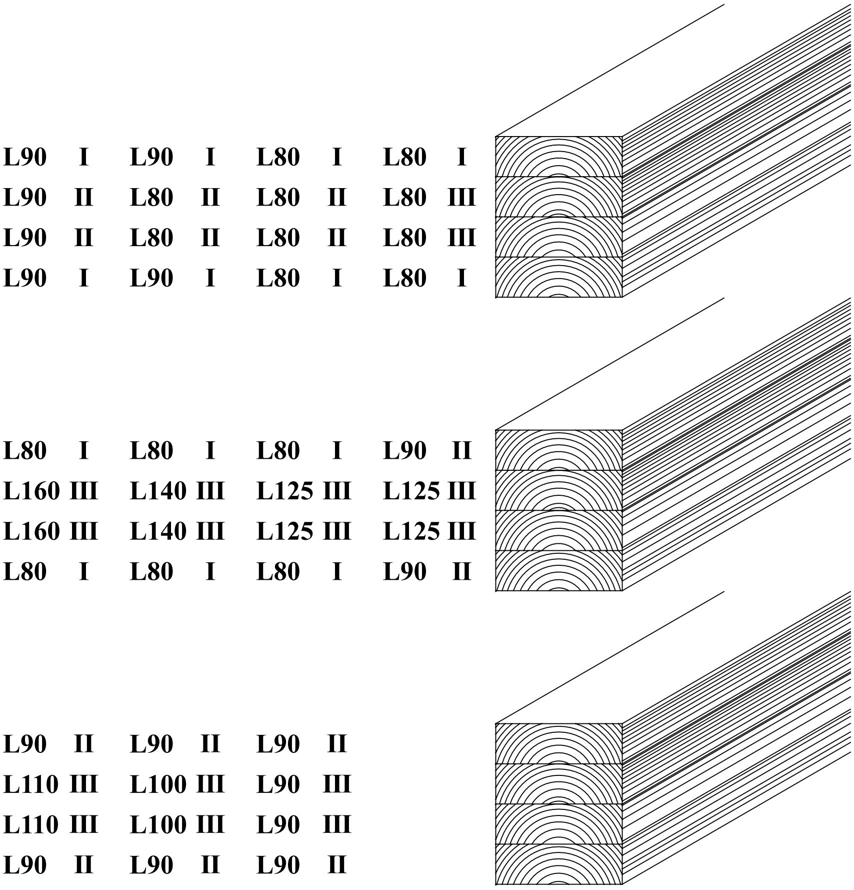

Fig. 2. Layout of Japanese cedar laminae with different grades for balanced symmetric structural glulam posts (I, knot ratio ≤ 17%; II, ≤ 25%; III, ≤ 33%).

Fig. 5. Detailed configurations of joints fastened with flat- and T-type connectors on the glulam column are shown in Fig. 6. A hydraulic loading machine with a capacity of 500 kN was used for the test. Figure 7 shows a schematic of a concentrated load applied to a specimen, which was constructed with a short beam and 2 columns. The shear capacity of the joints was evaluated using a flexural test. A concentrated load was applied to a 160-mm long steel plate in the middle of the beam with a 1500-mm span. The characteristic shear properties of the glulam joints were calculated based on a method proposed by The Japan Housing and Wood Technology Centre (2001). In total, 6 conditions were examined with 3 replicates for each joint configuration.

