Research paper

Moment-resisting Performance of Residential Portal Frames Constructed with Self-tapping Screws

Min-Chyuan Yeh,[1,2] Yu-Li Lin,[1] Gien-Ping Huang[1]

【Summary】

Structural symmetric glulam members which were manufactured from Japanese cedar plantation timber were constructed into a box-type portal frame to investigate the moment-resisting performance of the frame when subjected to a lateral load. The joints of the frame were connected using aluminium connectors and self-tapping screw fasteners, and the placement of fasteners on the connection was arranged into 3 patterns. The loading protocol was applied laterally in 7 cyclic stages in the racking test. The results indicated that the maximum lateral load, yield lateral load, ultimate lateral yield load, and initial stiffness of the portal frame fastened using self-tapping screws and arranged in square placement were higher than those when using single-circular and double-circular placements. The resultant dissipated energy obtained from the portal frame with the square pattern placement was 1224.2 kN·mm during the cyclic loading stages, which was higher than the other fastener arrangement by 20%. Based on the criteria for evaluating the horizontal force resistance of wooden wall structures, the allowable shear strength of the box-type portal frame was determined by the load corresponding to the shear deformation of 1/120 radian. The frames could provide a factor as a 4.4 of multiplier value when considered as a shear wall element. The equivalent viscous damping of the box-type portal frames assembled with self-tapping screws was around 4%.

Key words: portal frame, glulam, self-tapping screw, Japanese cedar, racking test.

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[1] Department of Wood Science and Design, National Pingtung Univ. of Science and Technology, 1 Shuehfu Rd., Neipu Township, 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。

[2] Corresponding author, e-mail:yehmc@mail.npust.edu.tw 通訊作者。

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研究報告

結構用自攻螺絲組合
之集成材住宅門型剛架之彎矩抵抗性能

葉民權[1,2) 林玉麗[1) 黃健評[1)

摘　要

本研究以柳杉造林木製造對稱異等級結構用集成材，並組合成箱型之門型剛架，用以探討在側向載重下之彎矩抵抗性能。門型剛架之接合採用鋁合金連接件及結構用自攻螺絲為扣件組合，且在接合部扣件之配置區分為三種形式作為組合條件。在水平剪斷試驗中，所施加之側向力區分為七循環階段進行。結果顯示，門型剛架在接合部以自攻螺絲方形配置所組合之條件，其最大側向載重容量、降伏載重、極限降伏載重、初始剛性均高於扣件分別採用單圓形及雙圓形配置之組合條件。同時，門型剛架在接合部以自攻螺絲方形配置所組合之條件，在循環載重階段所產生之能量散逸為1224.2 kN·mm，高於其他扣件配置之組合條件約20%。依據木質牆體之水平載重評估準則，箱型體之門型剛架容許剪斷強度是決定於牆體剪斷變形量在1/120弳度條件時之側向載重值，同時具有剪力牆乘數為4.4以上之性能，等效黏性阻尼值則為4%。

關鍵詞：門型剛架、結構用集成材、自攻螺絲、柳杉、側向力試驗。

葉民權、林玉麗、黃健評。2016。結構用自攻螺絲組合之集成材住宅門型剛架之彎矩抵抗性能。台灣林業科學31(4):305-21。

INTRODUCTION

Japanese cedar is the most important commercial timber with the largest plantation acreage in Taiwan. Instead of traditional usage as utility poles and concrete forms, there is a potential for it use for structural purposes such as glulam products. The majority of residential wood structures commonly seen locally are of post-beam construction. The rigidity of the connections or bracing between post and beam members must be well-designed to improve the lateral resistance of the structures for seismic and wind loads. Connections between post and beam members or the bracing members are usually fixed with bolt fasteners. However, joints assembled with bolts usually have a tendency to split early when subjected to a load, due to the large rigidity difference of the wood with the metal connectors and bolts (Fujiwara et al. 2007, Yeh et al. 2008, 2012, 2014). Nakata and Komatsu (2009a) developed compressed LVL (laminated veneer lumber) plates and pins for post-beam connections to replace the metal connectors and fasteners. The resultant connections showed little initial-slip and good ductility, the joint efficiency was 30%, and a ductility factor of 6.97 was found when those compressed pins were arranged in a circular pattern at the joint.

Self-tapping screws were recently introduced for housing construction for their operationed efficiency and better withdrawal resistance than other similar fasteners. Bajtka and Blaß (2002) suggested that an inclined self-tapping screw at a timber connection could take into account the timber embedding strength, the friction stress between members, and the withdrawal and bending capacities of the screws, and therefore, could provide opportunities for rationalization and cost reductions in timber connections during the design and installation processes. The withdrawal capacity of a self-tapping screw in wood is well-documented, and recommendations for design and construction purposes were made (Hübner et al. 2010, Uibel and Blaß 2010, Ellingsbo and Malo 2012, Ringofer and Schickhofer 2014). But few researchers have worked on the joint strength of wood members using metal connectors and self-tapping screws as fasteners, in which the shearing capacity of the screws is engaged. Although a better joint strength can be achieved by the shearing resistance of screws, the difficulty might be due to of the penetration screw through a thick metal plate during the connection assembly.

A portal frame is composed of at least 2 pairs of post-beam connections and is commonly used for residential and small commercial buildings. It is constructed to resist lateral loads such as seismic and wind loads and is designed to provide a flexible space without too many posts in a structure. Pirvu et al. (2000) assembled an LVL portal frame with glued metal plates, which showed a high multiplier for the shear walls and high ductility ensuring that the structure had a smaller possibility of fatal damage. Noguchi et al. (2006) modified 2 traditional portal frame structures with one adding an extra joint at the low-stress location and the other extending the joint panel zone. These modified frames showed improvements in stiffness by 1.7-and 3.5-times, and strength by 1.25-and 1.45-times, respectively, compared to the traditional frame. Yeh et al. (2015) reported that the major failure of a portal frame constructed with a steel plate and pin or bolt fasteners always occurred as wood splitting at bolted holes around the column base connection. Large differences in stiffness between the wood and metal connectors or fasteners might cause stress concentration around the interface and failure of the weaker material.

