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ORIGINAL ARTICLE

Investigation of the structural performance of glulam beam connections using self-tapping screws

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Abstract The characteristic strength properties of structural glulam connections assembled with self-tapping screws were examined following the ASTM testing procedure in the study. Four screw types with various numbers were designated at each connection of the beam–girder structure with different nailing schedules. The results indicated that the maximum load capacity and dissipated energy of a connection fastened with 10-mm self-tapping screws were higher than those with 8-mm screws. And, the screws with both double-threaded sections and fully threaded shanks were higher than those of single-threaded screws. An improvement on the initial stiffness of a connection was found when the number of self-tapping screws increased. The connections assembled with the toe-nailing approach from the beam's bottom surface provided higher maximum loading capacity, medium initial stiffness, and a larger ductility factor, resulting in higher dissipated energy with less fragile failure. The derived allowable loading values for a beam–girder connection fastened with self-tapping screws using the face-nailing approach were close to the code values for bolted and pinned connections. And, a toe-nailing approach provided higher allowable loads for connections than using a face-nail approach.

Keywords Joint strength · Glulam · Self-tapping screw · Japanese cedar

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Introduction

Most domestic plantation timbers available for commercial use in Taiwan are fast-growing species with short rotation years. Therefore, wood members used for timber construction contain a high percentage of juvenile wood, knots, and have low mechanical properties. To effectively utilize the low-quality wood resources for making commercially accepted structural glulam products, it is necessary not only to ensure the strength quality of glulam but also to evaluate the adequacy of the connection performance in timber construction application. Japanese cedar has the highest plantation area, i.e., 15 %, among major commercial wood species and was mainly used for utility pole application before concrete pole dominated. There are 72 % of forests at the ages of 20–70 years which can be harvested for market. Currently, commercial structural glulam products were made of Douglas fir and southern pine in Taiwan. Consequently, Japanese cedar becomes the most potential local plantation wood for glulam making.

Self-tapping screws of small sizes are commonly used in wood furniture and panel products on the assembly line or for do-it-yourself products applications. Self-tapping screws usually provide good holding ability and operation efficiency in wood working projects. In recent years, self-tapping screws, especially medium and large sizes, have drawn attention in timber engineering for connection application in Europe. They are not just an alternative fastener that can be used for timber connection. Certain requirements for current structure design and construction details need to be verified in the interest of safety. Most self-tapping screws can be laid out with small spacing and edge distance without the risk of splitting wood, which often happens with bolted connections. Uibel and Blaß [1] tried to identify suitable spacing and distance for self-tapping screws with corresponding minimum timber thickness. They further modeled a moving load during the screw-in process with factors of wood density, screw-in speed, angle between screw axis and growth ring tangent. The resulted split areas were simulated mostly by a FE model. This gave practical information about the application of self-tapping screws to timber construction.

Self-tapping screws hold two wood members tightly by penetration without the need of a pilot hole. Withdrawal capacity highly depends on the penetration length in main member and the angle between the screw and wood grain. Hübner et al. [2] tried to develop withdrawal capacity of screws for hardwood ash, a type of wood increasingly used in Europe. They reported the withdrawal strength increased as the angle between the screw axis and wood grain increased from 0° up to 30°, and decreased as screw diameters increased from 4 to 20 mm. The adoption of Hankinson function implemented $\sin^2\alpha + 1.42\cos^2\alpha$ instead of $\sin^2\alpha + 1.5\cos^2\alpha$ as suggested by Swiss code or $\sin^2\alpha + 1.2\cos^2\alpha$ suggested by ON EN1995-1-1. However, no embedment behavior of fastener was examined. Thus, fasteners may be not applicable to certain screw connections subjected to lateral loads. Further, Closen and Lam [3] developed a moment-resisting connection for glulam beam–column structures using 10 mm self-tapping screws assembled at 30°. The connection exceeded the bending moment design capacity of the glulam material by factors of 2 and 1.9 in positive and negative directions, respectively. This demonstrated the adequacy of self-tapping screws as fasteners in timber engineering application.

Bolt fasteners are frequently used in timber connection. Major failure in split along the wood grain always starts at the bolted hole because of the large difference in material strength and stiffness between the steel bolt and wood [4, 5]. When dealing with the fragile property of wood, compatibility between materials at the joint may be achieved by reducing the diameter of the steel fastener by using products such as self-tapping screws. Further, Bejtka and Blaß [6] suggested that a bolted joint can be further reinforced using self-tapping screws when the axial load-carrying capacity of the screw is larger than 30 % of the lateral load-carrying capacity per shear plane of each dowel. They reported an increase of the load-carrying capacity up to 80 % compared to a non-reinforced joint with ductile load-carrying behavior, and 120 % for a joint with brittle behavior.

