Research paper

Evaluation of the Moment Splicing Performance of Beam-to-Beam-Connected Structural Glulam Using Japanese Cedar[1)]

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【Summary】

A symmetrical mixed-grade composition glulam was fabricated using 30~40-yr-old Japanese cedar plantation timber in this study. Each glulam with size of 140×304×3000 mm was connected end-to-end longitudinally to form a 6000-mm beam member. Two types of metal connectors were designed for moment splicing at the beam connection with various numbers of fasteners. The beam-to-beam-connected member was subjected to a 4-point flexural test with 6 stages of repeated loading and a monotonic loading application. Results indicated that glulam beams joined with U-type connectors had 14 and 22% higher modulus of rupture (MOR) and modulus of elasticity (MOE), respectively, than those with T-type connectors. The MOR of beam-to-beam-connected glulam members assembled with both 6 and 8 fasteners using the T-type connector increased by 23% compared to that with 4 fasteners, and 43% when using the U-type connector. MOR values of beam-to-beam-connected glulam members with T- and U-type connectors reached 56~71 and 57~87%, respectively, of the given strength capacity for an assigned glulam grade. In the case of the MOE, values were 71~84% for T-type connection groups and 89~98% for U-type connection groups compared to the given MOE of the assigned grade for Japanese cedar. Stable envelop curves indicated that glulam beams connected with the T-type connector and 4 fasteners had a 35% lower bending load capacity and 37% lower stiffness among different connector types and various numbers of fasteners.

Key words: connection, glulam, bending strength, Japanese cedar.

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研究報告

柳杉集成材梁梁接合之抗彎矩性能評估[1)]

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摘 要

本研究利用30~40年生柳杉造林木製造對稱異等級結構用集成材，並以尺寸為140×304×3000 mm之集成材以縱向端接組成6000 mm長之梁構材。在梁接合處以所設計之兩種金屬連結件配合不同數量之扣件進行彎矩補強，所組成之梁-梁構材以6階段反覆載重及單向載重進行4點抗彎試驗。結果顯示，以U型連結件組合之集成材梁構材的彎曲破壞強度及彈性模數分別較以T型連結件組合之梁構材高出14及22%。在以T型連結件利用6或8支扣件組合之梁構材，其彎曲破壞強度比以4支扣件組合者改善23%，而在以U型連結件組合條件，則可以改善43%。依柳杉結構用集成材指定等級之強度容量而言，分別以T型及U型連結件組合之梁-梁接合集成材構材其彎曲破壞強度可以達到56~71及57~87%。在彎曲彈性模數方面，以T型連結件組合時可達71~84%，以U型連結件組合時可達89~98%。由穩定包封曲線顯示，T型連結件利用4支扣件組合之集成材梁構材，其彎曲載重容量較其他扣件數量或是連結件型式低35%，在剛性方面低37%。

關鍵詞：接合、集成材、抗彎強度、柳杉。

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INTRODUCTION

In many large commercial and public wood building applications, wood structures are sometimes designed using short beams joined end-to-end longitudinally for a long span or as an extension from the cantilevered end of a continuous beam member for cost and material efficiency. In such cases, location of the beam-to-beam connection and structural joint performance are major considerations for designing such wood framing works. Some research dealt with the bending moment resistance of a cantilevered wood beam member connected to a column or column to a sill member using bolts or pins when subjected to a bending load (Yeh et al. 2008, 2012a, Nakata and Komatsu 2009a, b). The shearing capacity of post-beam connections also needs to be considered in a short beam or short span application (Hayashi et al. 2002, Nakashima et al. 2006, Yeh et al. 2012b). Further, suggestions on moment splicing at the butt joint of beam-to-beam connections can be found in some technical notes for design or construction practice (DeStrefano 2004, APA 2007). However, little research related to moment splicing capacity evaluations of beam-to-beam connections was found.

Yeh et al. (2007) studied the tension performance of Japanese cedar glulam connections and indicated that the allowable strengths of 15- and 18-mm bolts were 18.3 and 23.5% of the measured yield bearing strength, respectively. Yeh et al. (2008) also reported that the bending moment capacity of glulam post and beam member connections could improve by 67.4 and 53.0% using steel plate connectors with 6 bolts of 18- and 15-mm diameters, respectively, compared to values with 4 bolts. The failure mechanism for post and beam structures and tension connections mentioned above seems difficult to match the expected force transmissions in the case of beam-to-beam connections. Hayashi et al. (2002) suggested that shearing capacities of joints were influenced by the depth of the glulam, type of connector, and type of joint. Three failure modes in glulam post-beam and girder-beam structures assembled with a standard metal connector were reported, and 1 major failure mode was found when assembled with Haratec connectors. This confirmed the influence of connector types on the structural performance of a connection. Further, allowable stresses of different fasteners in wood member connections as specified in design codes are limited in tension and shearing applications (Ministry of the Interior 2011). On the other hand, resisting stresses incurred at the connection becomes complex when wood structures are subjected to a bending moment load, and further investigation of full size members is suggested to assess their structural performance. Usually, positions of beam-to-beam joints are critical to sustain a bending moment and are recommended to be located at beam sections with low moment loads for safety. Thus, it is suggested to examine the performance of moment splicing of glulam connections within a pure bending zone along the beam span.