To increase the loading capacity through the double shearing resistance of fasteners, an inserted connection with an aluminum plate and structural self-tapping screws was proposed as the joint configuration for a portal frame. The difference in stiffness between the connector and wood materials was reduced by replacing the steel plate with an aluminum plate, which also facilitates the penetration of self-tapping screws. In this study, a portal frame was constructed using Japanese cedar glulam members with aluminum connectors and self-tapping screws in different arrangemenst to investigate the moment-resisting performance of the structures.

MATERIALS AND METHODS

Materials

Japanese cedar (*Cryptomeria japonica* D. Don) logs were harvested from Hsinchu Forest District, Taiwan Forestry Bureau. The logs were sawn and planed into a size of 38×135×3000-mm laminae. The laminae were graded based on the non-destructive modulus of elasticity after being kiln-dried and then measured with a tap-tone approach. By following the laminae arrangement recommendation from the glulam standard of CNS11031, an E85-F255 grade symmetric glulam member was assigned based on the grade distribution of the laminae produced. This was to ensure full usage of all laminae grades in order to maximize the log recovery. The glulam member were fabricated using RPF (resorcinol phenol formadehyde) adhesive with 250 g m^{-2} application and 0.98 MPa of pressure. The size of the glulam was 135×304 mm in cross-section. An aluminium plate was used for the connection between the beam and column members. The size of the 6061 aluminium connector was 5×280×590 mm. The fasteners used in the connection were self-tapping screws (M8-125, Shuenn Chang Fa Enterprise, Kaohsiung, Taiwan), which have a length of 125 mm and a diameter of 8mm.

Methods

A box-type portal frame with the height of 2600 mm and the width of 3000 mm was constructed. Each post and beam end was slotted, and an aluminium connector with 16 self-tapping screws was inserted during the structure assembly. The placement of self-tapping screws at the connection was arranged in 3 types, i.e., single-circular (C), double-circular (DC), and square (S) arrangements as shown in Figure 1. The moment-resisting performance of the portal frame was examined by applying horizontal loads at the top beam member end as shown in Figure 2. The protocol of the lateral loads consisted of 7 stages of cyclic application. 1/240, 1/170, 1/120, 1/100, 1/75, 1/50, and 1/30 radian. Three cyclic loadings were applied in each stage, and then a final monotonic load was applied until failure. In total, 3 conditions were examined with 3 replicates for each connection configuration. The strength properties of a portal frame were then estimated based on the method proposed by The Japan Housing and Wood Technology Centre (2001).

To determine the reference shear strength (P_r) of a constructed portal frame, 4 strength properties needed to be evaluated. Two-thirds of the recorded maximum lateral load, $2/3P_{max}$, and the yield load (P_y) were considered. An allowable load (P_{120}) of a portal frame was measured as the specimen was subjected to a shear deformation of 1/120 radian during the racking test. And, $0.2P_u/D_s$ was included, which considered both the ultimate yield load (P_u) and the structural characteristic factor (D_s). The D_s was calculated as $1/(2\mu-1)^{1/2}$. And, the ductility factor (μ) was defined as the ratio of the maximum deformation limit to the yield deformation limit. The P_r is equal to a mean value minus 3.152SD,

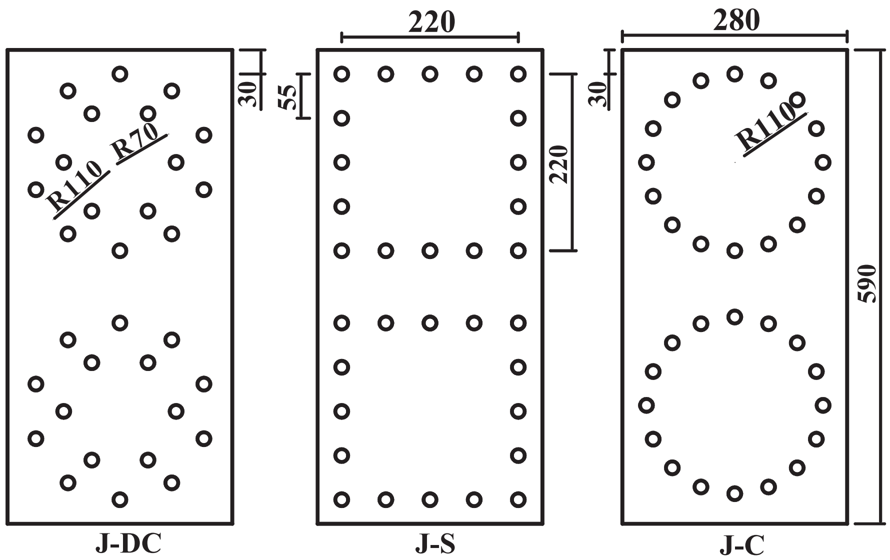

Fig. 1. Aluminum connectors with 3 types of self-tapping screw fastener arrangement. DC, double-circular; S, square; C, single circular.