RESULTS AND DISCUSSION

Basic properties of solid wood

The specific gravity of Japanese cedar lumber was 0.53±0.06. Shear strengths evaluated on radial and tangential sections of solid wood were 9.1±2.5 and 8.6±2.6 MPa, respectively. The shear resistance of the glued interface of wood blocks cut from the glulam members was 10.5±2.1 MPa, which met the minimum 5.4 MPa required in CNS 11031 for manufactured glulam products from Japanese

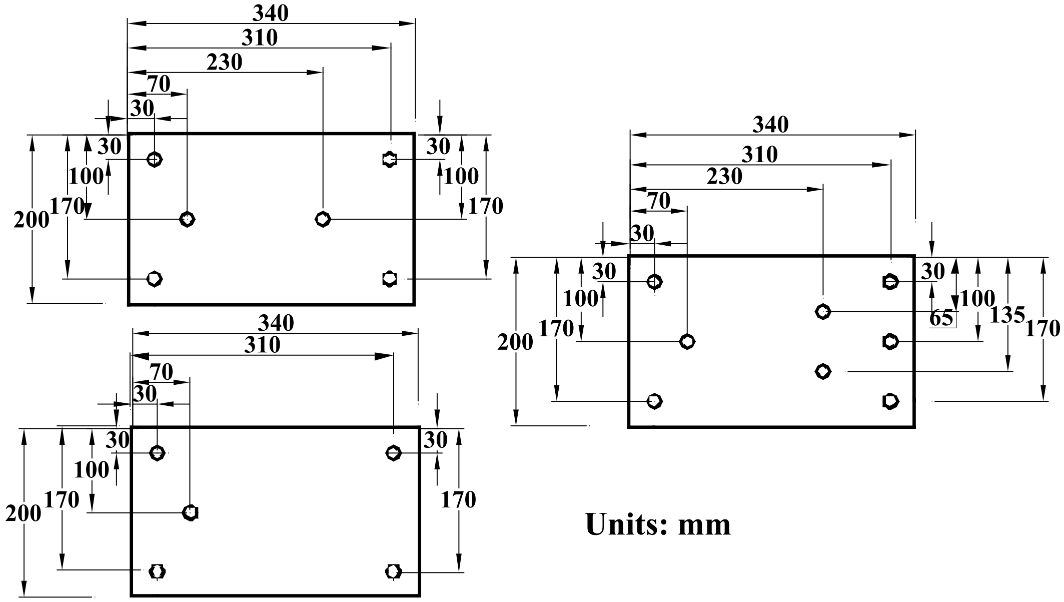

Fig. 3. Design of flat-type connectors for glulam beam-column joints.

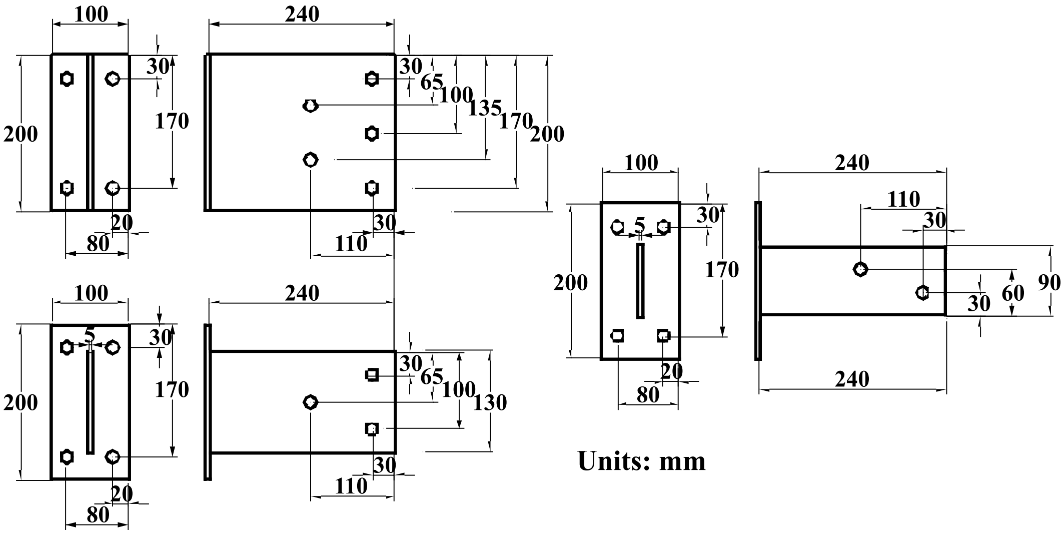

Fig. 4. Design of T-type connectors for glulam beam-column joints.

cedar (BSMI 2006). Cleavage resistance values of the radial and tangential sections of solid wood were 37.1±10.2 and 32.8±5.7 $N \cdot mm^{-1}$, respectively.