In this study, the characteristic strength properties of a joint constructed with structural glulam members made of fast-grown Japanese cedar was evaluated. Four self-tapping screw types with various numbers were designated to a beam–girder connection, and the effect of assembly approaches including the face-nailing approach and toe-nailing approach on the structural joint performance were also considered.

Materials and methods

Materials preparation

Thirty-five-year-old Japanese cedar (*Cryptomeria japonica* D. Don) plantation timber was harvested from Hsinchu Forest District, Taiwan Forestry Bureau. The size of laminae was 38 × 140 mm after being sawn, kiln-dried, and planed. The average width of growth ring was 5.5 ± 2.2 mm, and moisture content of the sawn lumber was 11.0 ± 0.3 % with density of 480 ± 60 kg m^{-3}. A resorcinol phenol formaldehyde adhesive (RPF) and a hardener of para-formaldehyde mixed at a ratio of 15:100 to RPF were used for the 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 the glulam fabrication. A total of 300 pieces of laminae with size of 38 × 140 × 3000 mm were graded based on the non-destructive modulus of the elasticity by a tap tone approach. The E75-F240 grade symmetric mixed-grade composition glulam with a size of 300 × 140 mm were then laminated in the laboratory with assigned lamina layout following CNS11031 procedures [7]. This also showed the adequacy of locally grown Japanese cedar quality for glulam production.

Four types of self-tapping screws with countersunk or flat heads were used in this study. There were two thread diameters, two screw lengths, and three different thread patterns as described in Table 1 and Fig. 1. Average torsion strength and surface hardness of self-tapping screws provided by Shuenn Chang Fa Enterprise Co. Ltd. were 30.9 kN mm and HV502 for ST8 × 260 screw, 47.8 kN mm and HV480 for ST10 × 260 screw, 34.9 kN mm and HV493 for ST10 × 300 screw, and 25.7 kN mm and HV567 for ST7.5 × 300 screw.

Beam–girder assembly and joint test

A bending test of a joint fastened with self-tapping screws forming an H-shape beam–girder structure was performed by following the recommendations in ASTM D7147-05 [8]. One Japanese cedar structural glulam member of 600 mm in length served as a beam and two 760 mm glulam members aligned perpendicular to the beam at both beam ends served as girders. The beam member was fastened to girders using two different approaches, i.e., face (F) and toe (T) nailing, with self-tapping screws. Four types of self-tapping screws with two different lengths were used for the member connections. Each joint was fastened with 8 or 12 screws using the face-nailing approach as shown in Table 2 and Fig. 2. The edge distance and spacing for the fastener placement were carried out following the recommendations specified in the building code. A total of 6 self-tapping screws were used for the

Table 1 Descriptions of self-tapping screw details

Specification	Length (mm)	Outside diameter (mm)	Root diameter (mm)	Thread length (mm)	Shank diameter (mm)	Head diameter (mm)	Pitch (mm)
ST8 × 260	260	7.99	5.33	93	5.77	14.5	5.20
ST10 × 260	260	9.99	6.45	95	7.11	17.9	5.60
ST8 × 300[a]	299	8.75/8.40	5.56/5.82	91/53	5.99	14.6	5.70
ST7.5 × 302	299	7.42	5.28	290	–	11.9	2.65

[a] Contains two threaded sections

Fig. 1 Self-tapping screws designed for large-scale wood-framing connections. From *top to bottom* ST10 × 260 with half-threaded shank, ST8 × 260 with half-threaded shank, ST8 × 300 with two threaded sections, ST7.5 × 302 with fully threaded shank

toe or inclination nailing at 45° for each joint as shown in Table 3 and Fig. 3. The drilling process was assisted through an adjustable jig (Ryobi, model:VSD-311RS, Japan). Two nailing arrangements were also considered including two pairs of screws nailed down from the top surface of the glulam members with one pair of screws fastened from the bottom surface (TU), and one pair from the top surface with two pairs from the bottom surface (TB). A total of 16 different fastening approaches were considered and each test condition had 3 replications. A concentrated load at a speed of 0.8–5.1 mm min^{-1} was applied at the center of the beam member to evaluate the joint strength characteristics when fastened with self-tapping screws. An initial load not exceeding 20 % of the ultimate load was applied before testing to failure. Blocking between girders was installed to prevent rotation of the girders inward towards the beam member. Dial gages installed within 38 mm from the end of beam measured the vertical displacement of the beam. Raised supports allowing a minimum girder overhang of 3 mm at the inside edges were considered.