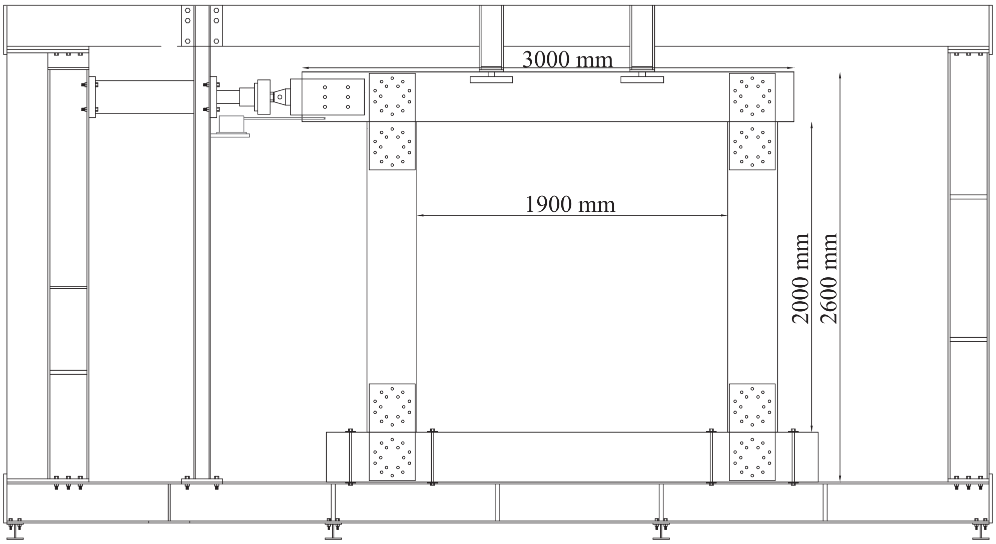

Fig. 2. Racking test for a box-type portal frame constructed with Japanese cedar glulam.

where SD is the standard deviation.

A multiplier (m_{frame}) was used to demonstrate how the portal frame acts as a shear wall and was compared to the required lateral resisting load capacity specified for a regular shear wall element. It was expressed as $m_{frame} = P_a/(L \times 1.275)$, where P_a is the allowable shear strength determined from the smallest value from P_r, and L is the portal frame span.

Energy dissipation (U_d) of a portal frame is calculated from inner area of hysteresis curves resulting from the racking test. Energy dissipation at the third cycle of each load application stage was evaluated (Park *et al.* 2014). The equivalent viscous damping (h_{eq}, %) was then calculated as heq = $U_d/(2\pi \times U_m)$, where U_m is the potential energy in the positive and negative halves of a cycle from the hysteresis loops.

To determine the resisting moment of a portal frame subjected to a lateral load, a slope-deflection method was used, which relates the internal moment at the ends of a glulam member to the member's slope and deflection at the ends. It is expressed as follows:

$$M_N = 2EK_N (2\theta_N + \theta_F - 3\varphi) + (FEM)_N; \quad (1)$$

where M_N is the internal moment, E is the modulus of elasticity of the glulam, $K_N = I/L$, I is the moment of inertial, L is the span between connections, θ_N and θ_F are the near and far end slopes of the span at the supports (the angles were measured in radians), φ is the span rotation due to settlement in radians, and *FEM* is the fixed-end moment at the near-end support.

A double shear capacity of a self-tapping screw with an aluminum plate on the Japanese cedar glulam was tested using a universal testing machine. A self-tapping screw was drilled through the glulam and aluminum plate, which was inserted into a slotted glulam block. The specimen was tested in compression while the loading head was applied directly onto the aluminum plate as shown in Figures 3 and 4. The size of the glulam specimen was 135×304×400-mm for evaluating the double shear capacity of the self-tapping screw tested perpendicular to wood grain, and 135×114×400-mm specimen was used to test that parallel to the wood grain. Each test condition had 12 replications.

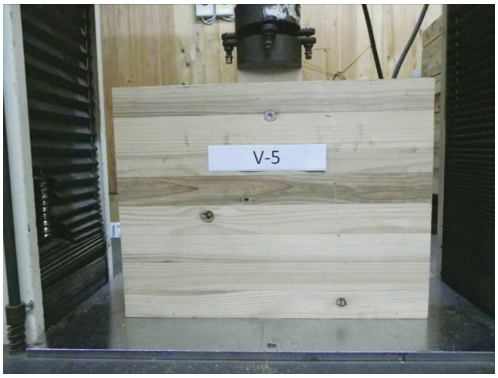

Fig. 3. Double shear strength of a self-tapping screw tested perpendicular to the wood grain.

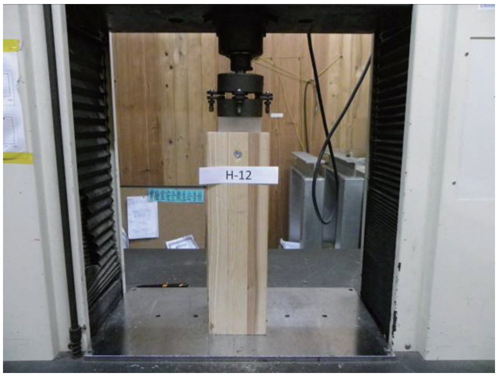

Fig. 4. Double shear strength of a self-tapping screw tested parallel to the wood grain.

RESULTS

Failure of portal frames and double shearing of the glulam

In all fastener placement conditions, the self-tapping screw heads showed an indentation into the wood surface during the racking tests as shown in Figure 5. The aluminium connector, which was inserted in the middle of the glulam member, held the fastener in place causing axial tension and shear forces on the self-tapping screw shanks. Broken screw heads were also found at the joints under tension in every portal frame specimen with no supports, such as the washer in the bolt application as shown in Figure 6. Obviously the juncture between the screw head and screw shank became critical and must be further refined for this commercial self-tapping screw. The portal frame failed with wood splitting at the post-beam connection for the self-tapping screws fastened mainly in the square placement as shown in Figure 7. The split occurred at both the beam and column members. A large force was resisted

Fig. 5. Self-tapping screws indented into the wood surface in the racking test.

Fig. 6. Self-tapping screw head broken during the racking test.

by the fasteners located further from the connection center, especially at the corner. This is similar to the bolted connection with square placement as reported by Yeh et al. (2015). All portal frame specimens experienced large lateral displacements as shown in Figure 8, and compression failure at the beam surface occurred between the juncture of the glulam post and beam members. Failures of both the glulam members and self-tapping screw fasteners showed their compatibility at the connection during the load-carrying process.