In this study, structural glulam was manufactured using local Japanese cedar plantation timber. Different metal connectors were designed that could be inserted into the glulam member ends to prevent a negative impression on the exposure of the connection hardware for interior design and to reduce the possibility of heating connector and fasteners causing strength loss during a fire. Glulam beams connected end-to-end longitudinally with different numbers of fasteners were developed to investigate the structural adequacy of glulam joints based on the moment resisting performance in relation to the mechanical fastener efficiency.

MATERIALS AND METHODS

Materials

Japanese cedar (*Cryptomeria japonica*) logs were harvested at the age of 35~40 yr from a forest plantation located in the no. 7 forest compartment in Hsinchu Forest District. The size of the laminae was 38×140 mm after being sawn, kiln-dried, and planed. The dynamic modulus of elasticity (MOE) of laminae was first measured using a tap-tone approach through Fast Fourier Vibration Analyzer software (Fakopp Enterprise, Agfalva, Hungary). Each lamina was then assigned a grade based on the dynamic MOE values for the further layout process of lamina combinations. Resorcinol phenol formaldehyde (RPF) adhesive mixed with a hardener of paraformaldehyde in a ratio of 100: 15 was used for glulam lamination. The adhesive was applied at a rate of 250 g m^{-2} with an applied pressure of 0.98 MPa for 6 h during glulam fabrication. A symmetrical mixed-grade composition glulam with a size of 140×304×3000 mm was assembled for beam members following the CNS 11031 procedure for structural glulam manufacturing. Two glulam members were then connected end-to-end with an inserted metal connector forming a long beam specimen with a joint at the beam center. Two types of steel connectors were designed, i.e., T- and U-types, using 5- and 9-mm thick steel plates for the connection (Figs. 1, 2). The beam-to-beam connections were further jointed with 4, 6, and 8 pin or bolt fasteners at each member end (Table 1). The metal connectors also provided additional moment splicing at the bottom plate through lag screws. The diameter of both the pin and bolt was 15.88 mm, and the lengths were 115 and 110 mm, respectively. Determination of SS400 steel connector sizes and layouts for fastener locations followed spacing requirement for the bolt application as specified in building codes (Ministry of Interior 2011).

Methods

Several basic tests were carried out with solid wood to provide information related to mechanical properties of Japanese cedar. Bending specimens with a size of 38×140×620 mm were tested using the CNS454 method. A shear test of solid wood

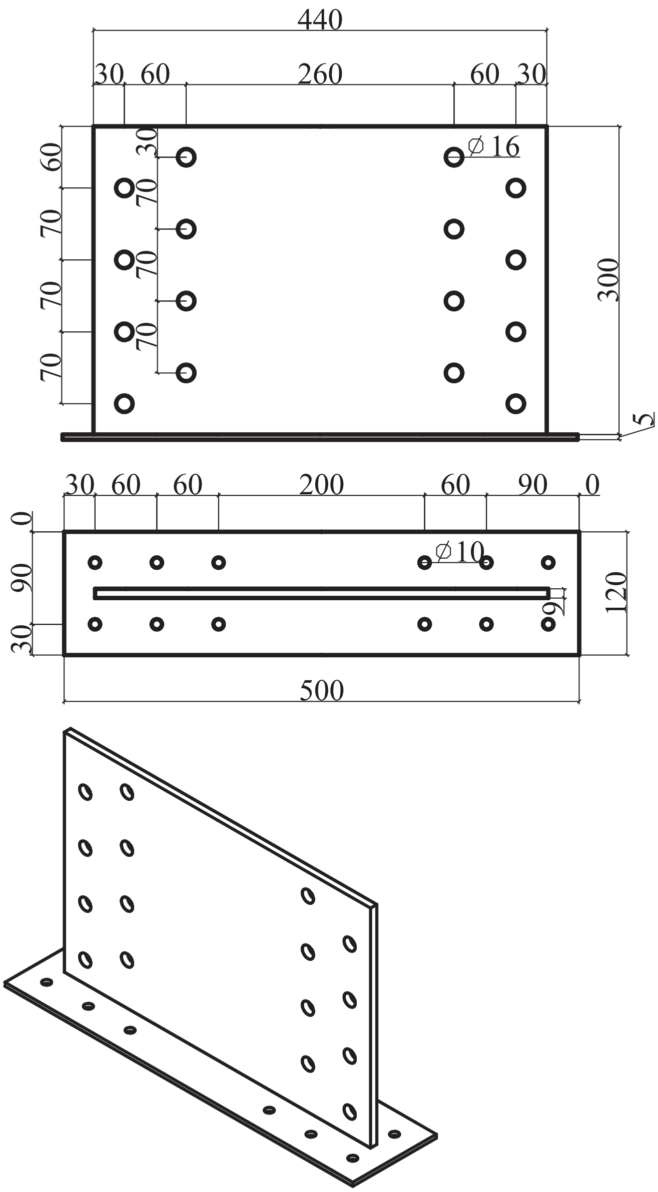


Fig. 1. Design of T-type connectors for a Japanese cedar glulam beam-beam joint (8 fasteners). (units: mm)

was performed using the CNS 455 method, and a wood block cleavage test was carried out using the CNS 6716 method. Both wood grain orientations, i.e., radial and tangential, were considered in the shear and split tests, and each test condition had 24 replicates. Further, a wood block shear test for adhesion was also investigated for glulam specimens using the CNS 11031 method with 100 replicates.