In total, 299 laminae of 3600 mm in total length were graded into L50 to L180 based on the measured MOE. Tsai and Yeh (2007) reported that nondestructive MOE values obtained using the tap-tone approach were 0.16~2.8% higher than the MOE from the bending test for 2×6 China fir lumber. And they suggested estimating acceptable MOE

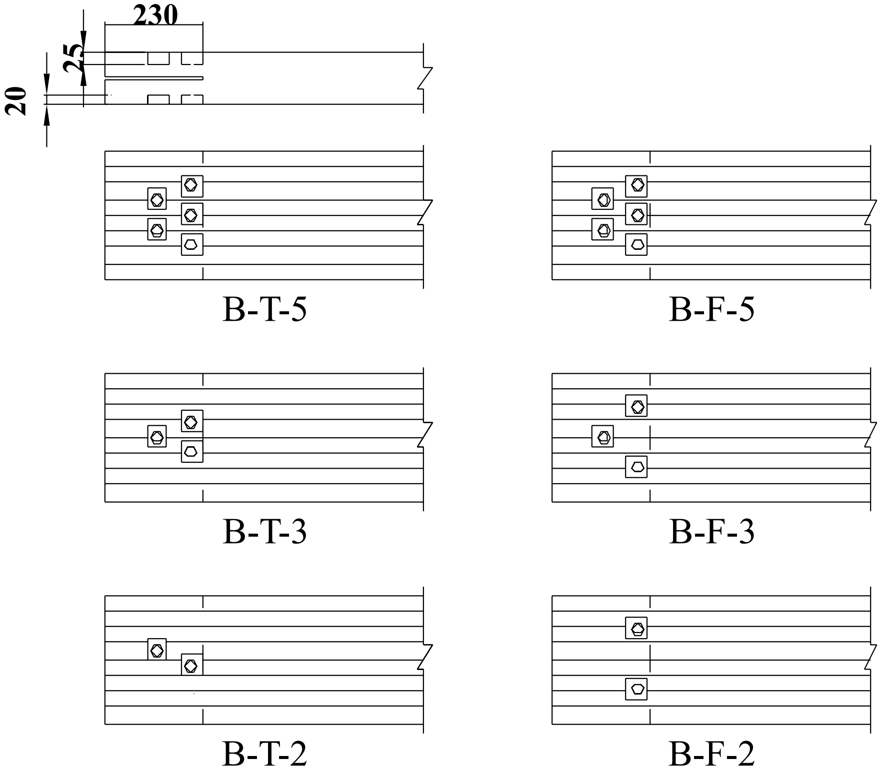

Fig. 5. Layout of mechanical fasteners at the ends of glulam beam members (units: mm).