In the case of the double shear strength test for single self-tapping screws, the screw shank was sheared off by the inserted aluminum plate under compression as shown in Figures 9 and 10. The self-tapping screw was bent and broken in the middle of the screw shank, which showed a good holding ability of the spiral teeth and screw head against the wood. Wood splitting was not observed, which indicated that the strength was compatible between the fastener and glulam member.

Fig. 7. Glulam column split along the fastener rows.

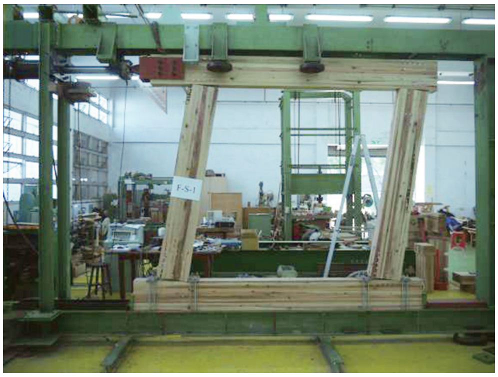

Fig. 8. Shear failure of a box-type glulam portal frame.

Fig. 9. Shearing off of a self-tapping screw by an aluminum plate in double shear testing perpendicular to the wood grain.

Fig. 10. Shearing off of a self-tapping screw by an aluminium plate in double shear testing parallel to the wood grain.

A similar failure mode was found when a compressive load was applied on both wood grain orientations, i. e, parallel and perpendicular, in the test.

Racking strength of the portal frame

The Japanese cedar glulam portal frame specimens assembled with self-tapping screws were laterally loaded with 7 cyclic stages and then monotonically loaded until failure. During the cyclic load applications, the load path for the second and third cycles in each loading stage basically followed the first load-displacement curve and showed no obvious damage to the frame connection (Figure 11). It was noted that no plastic deformation of the portal frame specimens was found after completing 7 loading cyclic stages. However, the portal frame specimens showed large portions of plastic deformation during the final monotonic load application.

The strength properties of the portal frames are listed in Table 1. The maximum lateral load capacities, P_{max} ranged 47.6~51.4 kN for frames assembled with 16 self-tapping screws at each member end or 32 screws at each connection.

Values of initial stiffness, K, ranged 627~857 kN rad^{-1} for portal frames assembled with 16 self-tapping screws at each member end, which was 58% of that of portal frames assembled using 8 dowels and steel connectors as reported by Yeh et al. (2015).

Dissipated energy

When an external force was applied, the energy disperses in structural systems and is defined as the energy dissipation. The dissipated energy of the boxed portal frames from the racking test was estimated from the hysteresis curve during the steady loading cycle, e. g., the third cycle in the study, for each cyclic stage during the cyclic loading application as shown in Figure 12. The area enclosed

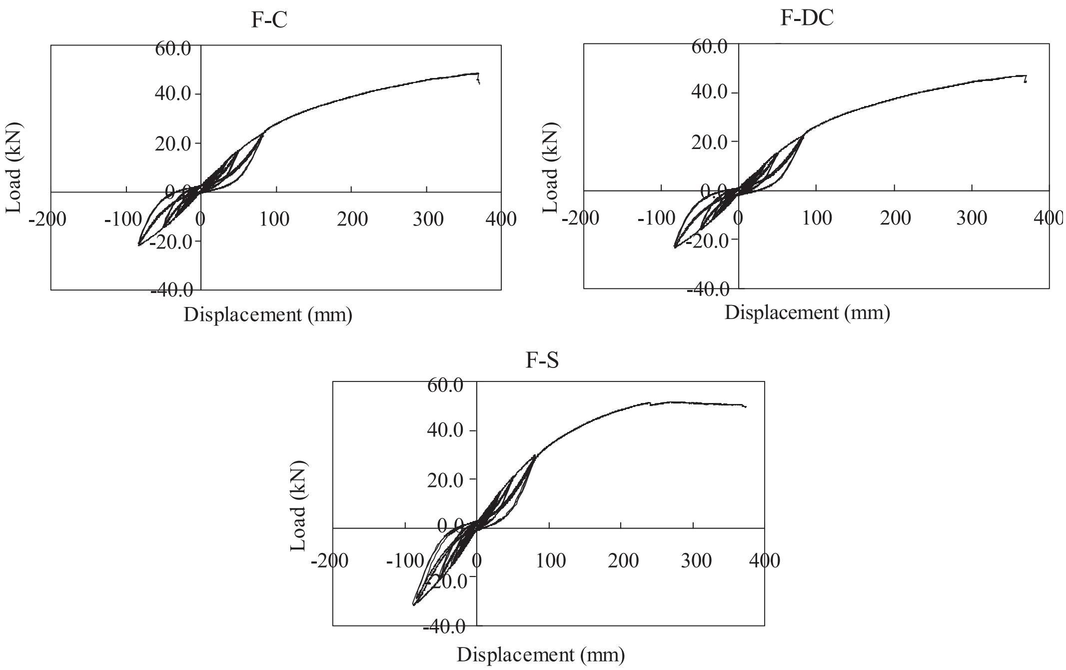

Fig. 11. Cyclic load-displacement relationship of portal frames fabricated with 3 different self-tapping screw placement patterns. C, single-circular; DC, double-circular; S, square.