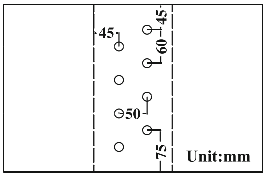
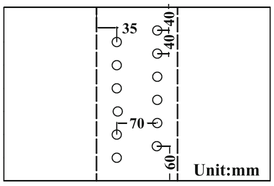
The vertical withdrawal resistance of self-tapping screws from Japanese cedar structural glulam was also examined. The screws penetrated vertically into both the end section and width surface of the glulam member to a depth of 120 mm measured from the tip of self-tapping screws. Three types of screws (ST8 × 260, ST10 × 260, ST7.5 × 302) and two penetration directions were investigated and each testing condition had 12 replications.

Results and discussion

Vertical withdrawal resistance of self-tapping screws

Figure 4 shows the vertical withdrawal resistance of three self-tapping screw types from Japanese cedar structural glulam. It is noted that weaker vertical withdrawal resistance was found as the self-tapping screws were pulled out of the cross-section of glulam, i.e., zero degrees between screw axis and wood grain, as compared with that from the width surface or perpendicular to wood grain. There was a similar vertical withdrawal resistance between 8 and 10 mm self-tapping screws, i.e., ST8 × 260 and ST10 × 260, as they were pulled out from the width surface of a glulam member. On the other hand, lower values were found in ST7.5 × 302 which had about half the distance of the threaded pitch as compared to the other two screw types. This implies that short wood fibers might result when short-pitch threads are embedded during screw penetration. This would reduce the shearing resistance and further cause a plug shear failure as suggested by Ellingsbo and Malo [9]. The building code only specified the usage of wood screws, however, the estimation equation of the allowable vertical withdrawal resistance might be considered for application with similar fasteners of larger size such as self-tapping screws. The equation for allowable tensile strength or vertical withdrawal resistance for a screw pulled out from a wood surface perpendicular to wood grain (P_w) is P_w (kN) $= 0.0127 \times \rho^{1.5} \times l \times d$, where ρ is the air-dried specific gravity (0.32 as specified for Japanese cedar in the code); l, penetration depth (mm); d, nominal diameter of screw (mm) [10]. Consequently, the allowable vertical withdrawal resistances of 8 and 10 mm screws with actual threaded shank in penetration depth would be 1.71 and 2.18 kN, respectively, which are 8.3 and 9.9 % of measured values. Therefore, in the case of a structural glulam made of Japanese cedar plantation

Table 2 Face-nailing conditions of self-tapping screws used for beam–girder connections

Code	Placement	Nominal diameter (mm)	Nominal length (mm)	Number of fasteners
F8-260-8		8	260	8
F10-260-8		10	260	8
FD8-300-8		8	300	8
FC8-300-8		8	300	8
F8-260-12		8	260	12
F10-260-12		10	260	12
FD8-300-12		8	300	12
FC8-300-12		8	300	12

F face nailing, *D* double-threaded sections in screw, *C* fully threaded screw

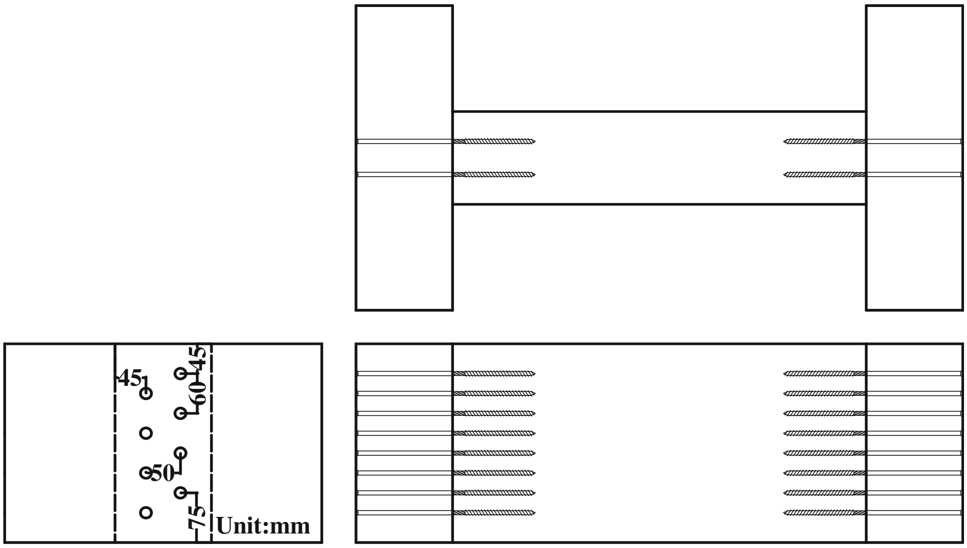


Fig. 2 Configuration of the beam–girder connection—face nailing (F10-260-8)

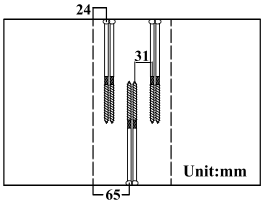
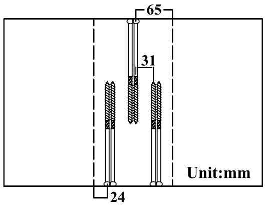
timber, the allowable vertical withdrawal stress of a self-tapping screw fastener is reliable for the design purpose.