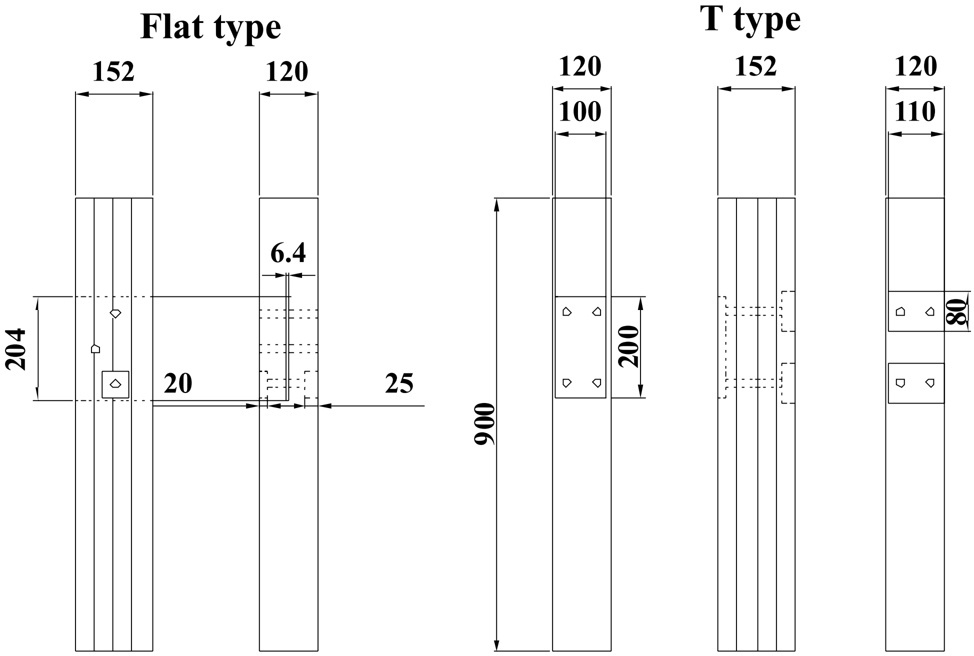

Fig. 6. Details of glulam post joints with flat- and T-type connectors (units: mm).

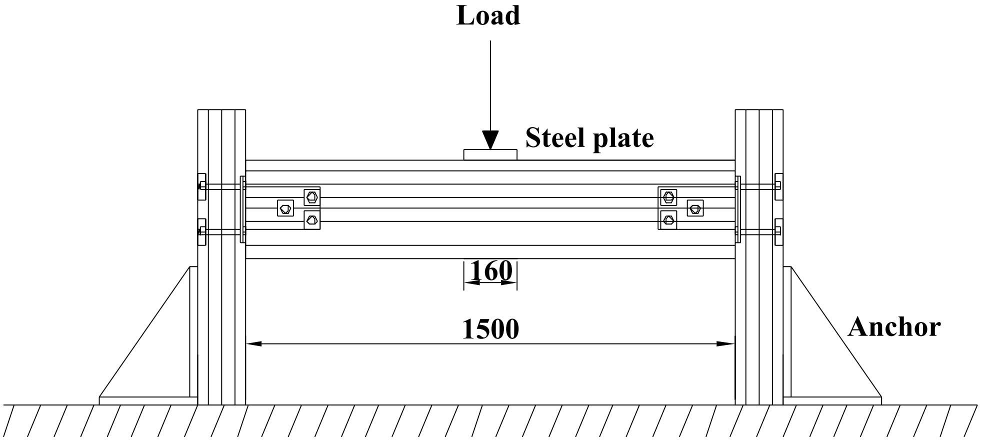

Fig. 7. Schematic diagram of the shear test for glulam beam-column joints (units: mm).

values with the tap-tone approach instead of the ultrasonic approach. Therefore, the tap-tone approach was applied for mechanical grading in this study. Results showed that 67.2% of the laminae were graded between L80 and L110, which can be designated for outer layer applications based on CNS standard procedures for glulam products (Table 1). In addition to 23.4% of laminae with better grades, results showed that Japanese cedar is an appropriate plantation timber species for glulam production. Laminae were also visually graded by the knot ratio as required by the machine evaluation process, and better grades were obtained, i.e., 38.8% of first grade and 46.8% of second grade, which showed their adequacy for the glulam process. When long pieces of laminae (3600 mm) were cut into 900- and 1500-mm lumber sizes before the lamination process, the measured nondestructive MOE values changed. Forty-five percent of short laminae showed higher nondestructive MOE values compared to the original long pieces, and 55.0% of laminae showed lower values. Huang et al. (1993) reported that nondestructive MOE values and sound velocity measured by the tap tone approach remained the same for ratios of length to width of lumber of > 7.3. In this study, ratios of 30, 12.5, and 7.5, respectively, were used for the 3 different lamina lengths, and the resultant nondestructive MOE values were applicable.