Table 1. Structural characteristics of Japanese cedar glulam portal frames subjected to cyclic lateral loads

Fastener placement		P_{max} (kN)	P_y (kN)	P_u (kN)	K (kN rad^{-1})	U_d (kN·m)	μ	D_s
F-C	Mean	49.3	26.7	43.1	682	12.8	2.4	0.51
	Max.	52.4	27.5	45.1	727	13.5	2.5	0.52
	Min.	46.9	25.4	41.2	641	12.1	2.4	0.50
	CV (%)	6	4	3	0.06	5	4	2
F-DC	Mean	47.6	25.5	41.3	627	12.3	2.3	0.52
	Max.	49.4	26.0	42.2	644	12.4	2.4	0.53
	Min.	46.3	24.8	40.6	606	12.0	2.3	0.52
	CV (%)	3	2	1	0.03	2	0	2
F-S	Mean	51.4	28.6	47.9	857	15.3	2.8	0.46
	Max.	52.0	29.7	48.6	915	16.2	3.1	0.48
	Min.	50.5	28.0	46.7	824	14.7	2.7	0.44
	CV (%)	2	3	1	0.06	5	7	4

F-C, F-DC, F-S, self-tapping screws in circular, double-circular, and square placements, respectively; P_{max}, maximum lateral load; P_y, yield load; P_u, ultimate yield; K, initial stiffness; U_d, energy dissipation; μ, ductility; D_s, structural characteristic factor; CV, Coefficient of variation.

by the cyclic curves of the load-displacement relationship of the boxed portal frame was calculated (Park et al. 2014).

DISCUSSION

Strength properties of portal frames

Based on the racking test results for the portal frame, it was noted that self-tapping screws arranged in a square placement at the connection showed a higher maximum lateral load, yield load (P_y), and ultimate yield load (P_u) than those arranged in the double-circular placement. Compared to a traditional portal frame assembled with 4 bolts at each member connection by Noguchi et al. (2006), a 3-fold higher P_{max} was obtained using self-tapping screws in this study. On the other hand, P_{max}, P_y, and P_u values were lower than those of portal frames assembled with 8 dowels and steel connectors as reported by Yeh et al. (2015). The resulting ultimate yield load, P_u, was 89% of the maximum lateral load on the average for 3 fastener placements, which was 63% higher than the yield load (P_y) values on average. Compared to a 27% difference in the bolted frame by Yeh et al. (2015), the large difference between P_u and P_y indicated a broader transition range from elastic to plastic behavior of a self-tapping screw-assembled portal frame subjected to a horizontal load.

Compared to the initial stiffness of the portal frame, Park et al. (2014) reported a lower value of 551 kN rad^{-1} in initial stiffness of a Korean post-beam structure, which was constructed with traditional dovetail joints. Results also showed that both the initial stiffness and energy dissipation of the frame using the square placement for self-tapping screws were higher than those using the circular placement pattern. Values of the energy dissipation of the Japanese cedar glulam portal frames ranged 12.3~15.3 kN-m in this study. This was about 3 times the energy dissipation on the frame which was assembled with 8 dowels at each member end as reported in previous work and showed that major plastic behavior was involved when resisting a

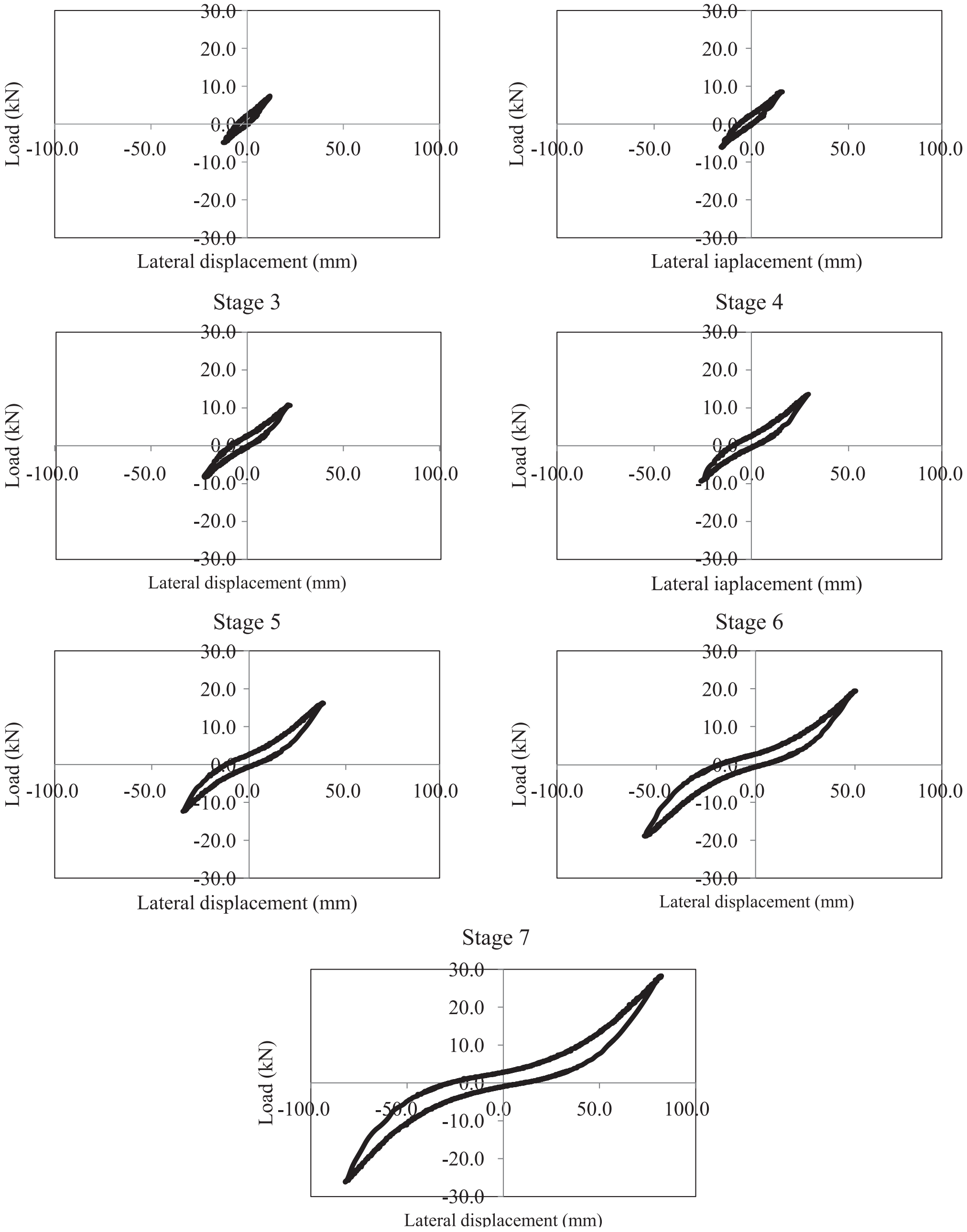

Fig. 12. Energy dissipation in the third cycle of each cyclic load applied stage.