Joint strength properties of beam–girder connections

Failure of connections

No severe failure was found at the connection of a glulam beam–girder structure assembled with the face-nailing approach after loaded on the beam center. However, crushes perpendicular to the grain around the driven holes was found for all the connections after the self-tapping screw was removed from the glulam girder. Also, further split from driven holes was found due to the resulting vertical shear force between the beam and girder junctures (Table 4). In the case of the face-nailing approach, the screws further experienced a slight bend bent causing one plastic hinge point, which is identified as the yield mode III in the NDS Code [11]. Most connections, especially those using screws with a fully threaded shank, show such yielding deformation due to fasteners with less stiffness. In the case of the connection fastened with an inclination nailing approach, the screw heads were sunken into wood surfaces by pulling forces for most of the fully threaded screw conditions subjected to higher loads. Most self-tapping screws also experienced a yield in bending at two plastic hinge points near the shear plane, with a localized crushing of wood fibers. This failure matched mode IV

Table 3 Toe-nailing conditions of self-tapping screws used for beam–girder connections

Code	Placement	Nominal diameter (mm)	Nominal length (mm)	Amount
TU8-260-6		8	260	6
TU10-260-6		10	260	6
TUD8-300-6		8	300	6
TUC8-300-6		8	300	6
TB8-260-6		8	260	6
TB10-260-6		10	260	6
TBD8-300-6		8	300	6
TBC8-300-6		8	300	6

T toe nailing, *U* top surface, *B* bottom surface, *D* double-threaded sections in screw, *C* fully threaded screw

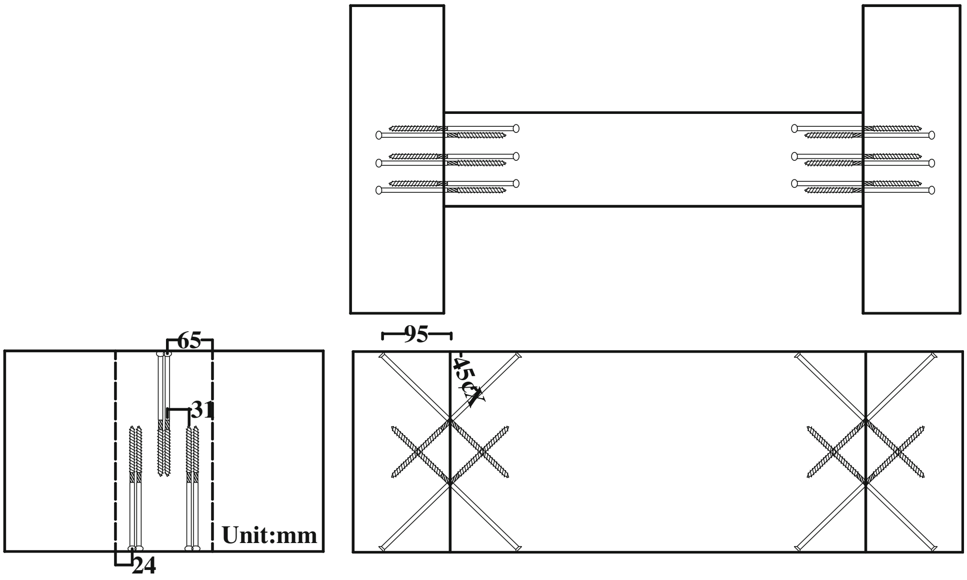


Fig. 3 Configuration of a beam–girder connection—toe nailing (T10-260-6)

connection yield mode for a dowel-type fastener as described in the NDS code and accounted for 66.7 % of connections. Some screws with fully threaded shanks were broken during the separation of beam members from the girder after testing. Prat-Vincent et al. [12] reported the majority of joist-to-header specimens failed due to screw tension fractures as the connections were assembled with one or two pairs of self-tapping screws. In that case, they indicated the applied loads were beyond the screw material strength, and further withdrawal failure due to screw length and high density of glulam timber were not observed. On the other hand, no major screw failure was found in this study. Therefore, it would be appropriate to use more screws at each connection.