Shear resistance of glulam joints

Glulam column and beam structures were fabricated with T- and flat-type steel connectors using 2, 3, or 5 bolts as fasteners at each joint. The results of the shearing performance were as follows.

(I) Effects of connection plate type

The maximum shear load capacity (P_{max}) and yield strength for the glulam members joined with flat steel connectors were 34 and 48% on average, respectively, higher than those with T-type steel connectors (Table 2). The yield strength can be estimated as the intersection between a line (III) tangent to the load-deformation curve which is parallel to a line (II) passing through the 0.4 and 0.9 P_{max} points and a line (I) passing through the 0.1 and 0.4 P_{max} points (Fig. 8). Nakashima et al. (2006) reported a maximum load of 60.8 kN obtained for a Japanese cedar glulam beam-column structure joined with double 3.2-mm shear plate connectors and four 12-

Table 1. Grade distribution of Japenese ceder laminae processed from plantation timber aged 35 yr

Machine grade	Knot ratio 17% (no. of pieces)[1)]	Knot ratio 25% (no. of pieces)	Knot ratio 33% (no. of pieces)	Decay (no. of pieces)	Total (no. of pieces)	Percentage (%)
L180	1	0	0	0	1	0.3
L160	3	4	1	0	8	2.7
L140	12	9	1	1	23	7.7
L125	19	15	3	1	38	12.7
L110	33	37	2	3	75	25.1
L100	17	20	9	3	49	16.4
L90	14	22	4	4	44	14.7
L80	14	16	1	2	33	11.0
L70	3	15	2	1	21	7.0
L60	0	1	2	1	4	1.3
L50	0	1	2	0	3	1.0
Total (no. of Pieces)	116	140	27	16	299	
Percentage (%)	38.8	46.8	9.0	5.4		

[1)] The knot ratio rating was based on the CNS 11031 requirement.

Table 2. Joint strength of Japanese cedar glulam structures assembled with slotted metal connectors using different numbers of fasteners

Joint type	Max. load (kN)	Yield strength (kN)	Initial stiffness ($kN\cdot mm^{-1}$)
T-2	$42.1\pm4.2^{b1)}$	21.3 ± 1.8^{c}	2.6 ± 0.3^{d}
T-3	43.4 ± 2.8^{b}	21.6 ± 2.3^{c}	10.6 ± 1.1^{abc}
T-5	59.6 ± 5.4^{a}	29.2 ± 3.5^{bc}	14.7 ± 4.3^{a}
Flat-2	64.5 ± 4.0^{a}	34.1 ± 1.6^{ab}	5.3 ± 1.6^{cd}
Flat-3	68.8 ± 7.0^{a}	40.0 ± 5.5^{a}	7.5 ± 0.2^{bcd}
Flat-5	60.9 ± 3.8^{a}	32.5 ± 3.1^{ab}	11.8 ± 1.6^{ab}

T, T-type connector; Flat, flat-type connector.
[1)] Tukey's grouping $\alpha = 0.05$, a > b > c.

mm fasteners. Their results were also close to results of a flat-type connector with a 5-mm thickness and were better than the T-type connector assemblies in this study. The difference may have been due to weaker stiffness of the T-type connector with a narrow depth especially for cases of the 2- and 3-fastener joints.

The average initial stiffness of the joint assembled with a flat-type connector was 88% that with a T-type connector. Hayashi et al. (2002) reported that an improvement in the initial stiffness was achieved from 4.86 to 7.54 $kN\cdot m^{-1}$ when a steel plate was used to reinforce the bottom forming an L-type connector to support the Japanese cedar glulam beam ends. However, this would leave the connection exposed, which might be a fire risk. Some failure or large deformation occurred at the welded location of the T-type metal connector, while the greatest deformation only occurred around the bolt holes for the flat-type connector (Fig. 9). It was noted that the bolt located at the lower corner of steel plate experienced severe deformation and was thought to sustain high vertical loads. Figure 10 shows a glulam beam that failed