For the full-size bending property evaluation, a glulam beam specimen was joined end-to-end with a 10-mm wide slot to accommodate 9-mm thick T-type metal connectors and two 6-mm wide slots for 5-mm thick

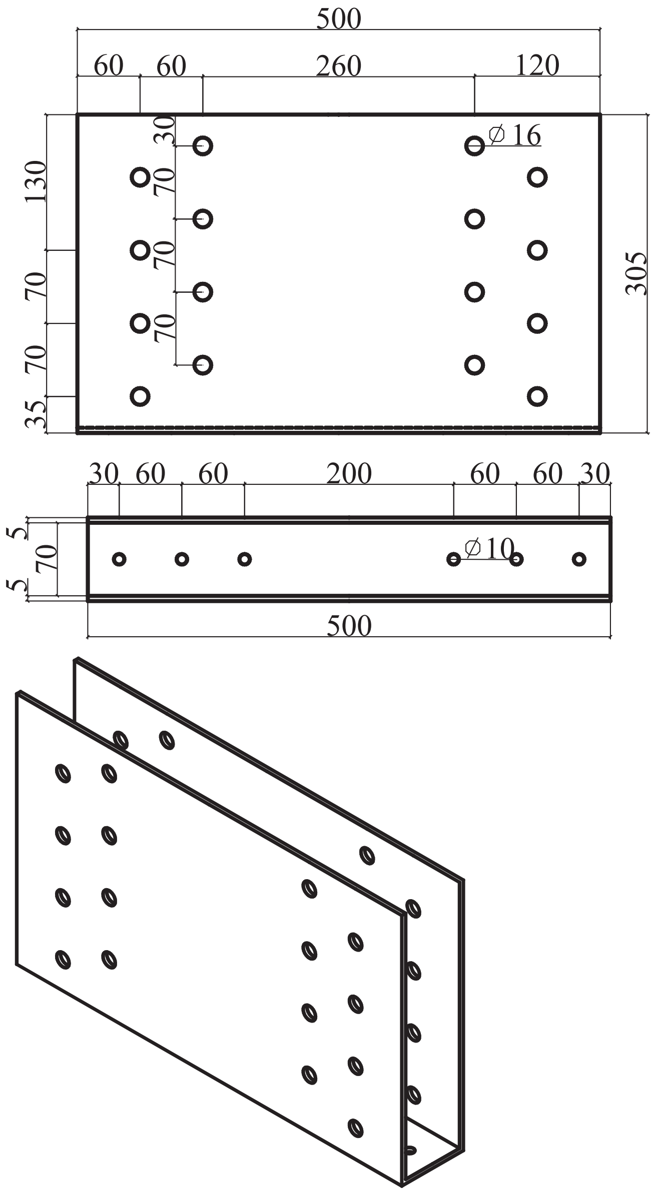


Fig. 2. Design of U-type connectors for a Japanese cedar glulam beam-to-beam joint (8 fasteners). (unit: mm)

Table 1. Test conditions of beam-to-beam connections fastened with pins/bolts for Japanese cedar glulam

Joint type	Size of connector (mm)[1)]	Number of pins	Number of bolts	Washer (mm)	Number of lag screws
T-4	120×300×320×9	3	1	50×50	4
T-6	120×300×440×9	5	1	50×50	6
T-8	120×300×440×9	7	1	50×50	6
U-4	80×305×380×5	4	0	0	2
U-6	80×305×500×5	6	0	0	3
U-8	80×305×500×5	8	0	0	3

T, T-type connector; U, U-type connector. The number of fasteners indicated in the table was used at 1 end of the glulam.

[1)] Size of connector is width×height×length×thickness.

U-type metal connectors to form a 6000-mm beam (Figs. 3, 4). A gap of 20 mm between the 2 glulam ends at the joint of the beam specimen was maintained to make sure a resisting moment could be transferred through the connectors and fasteners only. One bolt with 3, 5, and 7 pins was fastened at each glulam end for T-type connections and 4, 6, and 8 pins at each end for U-type connections. Due to difficulties in inserting a bolt into U-type connections and the small likelihood of it becoming loose with a pin fastener, the bolt fastener was not applied with U-type connections. Further, in the case of U-type connections, there were 4 or 6 lag screws of a size of 9 (ψ) by 127 mm (length) fastened beneath the beam bottom to reinforce the moment splices, while 8 or 12 lag screws were used for reinforcing T-type connections. A hydraulic loading machine with a capacity of 500 kN was used for the flexural test. Figure 4 shows a 4-point loading approach that was applied to a beam specimen in the flexural test with a loading span of 1220 mm and a full span of 5472 mm. A repeated loading protocol with 6 stages was applied to a beam specimen at beam deflections of 1/450, 1/300, 1/200, 1/150, 1/100, and 1/75 radians (Fig. 5). The loading speed was set to 1.5 kN/min. The characteristic bending properties of the beam-to-beam-connected glulam were calculated based on the CNS11031 method. In total, 6 conditions were examined with 3 replicates for each beam-to-beam connection configuration.