horizontal load. Consequently, a 98% higher ductility (μ) of the frame assembled with self-tapping screws was found than that with 8 dowels in Yeh et al. (2015). The structural characteristic factor, D_s, or the load reduction factor was between 0.46 and 0.51. It was close to the results of LVL portal frames (0.3~0.6) from Pirvu et al. (2000) and frames assembled with a compressed LVL plate and pins (0.54) from Nakata and Komatsu (2009b). This showed the adequacy using the aluminum plate as a connector and self-tapping screws as fasteners for constructing a portal frame.

Resisting moment and shearing strength of glulam joints

The maximum resisting moment or internal moment of the joint in a boxed portal frame can be calculated using the slope-deflection method in Eq. (1). An assumption was made that the vertical deflection of the beam members was restricted by the column members against the beam ends. Since the 4 corners of the boxed portal frame were the same connection configurations, the resisting moment at each joint would be the same. The modulus of elasticity (E) value uses 8.33 GPa from the assigned E85-F255 grade glulam for the boxed portal frame members. The moment of inertia was calculated using the cross-section of Japanese cedar glulam. The calculated maximum resisting moment (M_{Pmax}) and the resisting moment at the 1/120 radian deformation (M_{P120}) of the frame are listed in Table 2. The resisting lateral load of a wooden structure measured at the deformation of 1/120 radian is critical to design a shear wall. It considers the structural performance of a constructed wall element including a portal frame subjected to the horizontal load such as a seismic or wind load. The resultant M_{P120} values ranged 7.1~7.4 kN·m, which were 25% on average of the maximum internal moment of the frames. This assured the safety of the portal frame connection using the self-tapping screws as fasteners.

The double shear strength of a self-tapping screw which was applied on the

Table 2. Resisting moment capacities of joints for boxed portal frames subjected to a lateral load

Joint type	M_{Pmax} (kN·m)	M_{P120} (kN·m)
Square	30.2	7.1
Single circular	29.0	7.3
Double circular	28.0	7.4

M_{Pmax}, M_{P120}, internal moment based on the maximum lateral load and the load measured at a deformation of 1/120 radian, respectively.

Japanese cedar glulam member was obtained through the compressive test. The shear properties of the joint in double shear are usually dependent on the embedment on the contacted wood surface and rigidity of the screw shank. The results indicated a better performance in the case of a force applied perpendicular to the wood grain as shown in Table 3. The stiffness of the joints was similar between the applied loads in the direction either parallel or perpendicular to the wood grain.

Allowable shear strength and multiplier

To determine the allowable shear strength of the portal frames, 4 criteria were employed, and the reference shear strength needed to be calculated first from each criterion. Based on the P_{max}, P_y, P_u, and load measured at a rotation angle of 1/120 radian on the frame (P_{120}), the allowable shear strength of the portal frames was obtained from the lowest calculated reference shear strength value. The box-type portal frames assembled with an aluminium connector and self-tapping screws in square placement showed the highest reference shear strength values compared

Table 3. Double shear strength of single self-tapping screw joints in the compressive test

Wood grain direction	P_{max} (kN)	P_y (kN)	K (kN mm^{-1})
parallel	14.32±2.17	8.48±0.87	2.01±0.19
perpendicular	19.08±3.72	10.24±2.86	2.05±0.40

P_{max}, maximum lateral load; P_y, yield load; K, initial stiffness.

to those arranged in circular patterns in most cases, except the P_{120} criterion as shown in Tables 4~6. It was noted that the allowable shear strength of a portal frame assembled with self-tapping screws and aluminium connector were determined based on the critical P_{120}. The advantages of a higher load capacity and larger plastic characteristics of the portal frame assembled with a square placement of the fasteners were not fully utilized due to the small lateral deformation in the early cyclic loading stages considered for the P_{120} criterion. Consequently, similar allowable shear strength values were obtained for the portal frame among the 3 self-tapping screw placements.

The shear wall performance which is expressed as multiplier values for each portal frame is shown in Table 7. A value of 1.275 $kN{\cdot}m^{-1}$ or 130 $kgf{\cdot}m^{-1}$ was recommended for a basic shear wall element subjected to a lateral load to resist the 1/120 radian of shear deformation (The Architectural Association of Japan 1995). When the shear-resisting performance was considered, the Japanese cedar glulam portal frame constructed with an

Table 4. Reference and allowable shear strengths of Japanese cedar glulam portal frames with the fasteners in a square placement

No.	P_{120} (kN)	P_y (kN)	$2/3P_{max}$ (kN)	$0.2P_u/D_s$ (kN)	P_a (kN)
1	12.1	29.7	34.7	20.3	
2	12.0	28.0	33.7	19.9	
3	12.3	28.0	34.5	22.0	
Avg.	12.1±0.1	28.6±1.0	34.3±0.5	20.8±1.1	
Pr	12.1	28.1	34.0	20.2	12.1

P_{120}, lateral load measured at 1/120 radian; P_r, reference shear strength; P_a, allowable shear strength; P_y, yield load; P_{max}, maximum lateral load; P_u, ultimate yield; D_s, structural characteristic factor.