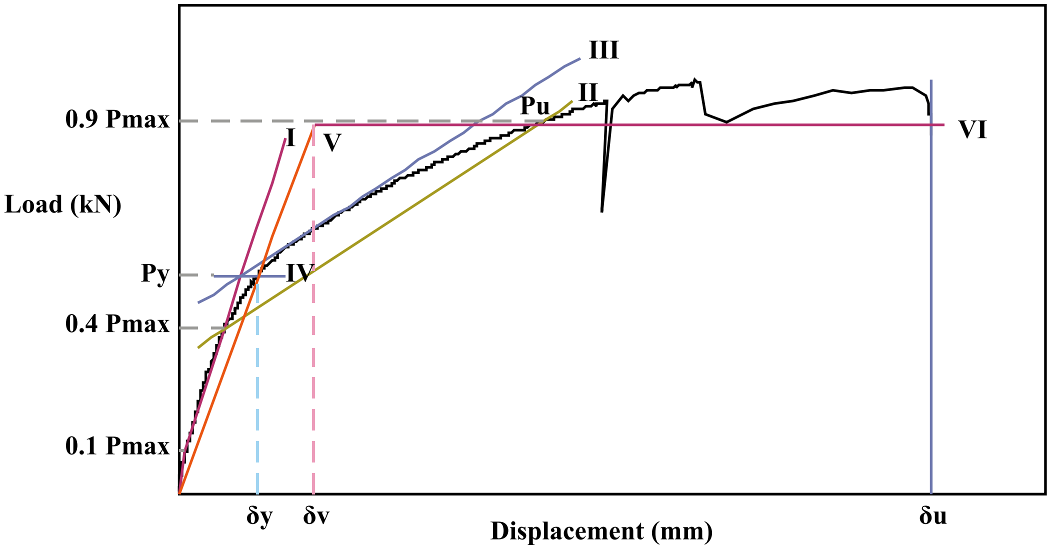

Fig. 8. Estimation of strength properties of a glulam joint subjected to a shear load.

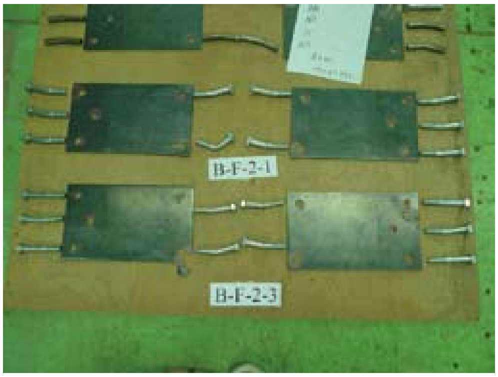

Fig. 9. Failure of flat-type metal connectors assembled with 2 bolts on a beam member.

Fig. 10. Horizontal shearing failure on a glulam beam member assembled with 3 bolts.

as a horizontal split through the bolt holes. The split began at the bolt hole nearest the neutral surface of the beam member or at the lower bolt hole, and then propagated along the wood grain. Therefore, the shear strength of the wood may play a key role in resisting a shear load.

The deformation energy of glulam joints was measured over the maximum load until dropping to $0.8P_{max}$ based on the elastic-plastic behavior (lines V and VI) estimated from the relationship between the applied loads and the resulting deformation. Glulam members assembled with a flat steel connector showed a dissipated energy value of 1755.2 kN·mm, which was 111.7% on average higher than that with the T-type steel connector (Table 3). This indicates that a fragile tendency can be expected for joints assembled with T-type connectors. The ductility factor (μ) of a joint

Table 3. Structural characteristics of Japanese cedar glulam joints assembled with slotted metal connectors using different numbers of fasteners