RESULTS AND DISCUSSION

Basic properties of solid wood

The density of Japanese cedar lumber in an air-dried condition was 0.48±0.06 g cm^{-3}. The moisture content of sawn lumber was 11.0±0.3%. The average MOR of Japanese cedar laminae was 77.4±8.3 MPa, and the average MOE was 11.48±1.39 GPa. Shear strength values on radial and tangential sections of solid wood were 9.5±1.7 and 8.8±1.4 MPa, respectively. The shear resistance of a glued interface of wood blocks cut from glulam members was 10.0±1.3 MPa, which was higher than the minimum value of 5.4 MPa required in CNS 11031 for manufactured glulam products from Japanese cedar species (BSMI 2006). Cleavage resistance values of solid wood in the radial and tangential sections were 26.9±5.8 and 28.1±5.4 $N \cdot mm^{-1}$, respectively. Results of cleavage resistance of the harvested Japanese cedar were

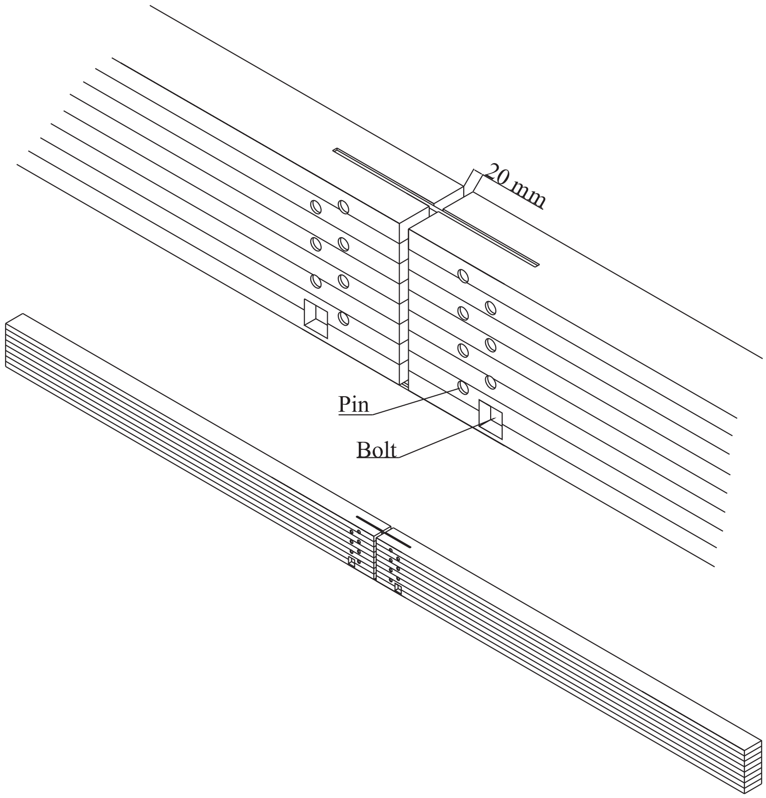


Fig. 3. Schematic diagram of Japanese cedar glulam beam-to-beam connected longitudinally with the T-type metal connector. (8 embedded fasteners)

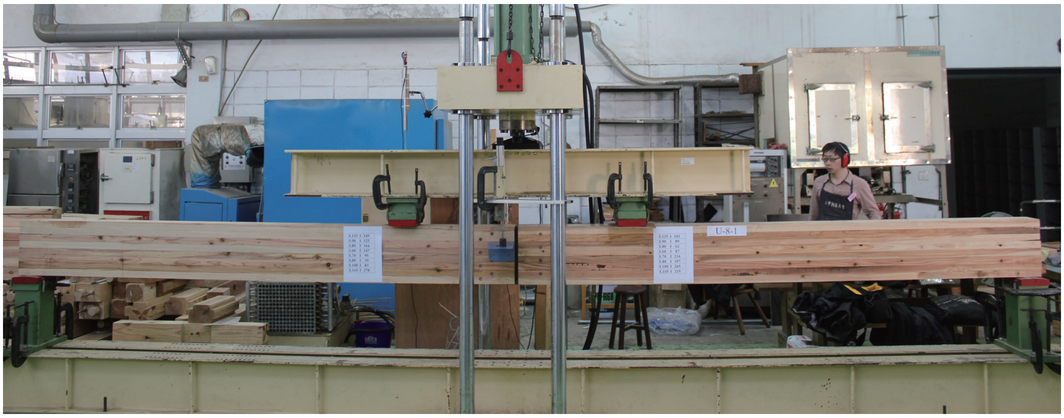
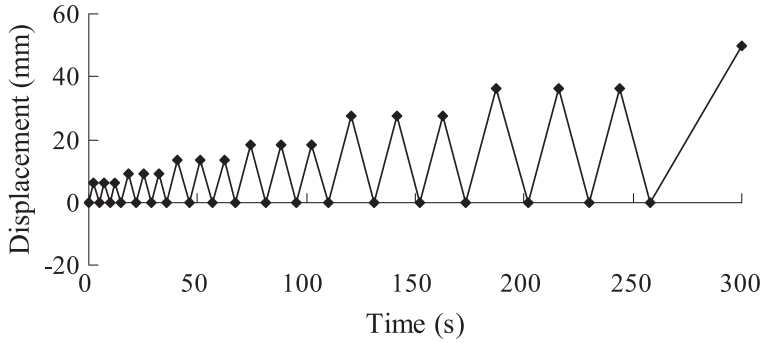


Fig. 4. Four-point repeated bending test for Japanese cedar glulam member with a beam-to-beam U-type connection at the center.

lower than reported values by Wang (1986) and Yeh et al. (2012b) indicating a risk of wood splitting at the joint, especially when it is subjected to an external force perpendicular to the wood grain. Hayashi et al. (2002) also reported that glulam joints had different



Stages	Cycles	Deflection (radian)
1	3	1/450
2	3	1/300
3	3	1/200
4	3	1/150
5	3	1/100
6	3	1/75
7	1	fail

Fig. 5. Schematic diagram of the repeated loading protocol for a flexural test of beam-to-beam-connected glulam member.

maximum loads and failed in a shear or cleavage split depending on the wood species and layouts of the laminae.