Table 5. Reference shear strength of Japanese cedar glulam portal frames with the fasteners in a single-circular placement

No.	P_{120} (kN)	P_y (kN)	$2/3P_{max}$ (kN)	$0.2P_u/D_s$ (kN)	P_a (kN)
1	12.5	27.5	34.9	18.0	
2	12.3	27.3	32.3	16.8	
3	12.3	25.4	31.3	16.0	
Ave.	12.4±0.1	26.7±1.2	32.8±1.9	16.9±1.0	
P_r	12.3	26.2	32.0	16.4	12.3

Parameters are defined in the footnotes to Table 4.

Table 6. Reference shear strength of Japanese cedar glulam portal frames with the fasteners in a double-circular placement

No.	P_{120} (kN)	P_y (kN)	$2/3P_{max}$ (kN)	$0.2P_u/D_s$ (kN)	P_a (kN)
1	13.1	25.7	32.9	16.0	
2	12.7	26.0	31.4	15.9	
3	12.1	24.8	30.9	15.7	
Ave.	12.6±0.5	25.5±0.6	31.7±1.1	15.9±0.2	
P_r	12.4	25.2	31.2	15.8	12.4

Parameter are defined in the footnotes Table 4.

Table 7. Multiplier (mframe) for the shear wall and safety factors

Fastener placement	m_{frame}	Safety factor
Square	4.31	4.2
Single circular	4.38	4.0
Double circular	4.42	3.8

aluminium connector and self-tapping screws showed an increased lateral load resistance by a factor of 4 compared to the basic shear wall element. The 3 self-tapping screw placements at the connection showed similar load-resisting performances. The safety factor was defined as a ratio of the maximum lateral load to the allowable shear strength. Values of around 4 were obtained, indicating a conservative derivation. Pirvu et al. (2000) also reported multiplier values of 3~5 for frames constructed with 9-mm-thick steel plates with 4 bolts after reinforcing with glued metal plates at the member ends.

Dissipated energy

Total dissipated energy values of Japanese cedar glulam portal frames using self-tapping screws in a square arrangement were 16.3 and 22.9% on average higher than those of frames using screws in single- and double-circular arrangement, respectively (Table 8~10). Significant increases in energy dissipation for the portal frame constructed with the square placement assignment were found from the fifth cyclic loading stage. It was suggested that significant energy dissipation is

Table 8. Energy dissipation in each loading stage for box-type portal frames constructed with square placement of fasteners

Loading stage	Frame 1 (kN·mm)	Frame 2 (kN·mm)	Frame 3 (kN·mm)
1	40.0	39.7	42.5
2	60.9	54.8	67.3
3	106.7	98.9	116.2
4	156.7	145.5	162.2
5	236.8	239.1	244.9
6	413.2	422.8	418.7
7	795.1	806.2	816.5
Total	1208.3	1229.0	1235.2
Eq. viscous damping (h_{eq})	4.18%	4.41%	4.41%

Table 9. Energy dissipation in each loading stage for box-type portal frames constructed with a single-circular placement of fasteners

Loading stage	Frame 1 (kN·mm)	Frame 2 (kN·mm)	Frame 3 (kN·mm)
1	25.5	30.2	32.8
2	54.2	60.7	61.3
3	76.6	92.5	79.8
4	107.6	136.2	132.8
5	161.1	197.5	188.4
6	321.8	354.3	343.9
7	648.7	754.1	732.6
Total	970.5	1108.4	1076.5
Eq. viscous damping (h_{eq})	4.08%	4.86%	4.84%

Table 10. Energy dissipation in each loading stage for box-type portal frames constructed with a double-circular placement of fasteners

Loading stage	Frame 1 (kN·mm)	Frame 2 (kN·mm)	Frame 3 (kN·mm)
1	27.8	28.6	28.1
2	54.4	57.8	55.5
3	80.2	88.2	85.5
4	112.2	120.3	117.7
5	161.7	171.6	168.4
6	322.8	335.3	320.8
7	648.6	672.8	688.4
Total	971.4	1008.1	1009.2
Eq. Viscous damping (h_{eq})	4.09%	4.42%	4.54%

caused by inner deformation through the bearing that occurred at the contact surface between beam and column joints as mentioned in the failure modes. When the potential energy was considered, the glulam portal frames assembled with screws all showed similar equivalent viscous damping (h_{eq}) values of around 4%. This was close to the arched frame and frames constructed with moment-resisting connections, of 2~6%, reported by Yasumura (1996). But the result was lower than braced frames, e.g., 15~20%, as also suggested by that study and LVL frames constructed with glued metal joints, e.g., 5~25% by Pirvu et al. (2000).

Envelop curves of frames in loading

The initial envelop curves were used to describe the overall lateral resistance of a portal frame subjected to the first loading cycle of each cyclic loading stage during the racking test. Load-deformation relationships were constructed using the highest load among each first loading cycle. It showed the stiffness of a frame recovering from former lateral load stages and could identify possible early failure of a wood structure from the tendency of the curve developed. Results showed that all tested frames were within an elastic range for loads applied in the 7 consecutive stages up to 1/30 radian as shown in Figure 13. And the portal frame constructed with self-tapping screws in the square arrangement was stiffer against a lateral load than those frames in the double-circular arrangement followed by those in the single-circular arrangement.

The load-deformation relationships could also be constructed using the highest load among each third loading cycle as the steady envelop curves. The steady envelop curves describe the remaining stiffness of a frame after being subjected to repeated cyclic loadings as shown in Figure 14. It was noted that the steady envelop curves were close to the initial envelop curves indicating a better holding ability of the self-tapping screws as fasteners in a connection, and no significant damage occurred during the cyclic load application.