Effect of self-tapping screw types

Figure 5 showed the load–displacement relationship of Japanese cedar glulam beam–girder connections subjected to a shearing load for some self-tapping screw fastening conditions and the load capacities are listed in Table 5. Combining the different nailing approaches and various screw numbers for beam–girder assembly, the average maximum load capacity of a connection fastened with 10 mm self-tapping screws was 27.8 % higher than that with 8 mm screws at the same length of 260 mm. Also, the 300-mm-long self-tapping screws with both double-threaded sections and fully threaded shanks showed 46.5 and 94.9 %, respectively, higher in average maximum load

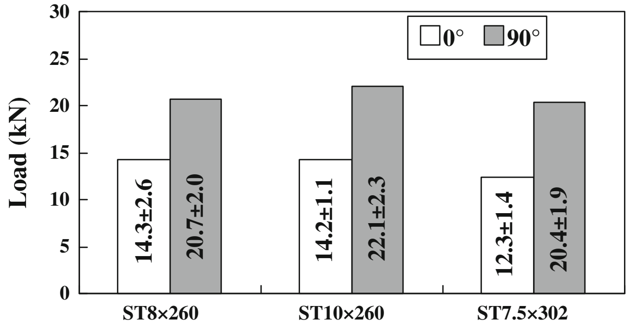


Fig. 4 Vertical withdrawal capacities of self-tapping screws based on the penetration depth of 120 mm from Japanese cedar glulam members. 0° screw axis parallel to wood grain, 90° screw axis perpendicular to wood grain

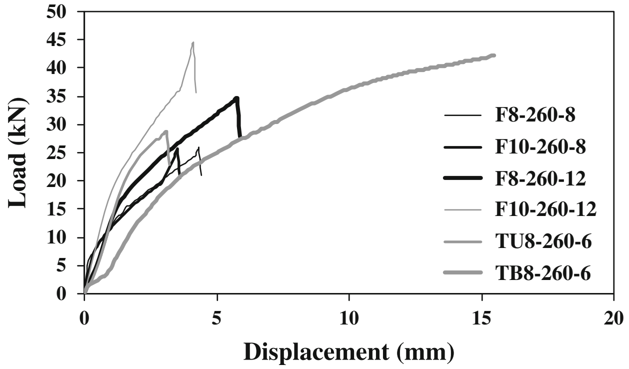


Fig. 5 Examples of load–displacement relationship of some beam–girder connected specimens subjected to a shearing load. Refer Tables 2 and 3 for specimen code

Table 4 Failure modes of beam–girder connections assembled with self-tapping screws

Connection type	Split around screws	Single hinge point of screw	Two hinge points of screw	Screw head sunken	Screw head pull out
F8-260-8	3[a]	0	0	0	0
F10-260-8	3	0	0	0	0
FD8-300-8	3	1	0	0	0
FC8-300-8	3	2	0	0	0
F8-260-12	3	0	0	0	0
F10-260-12	3	0	0	0	0
FD8-300-12	3	1	0	0	0
FC8-300-12	3	3	0	0	0
TU8-260-6	3	0	1	0	0
TU10-260-6	3	0	0	0	1
TUD8-300-6	3	0	1	1	0
TUC8-300-6	3	0	2	2	3
TB8-260-6	3	0	3	2	3
TB10-260-6	3	0	3	0	3
TBD8-300-6	3	0	3	1	3
TBC8-300-6	3	0	3	3	3

F, *T* face and toe-nailing approach, *8*, *10* screw diameter in mm, *D*, *C* double section and fully threaded screws, *U*, *B* nailed from top or bottom surface, *260*, *300* nominal screw length in mm; *6*, 8, *12* screw quantity per connection

[a] Frequency of failure resulted

Table 5 Shearing load capacity of Japanese cedar glulam beam–girder connection assembled with self-tapping screws

Connection type	Max (kN)	Min (kN)	Mean (kN)	$P_{\text{a-SL}}$ (kN)	$P_{\text{a-DL}}$ (kN)
F8-260-8	25.84	22.08	23.85	7.36	20.31
F10-260-8	28.54	25.51	26.53	8.50	20.99
FD8-300-8	41.07	31.61	35.90	10.54	15.34
FC8-300-8	50.08	33.65	44.57	11.22	20.57
F8-260-12	36.58	27.94	33.07	9.31	24.64
F10-260-12	47.21	38.23	43.31	12.74	31.98
FD8-300-12	44.31	34.25	39.29	11.42	24.78
FC8-300-12	33.60	27.94	30.51	9.31	28.21
TU8-260-6	34.59	27.30	30.21	9.10	28.75
TU10-260-6	34.26	26.18	31.44	8.73	25.12
TUD8-300-6	49.86	35.86	43.56	11.95	46.50
TUC8-300-6	94.32	87.54	90.58	29.18	47.49
TB8-260-6	49.34	41.31	44.30	13.77	22.62
TB10-260-6	69.84	64.40	66.64	21.47	30.06
TBD8-300-6	75.66	70.48	73.86	23.49	44.36
TBC8-300-6	92.52	88.32	90.56	29.44	47.24