Processed Japanese cedar laminae were classified into L40 to L140 grades based on the measured MOE. Tsai and Yeh (2007) reported that nondestructive MOE of 2×6 China fir lumber obtained using a tap-tone approach was 0.16~2.8% higher than the MOE from static flexural test results. They suggested acceptable MOE values were obtained with the tap-tone method instead of the ultrasonic method. Consequently, the tap-tone method was employed for lamina grading in this study. Results showed that most laminae were graded between the L70 and L110 grades with most laminae of the L80 grade (18.5%), followed by the L100 grade (17.5%) (Fig. 6). According to the outer layer application for lamina layout as specified in the CNS standard procedure for glulam products, Japanese cedar laminae obtained from the Hsinchu Forest District were adequate to make third-grade glulam. Consequently, Japanese cedar glulam with a grade of E75-F240 was fabricated in the study and was shown to be an appropriate plantation timber species for a medium-strength grade of structural glulam products.

Failure of glulam beam connections

All Japanese cedar glulam beam specimens failed at the center position where a connector was located that was subjected to 4-point loadings. Five major failure modes were identified, i.e., splitting at the lag screw splicing, wood shear failure along bolted holes, and splitting from pinned holes at the outer, middle, and inner lamina layers (Table 2). Large bending deflections at the beam center resulted with both T- and U-type connections which caused high-tension stress

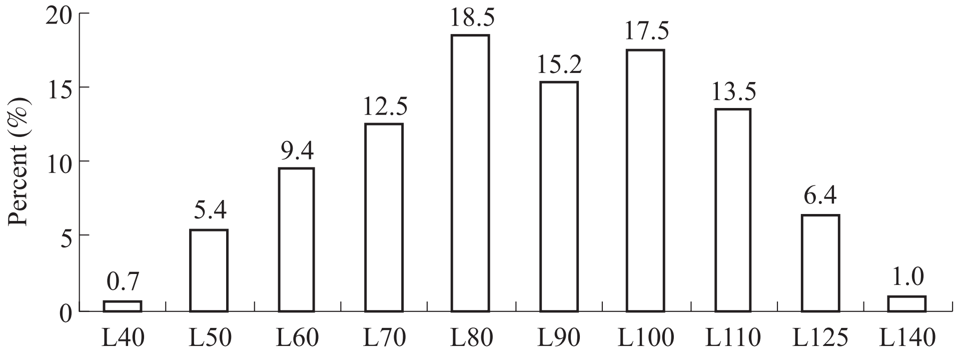


Fig. 6. Frequency distribution of the modulus of elasticity graded Japanese cedar laminae.

Table 2. Failure modes of beam-to-beam-connected glulam members subjected to flexural loading

Failure mode	T-type connection				U-type connection			
	T-4	T-6	T-8	Total	U-4	U-6	U-8	Total
Split at screw splicing	3 (33.3)[1)]	3 (33.3)	3 (33.3)	9 (100)	3 (33.3)	3 (33.3)	3 (33.3)	9 (100)
Shear along bolted hole	3 (33.3)	3 (33.3)	3 (33.3)	9 (100)	0	0	0	0
Split at outer laminae	0	1 (11.1)	0	1 (11.1)	3 (33.3)	3 (33.3)	3 (33.3)	9 (100)
Split at middle laminae	3 (33.3)	3 (33.3)	3 (33.3)	9 (100)	3 (33.3)	3 (33.3)	3 (33.3)	9 (100)
Split at inner laminae	0	3 (33.3)	3 (33.3)	6 (66.7)	2 (22.2)	2 (22.2)	3 (33.3)	7 (77.8)

[1)] Values in parentheses are in percentage (%).

beneath the glulam members. Consequently, shear deformation of lag screw shanks and splitting of wood from each screw hole resulted for all screws ranging from 4 to 12 pieces at the connections (Fig. 7). It was suggested that reinforcing the moment splice at the end-to-end connection is important to improve flexural performance of integrated glulam beams. In the case of T-type connections only, all glulam beams also failed in local wood shear where an embedded bolt was fastened (Fig. 8). The resulting tension at the lower beam cross section was resisted by the bolt and washer, which in turn caused pushing against the wood surrounding the embedded bolt hole. The embedded depth at bolted holes might reduce the member's effective cross sectional area to resist the resulting bending moment. Consequently, a longer end distance for a fastener beyond 120~180 mm might be required to improve the shear-resisting capacity or splitting, even when Japanese cedar specimens showed satisfactory shear strength for glulam products. It was noted that glulam beams with U-type connections split at both the outer and middle laminar layers starting from the pinned holes due to major internal tension and compressive stresses distributed across critical beam sections, i.e., the top and bottom sides (Fig. 9).

Fig. 7. After the connector and fasteners were removed, wood splitting was shown along the lag screw holes beneath the glulam member.