Joint type	Energy (kN·mm)	Ductility factor	Structural characteristic factor
T-2	1811.8±292.7[ab1)]	4.96±1.30[a]	0.34±0.05[b]
T-3	441.7±52.6[b]	3.57±1.09[a]	0.42±0.07[b]
T-5	233.9±26.7[b]	1.68±0.70[b]	0.71±0.19[a]
Flat-2	2923.3±212.0[a]	4.30±1.13[a]	0.37±0.05[b]
Flat-3	1840.6±163.1[ab]	3.65±1.94[a]	0.44±0.13[ab]
Flat-5	501.6±187.3[b]	2.45±0.44[b]	0.51±0.06[ab]

T, T-type connector; Flat, flat-type connector.
[1)] Tukey's grouping $\alpha = 0.05$, a > b > c.

is defined as the ratio of the maximum deformation limit (δ_u) to the yield deformation limit (δ_v) as calculated from the test results. It is commonly used to measure the deformation capacity of joints and structures. The results indicated that the average value of the ductility factor for the glulam joint using T-type steel connectors was 3.40, which was similar to that of the flat steel connector. With a similar ductility factor but lower energy absorption, the joint fixed with the T-type connector would experience early splitting or failure during load application. The structural characteristic factor (D_s) can be obtained from the calculation of $(2\mu - 1)^{-1/2}$. The value of D_s also indicates the adequacy of ductility of a joint but with nonlinear expression, which is more sensitive to the non-ductile behavior of a material or joint. Pirvu et al. (2000) suggested a scale of 0.3~0.45 for wooden portal frames, where 0.3 indicates excellent ductility. Between these 2 developed connectors, average values of D_s of joints were 0.49 for the T-type connector and 0.44 for the flat-type connector, which showed a more-acceptable structural performance.

(II) Effects of the number of fasteners

The placement of bolts at the joints between the glulam beam and column members followed the code requirements. The maximum shear load capacity and yield strength of glulam structures assembled with 5 bolts at each joint were significantly higher than those with 2 or 3 fasteners when using the T-type steel connectors. However, no significant difference was found among joints assembled with 2, 3, and, 5 fasteners using the flat-type steel connectors. In general, the shear load capacity of the joint did not show a linear improvement with an increasing number of fasteners. This indicated that uneven loads were distributed to each fastener, and early failure would occur at locations that reached a critical load.

On the other hand, the initial stiffness of joints improved as the number of bolts increased for both connector types. There were 2.8- and 4.0-times the initial stiffness on average for glulam structures assembled with 3 and 5 fasteners, respectively, at each joint compared to that with 2 fasteners. The major failure was horizontal shearing on the beam member. Cleavage was always initiated from the bolted sink hole near the bottom side of a member for joints assembled with both 2 and 5 fasteners, while members assembled with 3 fasteners split along the neutral surface. Further, the deformation energy of each glulam joint was significantly reduced as the number of fasteners increased. There were only 43.7 and 15.1% of dissipated energy for glulam structures assembled with 3 and 5 fasteners at each joint, respectively, compared to that with 2 fasteners. Figure 11 shows the non-linear relationship between the dissipated energy and the number of fasteners used in a joint. This indicated that a rigid tendency can be expected for a joint assembled with more fasteners which might be sensitive to a seismic event. Ductility factor values of 4.63 and 3.61 on average for glulam members fastened with 2 or 3 bolts, respectively, on each joint showed larger plastic deformation, while a ductility factor value of 2.07 for glulam members fastened with 5 bolts on each joint showed rigid deformation. Figure 12 shows the non-linear relationship between the ductil-