F, *T* face and toe-nailing approach; *8*, *10* screw diameter in mm; *D*, *C* double section and fully threaded screws; *U*, *B* nailed from top or bottom surface; 260, 300 nominal screw length in mm; *6*, *8*, *12* screw quantity per connection; $P_{a\text{-}SL}$, $P_{a\text{-}DL}$ allowable load based on the test strength limit and test deflection limit

capacity than that of single-threaded screw with the same diameter but 260 mm in length. The joint capacity can be related to the maximum effective penetration the length (l) and diameter (d) of screws, which can be defined as slenderness (l/d). Hübner et al. [2] suggested the slenderness increases from 4.8 to 9.9 when increasing the screw diameter for ash wood, which is less than the common slenderness suited for softwood, i.e., 11–27. For the case of Japanese cedar glulam beam–girder connections in this study, slenderness values of 12–22 for the face-nailing approach and 13–20 for the toe-nailing approach were found, showing adequate screw penetration length.

The initial stiffness of the glulam joint was estimated based on the method proposed by the Japan Housing and Wood Technology Centre [13]. The yield strength was first estimated as the intersection between a line tangent to the load–displacement curve which is parallel to a line passing through the 0.4 and 0.9 $P_{\max}$ points and a line passing through the 0.1 and 0.4 $P_{\max}$ points. The initial stiffness

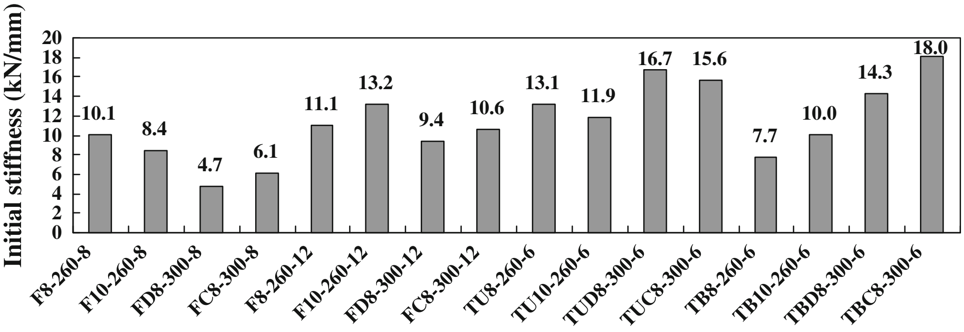


Fig. 6 Initial stiffness of Japanese cedar glulam beam–girder connections fastened with self-tapping screws

was then obtained from the slope of a line passing through both the origin point and yielding point on the load–displacement curves. Results showed the joint fastened with 300-mm-long fully threaded screws had better initial stiffness, 19.8 % on average, than that fastened with 260-mm-long screws with half-threaded shank, especially using the toe-nailing approach (Fig. 6). As compared to 8-mm self-tapping screws with half-threaded shank, the screws with 10-mm diameter or with double-threaded sections did not show further improvement in the initial stiffness of the connection.

The ductility factor (μ) of a connection is defined as the ratio of the maximum deformation limit (δ_u) to the yield deformation limit (δ_y) measured from the test results, where (δ_u) is the deformation of a connection at 0.8 P_{max} after reaching maximum load [13]. A lower value of ductility shows a tendency toward brittle joint performance. This showed that joint fastened with 8 mm self-tapping screws with threaded shank had better ductility ($\mu = 2.28$ on average) while the fully threaded screws showed brittle joint performance ($\mu = 1.40$) (Fig. 7). The plastic behavior or ductility of a joint in wood structure depends on the types of fasteners and connectors. Nakata and Komatsu [14, 15] reported values of 1.84 and 2.50 of ductility factor for glulam column-to-base joint connected with steel plates and pins while values between 6.34 and 6.97 for the joint connected with compressed LVL plates and pins showed a large amount plastic behavior. Consequently, the characteristic ductility of a joint assembled with the self-tapping screws was close to that with steel plates and pins.