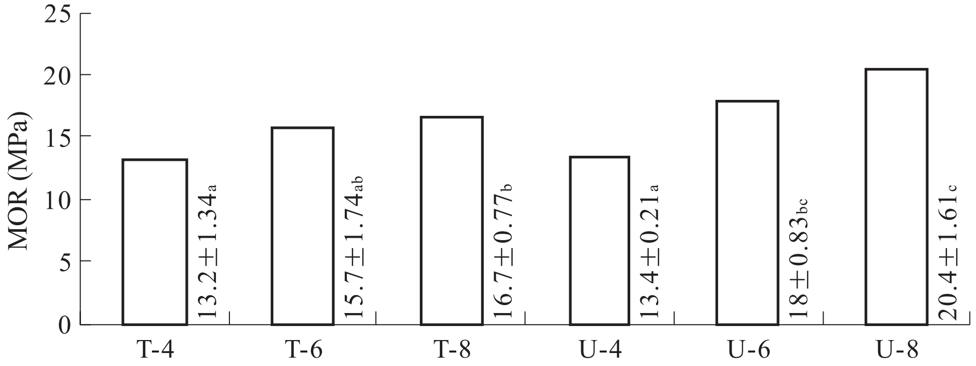
Fig. 8. Shear failure of middle-layer laminae at the bolt hole with a processed embedment.

Fig. 9. Split at the outer laminae on both the top and bottom sides of the beam-to-beam connection.

Bending properties in monotonic loading

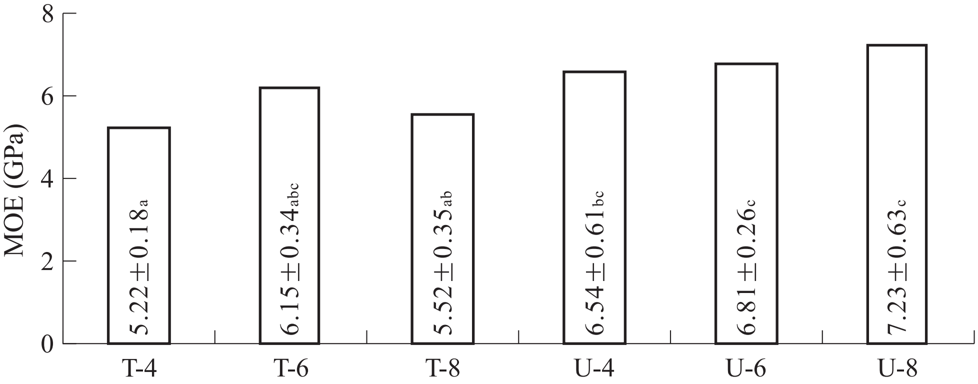
Beam-to-beam connected specimens were loaded to failure monotonically after experiencing 6 stages of repeated loadings. The resulting bending MOR is shown in Fig. 10. A significant improvement in the MOR was found as the number of fasteners increased. The MOR of T-6- and T-8-connected beams was 23% on average higher than that of the T-4 group. The MORs of U-6- and U-8-connected beams were 34 and 52%, respectively, higher than that of the U-4 group. In general, glulam beams joined with U-type connections were stronger than were those with T-type connections, i.e., 14% on average. It is suggested that pin- or bolt-supported 2 steel plates of the U-type connector inside the beam section could transmit forces more evenly than could a single plate of the T-type connector. Consequently, the U-8-connected beam had the highest MOR values among the 2 connectors and 3 different numbers of fasteners used in the study. Yeh et al. (2012b) also reported that the shear resistance of glulam connections was highly dependent on the type of connector. In that study, differences of 34% in the maximum shear load capacity and 48% in the yield strength were also observed between flat and T-type connectors.

A similar trend was found for the MOE, as glulam beams joined with U-type connections were stiffer than those T-type connections by 22% on average (Fig. 11). However, an effect of the number of the fasteners, i.e., 4, 6, and 8 pieces at each beam end, on the connected beam stiffness was not found. On the other hand, Yeh et al. (2012b) indicated a significant difference in the initial stiffness of connections obtained due to different numbers of fasteners assembled between glulam post and beam members in shear tests. There were 2.8- and 4.0-times the initial stiffness for glulam structures assembled with 3 and



*Tukey's HSD, α = 0.05, a < b < c

Fig. 10. Modulus of rupture (MOR) of end-to-end-connected Japanese cedar glulam beams with slotted metal connectors (T- and U-type) using different numbers of fasteners (4, 6, and 8).



*Tukey's HSD, α = 0.05, a < b < c

Fig. 11. Modulus of elasticity (MOE) of end-to-end-connected Japanese cedar glulam beams with slotted metal connectors (T- and U-type) using different numbers of fasteners (4, 6, and 8).

5 fasteners at the connections, respectively, compared to that with 2 fasteners. Therefore, it is suggested when fasteners increase to a certain number, the influence on the connection stiffness may become less critical.

Compared to the criterion for the E75-F240 grade of symmetrical mixed-grade composition glulam, the MOR values of Japanese cedar beam-to-beam-connected specimens respectively reached 56~71 and 57~87% of the required capacity for T- and U-type connectors. In other words, at least 2/3 of the loading capacity of a glulam beam can be maintained by connecting end-to-end with designed inserted metal connectors using 6 or 8 fasteners. For the MOE of longitudinally beam-to-beam-connected glulam, values were 71~84% for T-type connection groups and 89~98% for U-type connection groups compared to the assigned MOE for the glulam grade. It is suggested that a more-even stress distribution from the U-type metal connectors, with 2 inserted plates could reduce large deformation around the fastener holes and prevent early split failure of beam members.