CONCLUSIONS

An adequate grade of structural glulam products conforming to CNS standards was obtained using Japanese cedar plantation timber. The boxed type glulam portal frame constructed with structural self-tapping screws and aluminium connectors exhibited good ductility and high energy dissipation in the cyclic racking test. The portal frames assembled

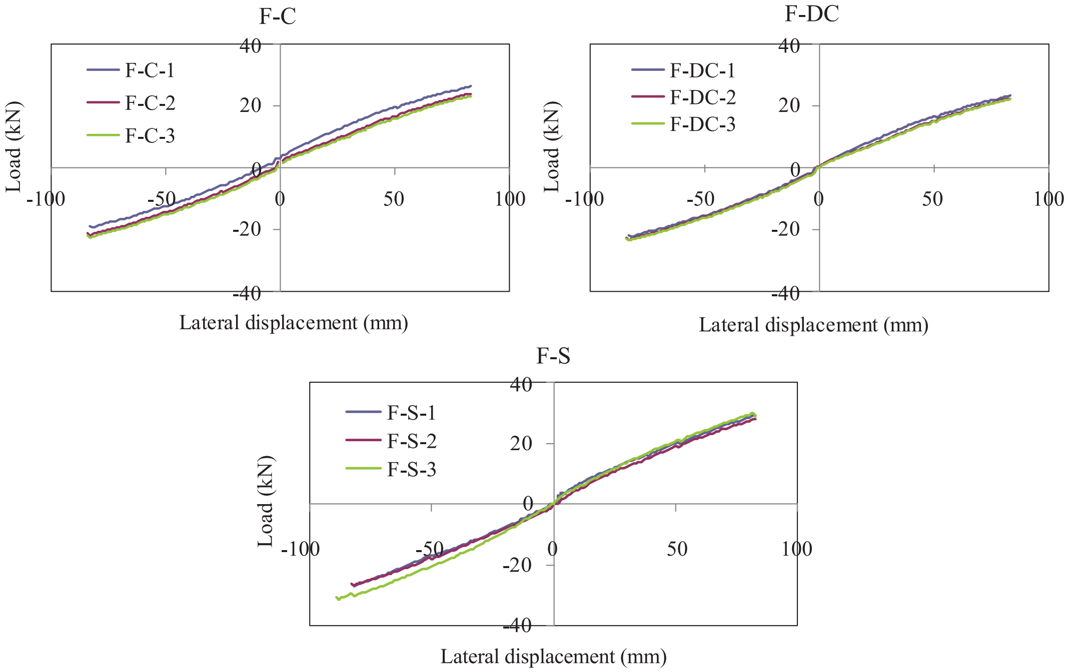

Fig. 13. Initial envelop curves of cyclic loading for boxed portal frames constructed with 3 different self-tapping screw arrangements. C, single-circular; DC, double-circular; S, square.

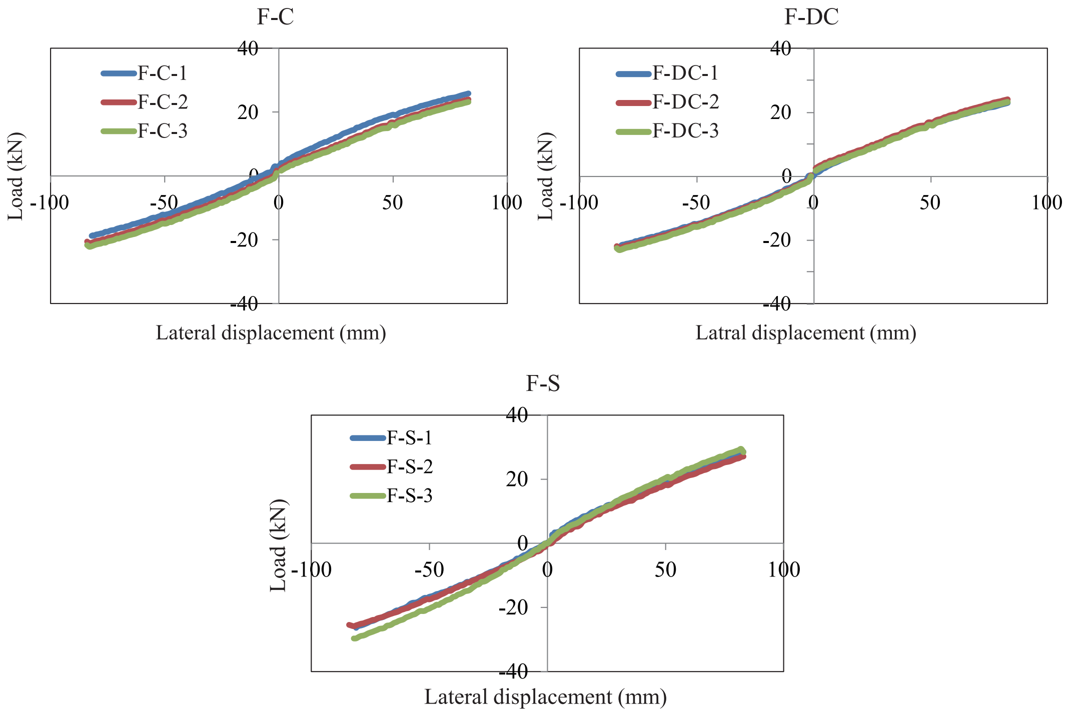

Fig. 14. Steady envelop curves of cyclic loading for boxed portal frames constructed with 3 different self-tapping screw arrangements. C, single-circular; DC, double-circular; S, square.

with structural self-tapping screws in a square placement showed better lateral load resistance in terms of the maximum load, yield load, ultimate yield load, and initial stiffness than those for the single-and double-circular placements. The internal resisting moment estimated at 1/120 radian at the frame joint was 25% of the maximum resisting moment capacity, which ensures a safety factor of 4.0 for lateral load applications. As to the shear wall element, portal frames connected with self-tapping screws could provide a multiplier value with a factor of 4.4 compared to the basic shear wall criterion. The resultsnt allowable shear strengths of the portal frames were the same among the 3 arrangements of self-tapping screws at the connection. Consistency between the initial and steady envelop curves assured a good holding ability of structural self-tapping screws for the box-type glulam portal frame assembly.

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