The dissipated energy of a glulam beam–girder connection was measured over the maximum load until dropping to 0.8 P_{max} based on the idealized elastic–plastic behavior estimated from the relationship between applied load and corresponding deformation [13]. Higher dissipated energy of a joint indicates less tendency toward instant crush failure during the load application. The dissipated energy of a connection fastened with 10-mm self-tapping screws was on average 39.3 % higher than that with 8 mm screws at the same length of 260 mm, especially when using the toe-nailing approach (Fig. 8). Also, the 300-mm-long self-tapping screws with both double-thread sections and fully threaded shanks were 36.9 and 81.3 % higher, respectively, in dissipated energy than that of single-threaded screw with the same diameter but 260 mm in length. It was noticed that the glulam girder-beam joint using standard connectors with two 13-mm drift pins would provide with dissipated energy between 1895 and 3058 kN mm as reported by Hayashi et al. [16]. The joint showed low initial stiffness and large displacement which could provide higher dissipated energy in that study, while values of ductility factor between 56.1 and 658.6 kN mm were due to small amount of displacement at the joint fastened with self-tapping screws in this study.

Effects of number of self-tapping screws

To examine the influence of the number of fastened self-tapping screws on the strength of a connection, this study tested Japanese cedar glulam beam–girders fastened using the face-nailing approach. In general, the maximum load capacity of a connection fastened with 12 self-tapping screws was 11.7 % higher than that with 8 screws. Findings further showed the maximum load capacity of a connection fastened with a half-threaded shank and self-tapping screws had significant improvement when increasing from 8 to 12 screws, i.e., 38.6 and 63.3 % for 8 and 10 mm screws (F8-260-12 and F10-260-12), respectively. However, no further improvement in the maximum load capacity was found for the double-threaded and fully threaded screws as assembled from 8 to 12 screws. Some specimens fastened with 12 screws failed with a split along the glue line where screws were arranged during the assembly. It might limit the improvement of a connection through increasing number of fasteners. In the case of initial stiffness of a beam–girder connection, an improvement of 50.4 % was found when the number of self-tapping screws used to assemble the glulam structure was increased from 8 to 12. It also was noticed that the initial stiffness of the connection was doubled for the 8-mm screw with double-threaded sections (FD8-300-12). Although similar ductility was found for the connections fastened with 8 and 12 self-tapping screws, a 28.8 %

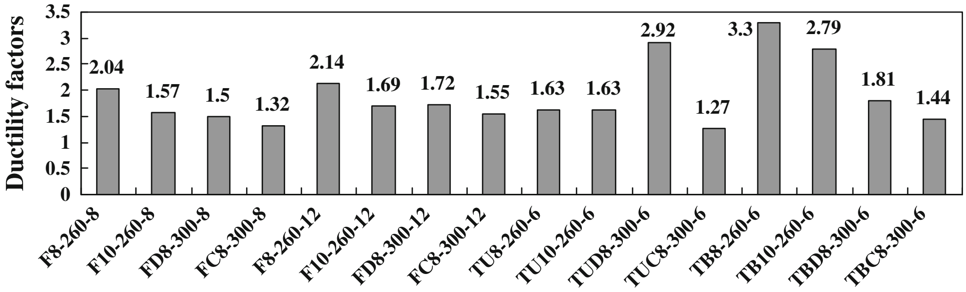


Fig. 7 Ductility factors of Japanese cedar glulam beam–girder connections fastened with self-tapping screws

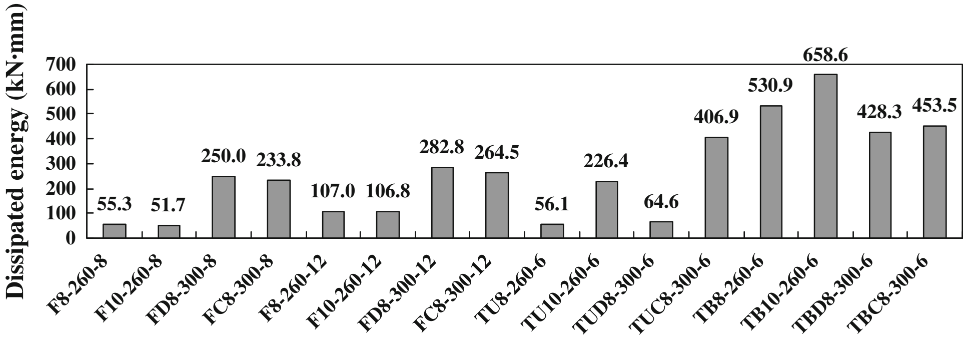


Fig. 8 Energy dissipation of Japanese cedar glulam beam–girder connections fastened with self-tapping screws

higher dissipated energy was obtained for the connection with 12 screws.