Bending properties with repeated loading

The beam-to-beam-connected glulam specimens were subjected to 6 stages of repeated load application from 1/450 to 1/75 radians. The relationship between flexural loads and deflections of Japanese cedar glulam beams assembled with the designed connectors is shown in Fig. 12. Basically the tendency of continuously increasing the load resistance with the applied beam displacement at each stage was similar to the resultant slope in previous stages. A large residual beam deflection occurred after releasing the first loading for each stage, indicating that certain joint plastic deformation or damage had resulted around the fastener holes and connectors. Further residual beam deflections caused by the subsequent 2 loadings at every stage were minor. Figure 12 also shows that the loading

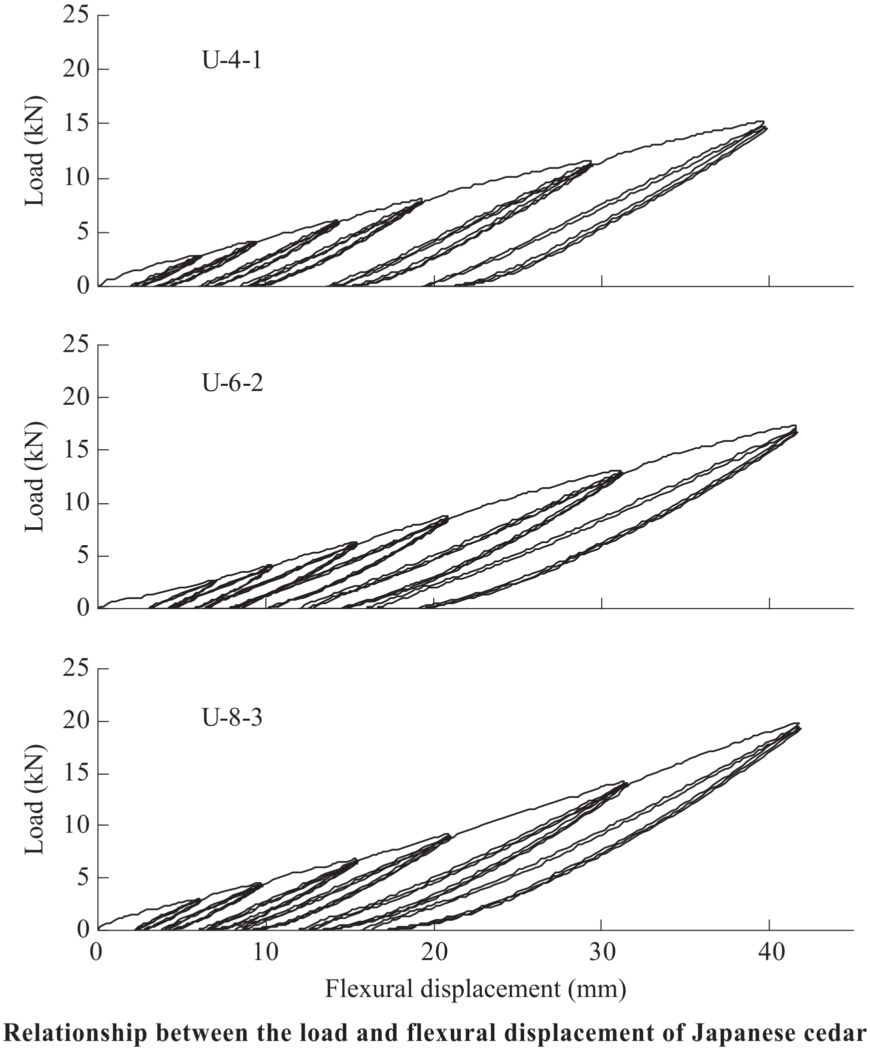


Fig. 12. Relationship between the load and flexural displacement of Japanese cedar glulam beams joined with U-type connectors subjected to a repeated loading application.

resistance of beam-to-beam-connected specimens increased during the repeated loading application as the number of fasteners at the joint increased.

An initial envelop curve was estimated from the resultant maximum load at each first loading cycle of every loading stage when a glulam beam was subjected to 6 stages of the repeated loading application. It shows changes in the original stiffness of the wood structure under escalated loads and was used to describe the rigidity of wood-framed shear walls when subjected to a series of lateral cyclic loadings (Jang 2000, Yeh et al. 2003). The initial envelop curve can also be used to demonstrate the structural behavior of the resisting bending moment for a beam connection experiencing an intermittently increasing load history. Figure 13 shows initial envelop curves of Japanese cedar glulam beam-to-beam-connected specimens using T- and U-type metal connectors. Beams connected with the T-type connector with 4 fasteners showed a lower stiffness and loading capacity, while similar bending performances were found between the T-6 and T-8 groups. In the case of glulam beams connected with U-type connectors, the stiffness indicated obvious variations in resisting bending loads for the U-4 and U-8 groups. The resisting capacity of a wood structure is assumed to become stable after experiencing repeated low loads. A stable envelop curve of the glulam beam was then estimated from the resulting maximum load at each last loading cycle during the 6 stages of the repeated loading application in the