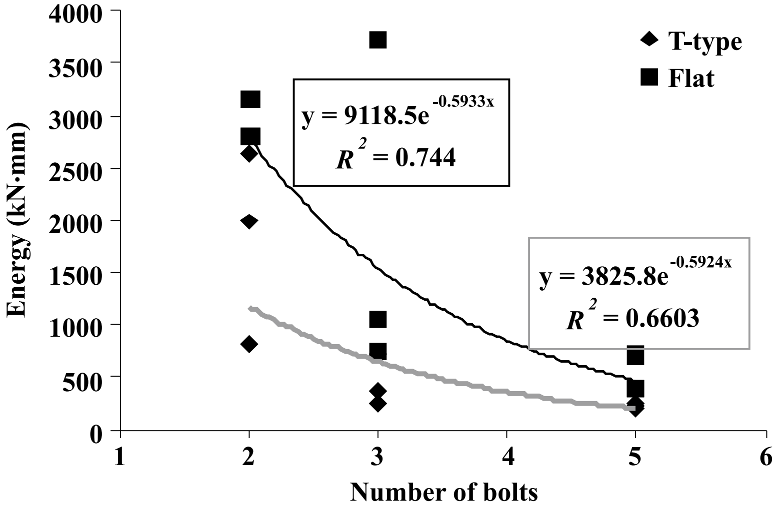

Fig. 11. Effects of the number of bolts on the dissipated energy of Japanese cedar glulam joints using flat- and T-type connectors.

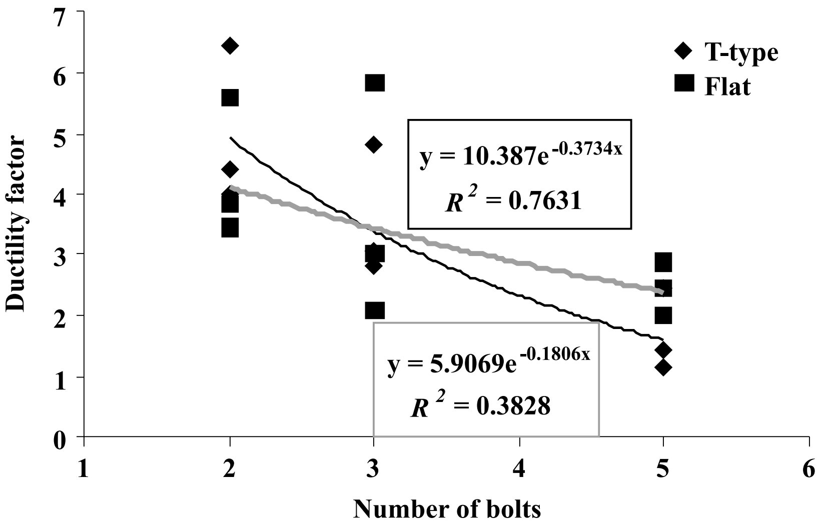

Fig. 12. Effects of the number of bolts on the ductility factor of Japanese cedar glulam joints using flat- and T-type connectors.

ity factor and the number of fasteners used in a joint subjected to a shear load. The higher dissipated energy and ductility factor for joints assembled using fewer fasteners suggested better performance to resist seismic forces. An adequate range for the structural characteristic factor is 0.30~0.45. The results indicated that joints fastened with 2 and 3 bolts were within this range, at 0.34 and 0.44, respectively, and also showing better structural performance than joints fastened with 5 bolts (Table 3).

CONCLUSIONS

Timber from a 35-yr-old Japanese cedar plantation is suitable for making structural glulam members with a symmetrical layout of laminae ranging from L80 to L110 or better grades in this study. Glulam column and beam structures fabricated with embedded flat-type steel connectors at each joint showed a better maximum shear load capacity, yield strength, initial stiffness, and dissipated energy compared to those with T-type connectors. With a similar ductility factor but lower energy absorption, the glulam joint fixed with the T-type connector would experience early splitting or failure during load application. Between these 2 developed connectors, joints assembled with flat-type connectors showed a more-acceptable structural performance in resisting a shearing load based on the structural characteristic factor evaluation. The influence of the number of bolts on the maximum shearing capacity and yield strength of a glulam joint became profound with the T-type connector design. The initial stiffness of glulam joints improved as the number of bolts increased, but the deformation energy of each joint was significantly reduced. Both an adequate ductility factor and the structural characteristic factor confirm better shear resistance of joints fixed with fewer fasteners.

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