Effect of nailing schedules

Two major nailing approaches, i.e., face nailing and toe nailing, using self-tapping screws to assemble the glulam beam–girder connections were compared. The toe-nailing approach had two screw arrangements (TU and TB) on the connection during the assembly. The maximum load capacities of the connections fastened using TU and TB toe-nailing approaches were 41.3 and 98.8 %, respectively, higher than those the using face-nailing approach. In the case of the face-nailing approach, self-tapping screws sustained a shearing force, and wood members resisted with both the compressive force and tensile force perpendicular to the grain at the interface of connections. Consequently, the shear force caused the dowel-type fastener to bend. Moreover, both the compressive force and tensile force perpendicular to the grain are weak strength properties of wood, which cause a split or cleavage failure on the glulam member [16, 17]. In the case of the toe-nailing approach, self-tapping screws strained axially in tension, and the withdrawal strength might contribute to the load-bearing capacity of a connection. Further, the withdrawal strength can be the same when the penetration angles between the screw axis and wood grain range from 30° to 90°, as suggested by Hübner et al. [2]. They proposed a bilinear model which is constant withdrawal strength between 30° and 90° and then decreases from 30° to 0° to 70 % of 5 %-percentile at 30°. This might explain the higher loading capacity achieved for connections fastened using the toe-nailing approach.

The initial stiffness of the Japanese cedar glulam beam–girder connections fastened using the TU and TB toe-nailing approaches were 55.6 and 35.9 %, respectively, higher than those using the face-nailing approach. The ductility factors of the connections ranging from 1.27 to 3.3 indicated fragile structural behavior. There was no significant difference in the connection ductility between the two nailing approaches. Similar results were found in the report of Closen and Lam [3], which developed a high moment-resisting beam–column connection using self-tapping screws with 30° inclination. However, the major failure mode in the glulam beam member was tension fracture and withdrawal of screws, resulting in a low ductile connection. The dissipated energy of the TB beam–girder connection was 3 times of that assembled with the face-nailing approach. In fact, the connections assembled using the TB nailing approach provided higher maximum loading capacity, medium initial stiffness, and larger ductility factor, resulting a higher dissipated energy with less fragile failure.

Allowable loading capacity of a connection

To estimate an allowable load for the Japanese cedar beam–girder glulam connection fastened with self-tapping screws, the ASTM recommendation was followed by choosing a smaller derived value for both the test strength limit and test deflection limit. The test strength limit or ultimate load rating of a specific joint was the lowest ultimate load among the tested beam–girder specimens divided by 3.0. The test deflection limit load is the average value for all tested joint specimens measured at 3.175 mm vertical deflection. Table 4 shows that the allowable loads of the beam–girder joints fastened with self-tapping screws using a face-nailing approach were about 25.2–32.0 % of average $P_{\max}$. It also indicates that the test strength limit, rather than the joint deformation, was a decisive factor because a small vertical displacement was measured when the connection was subjected to a shearing load. The allowable loads of a joint would then be 13.8 % higher on average when the number of screws used for fastening is increased from 8 to 12 screws. Yeh et al. [17] estimated the allowable joint stresses of 304 × 120 mm Japanese glulam structure assembled with 2, 3, and 5 bolts with a slotted metal connector based on building code suggestions, and the values of 3.39, 5.08, and 8.47 kN, respectively, were obtained by using 15.8 mm bolts. These are close to the derived values of beam–girder connections fastened with 8 self-tapping screws using the face-nailing approach. In the case of 15.8-mm pin fasteners, Huang estimated allowable joint stresses of 5.13, 7.70, and 12.83 kN, respectively, for the joints fastened with 2, 3, and 5 pins and slotted metal connectors. These are close to the derived values of connections with 12 self-tapping screws using nailing approach in this study.

Similarly, the joint fastened with self-tapping screws from the beam bottom with a toe-nailing approach showed the allowable load values of about 27.4–32.5 % on average $P_{\max}$. A 49.6 % higher finding for allowable load was obtained in the case of the toe nailing from the beam bottom, rather than from the top surface. In general, the allowable load of a self-tapping screw jointed connection using a toe-nailing approach was 83.0 % higher than that using a face-nail approach.

Conclusions

The structural glulam members fabricated with rapid-grown Japanese cedar plantation timber were constructed into a beam–girder structure with self-tapping screws to evaluate characteristic strength properties of the connection for the purpose of wood-framed construction application. It is suggested that self-tapping screws with 10 mm diameter showed better joint performance in maximum load capacity and dissipated energy than did 8 mm screw connections. Self-tapping screws with fully threaded shanks showed better initial stiffness on the joint than did half-threaded screw connections, but also showed less ductility. Further, both fully threaded and double-threaded sections also provided the joint with higher maximum load and better dissipated energy than did connections using screws with half-threaded shank. The nailing approach of using self-tapping screws is a key to influencing the structural performance of a joint. The results indicated that toe-nailing approach is superior to the face-nailing approach in the maximum load capacity, initial stiffness, and dissipated energy of a beam–girder connection. A self-tapping screw connection with derived allowable loading capacity for Japanese cedar glulam structure could compete as a viable bolt connection for use in wood-framed construction.

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