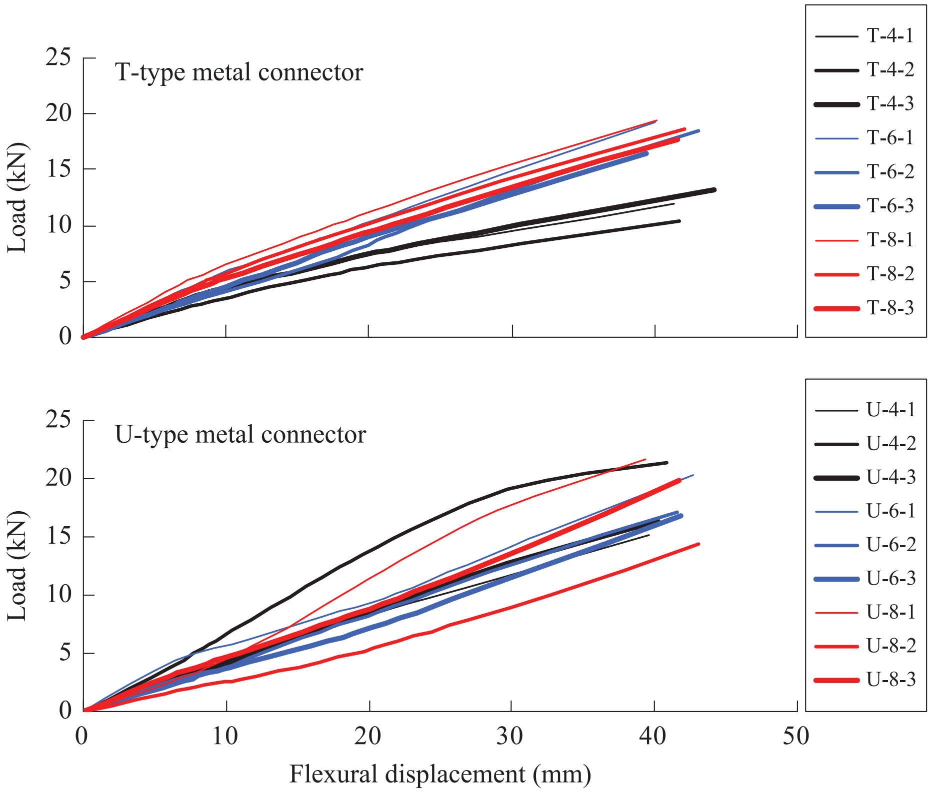


Fig. 13. Initial envelop curves of Japanese cedar glulam beams connected with T- and U-type connectors subjected to repeated loading.

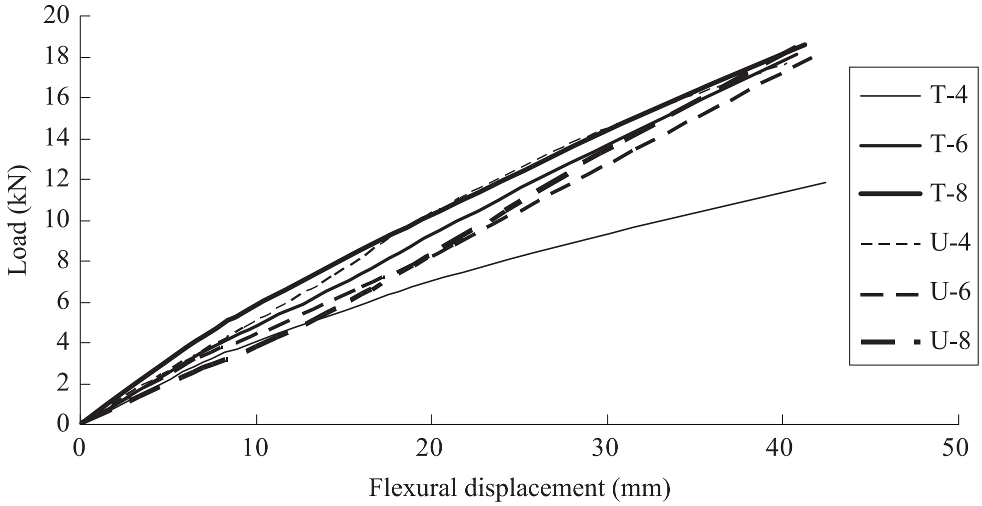


Fig. 14. Stable envelop curves of beam-to-beam joints subjected to repeated loading for structural Japanese cedar glulam members.

study. Figure 14 shows results of stable envelop curves of Japanese cedar glulam beams subjected to the repeated loading application in bending. Compared to the initial envelop curves, 97% of the loading capacity still remained. Most beam-to-beam connections showed similar bending moment resistance to repeated loading, while the T-4 group showed a lower bending load capacity (65% in average) and stiffness (63% in average) for the different connector types and various numbers of fasteners. This might have been due to the shorter connector size and layout of a single row of fasteners used in the T-4 group.

CONCLUSIONS

Timber from a 35~40-yr-old Japanese cedar plantation could provide major laminae ranging from L80 to L110 grades and was suitable for making medium-strength grades of structural glulam products with a symmetrical layout of laminae in the study. Glulam beams could be joined end-to-end longitudinally with short members using adequate connectors while maintaining required flexural performance. Beam-to-beam glulam members joined with inserted U-type connections showed higher MOR and MOE than these with T-type connections. At least 2/3 of the designed bending strength of a glulam beam could be maintained for a member connected with inserted metal connectors using 6 or 8 fasteners. An effect of the number of fasteners on the MOE of beam-to-beam glulam member was not found. A large residual flexural deflection resulted for beam-to-beam-connected glulam after being subjected to each first loading cycle during a repeated loading application. Only a minor reduction in the bending resistance resulted from further repeated load cycles at each loading stage, which showed the adequacy of the designed metal connectors for beam-to-beam connections.

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