Research paper

Evaluation of the Tensile Strength of Structural Finger-Jointed Lumber[1]

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

【Summary】

A study was undertaken to evaluate the tensile strength performance of both vertically and horizontally finger-jointed laminae with 3 different lengths of finger profiles for 5 softwood species. Douglas fir finger-jointed lumber showed the best joint efficiency at 74.1%, followed by spruce-pine-fir (SPF) groups, at 65%, among the 5 wood species. Both Japanese cedar and southern pine finger-jointed lumber had lower joint efficiencies due to weak finger profiles causing early failure in tension. Southern pine finger-jointed lumber was found to have the highest tensile strength, 116.6% higher than the lowest Japanese cedar group, followed by the Douglas fir group which was 65.9% higher. The hemlock and SPF groups had similar tensile strengths, and they were also higher than the Japanese cedar group by 46.8 and 40.7%, respectively. The tensile strength of lumber joined with a 21-mm long finger profile showed a significantly lower value than those with 18- and 24-mm finger profile groups by 11.3 and 8.5%, respectively, due to the wide finger tips. The results show that there was no significant difference in tensile strength of finger-jointed lumber between horizontal and vertical finger formation. With the exception of the 21-mm finger-jointed group, slightly higher tensile strength (7.4%) for the 18- and 24-mm finger length groups with vertical finger-joints was obtained, compared to those with horizontal joints.

Key words: finger joint, glulam, tensile strength, Japanese cedar.

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[2] Deparment of Wood Science and Design, National Pingtung University of Science and Technology, 1 Xuehfu 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。

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

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研究報告

結構用指接材之抗拉強度評估[1)]

葉民權[2,3)] 林玉麗[2)] 黃永欽[2)]

摘　要

本研究針對5種針葉材集成元以3種不同指榫長度及分別以垂直或水平方向指接後進行抗拉強度性能評估。結果顯示花旗松指接材之指接接合效率最高為74.1%，其次為雲杉–松–冷杉指接材65%。柳杉及南方松指接材由於指榫弱，在拉伸力下形成斷裂破壞而具較低之接合效率。在指接材之抗拉強度方面，南方松為最佳，優於最弱之柳杉116.6%，花旗松亦高於柳杉65.9%。鐵杉及雲杉–松–冷杉指接材有相近之抗拉強度，分別優於柳杉46.8及40.7%。指榫長21 mm之指接材由於受到較大之指端寬之影響，其抗拉強度分別低於18及24 mm指榫長之指接材11.3及8.5%。結果顯示指榫以水平成型組合與垂直成型組合之指接材的抗拉強度間並無差異，但除了指榫長21 mm條件之外，18及24 mm指榫接合條件下，垂直成型組合之指接材抗拉強度高於水平成型組合者7.4%。

關鍵詞：指接、集成材、抗拉強度、柳杉。

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INTRODUCTION

The engineered wood of structural glued laminated timber, called glulam, is extensively used for large wood structures requiring long-span members, carrying heavy design loads, or forming a curved appearance. It has recently become a very important design element for wood construction projects in Taiwan. To manufacture such glulam products with no size limitation especially in length requires connecting short pieces of lumber end to end into long laminae by finger joints or similar effective joining methods. A bending test is an easy way to evaluate the structural performance of such finger-jointed lumber or to identify the key parameters from the finger geometry and related joint assembly process (Liu and Lii 1989, Li 1992). In the case of a large glulam beam subjected to a bending load, laminae under the lower portion of the glulam beam member are actually in tension instead of bending. Therefore, finger-jointed laminae of the utmost layer of glulam lower part might experience tensile fracture not due to bending. Yeh et al. (2006) indicated that 74.1% of glulam beam failures were initiated at the finger joints of laminae on the tension side of members. Therefore, it is suggested that the tensile test of finger-jointed laminae may provide a more-precise explanation of the flexural performance of a glulam beam in service. Usually tension is the weakest direction for glued bonds between wood substrates, and the glue line is more uniformly stressed in tension. Ayarkwa et al. (2000b) also reported that the joint efficiency of finger-jointed hardwood lumber tested in bending was higher than that tested in tension, and suggested that the tensile test was much more critical because it presented smaller values for the finger-jointed properties than the bending test. Morita et al. (2003) tried to predict the tensile performance of

Japanese cedar finger-jointed lumber using the modulus of elasticity through strain gages attached to the finger profiles by ignoring the effect of the finger tips. The results showed a good correlation between the tensile strength of a finger joint and the maximum strain energy instead of the maximum strain. This cannot be applied to some finger profiles with wider tips or some wood species with significant density changes between earlywood and latewood. Martinez and Calil (2003) found both frequencies of 1~17 Hz and stress levels of 60~90% of the maximum tensile strength had significant effects on the fatigue strength of finger-jointed pine wood. They proposed an orthogonal polynomial model with logarithmically transformed data to describe the fatigue behavior and tried to obtain results with a fewer number of tests, shorter testing times, lower cost, less variability, and greater reliability. However, that experimental work was done with small clear wood specimens, and further study may be needed for actual sizes used in structural applications. Recently, there has been interest in Taiwan in the use of glulam products in structural applications. This study was designed to investigate the effects of finger length and orientation of the finger profile using different softwood species on the structural performance of finger-jointed laminae with a tensile test.

MATERIALS AND METHODS

Materials

Five wood species commonly used for making glulam products including imported Douglas fir (*Pseudotsuga menziesii*, D), southern yellow pine (*Pinus* spp., S), western hemlock (*Tsuga heterophylla*, Hem), and SPF (spruce-pine-fir), and domestic plantation timber Japanese cedar (*Cryptomeria japonica*, J) were kiln-dried and machined. The equilibrated moisture contents of lumber for each wood species were 12.6~14.5%. All specimens were planed into a cross-section of 33 × 81 mm before finger formation. Resorcinol phenol formaldehyde adhesive (RPF, D-40, Wood Glue Industrial, Tainan, Taiwan) with a 60% solids content was used for the glue application. The hardener was paraformaldehyde powder.

Finger joint preparation

The finger formation of the wood components was processed using an 18Hp finger shaper equipped with a clamp device and a cut-off saw (KMFJ-400, Chuan Chier Industrial, Kaohsiung, Taiwan). Three finger joint cutters were selected to investigate the influence of finger length, of 18, 21, and 24 mm, on the joint strength. Each cutter had 2 tungsten blades 6 mm thick which made a finger pitch or spacing 6 mm wide with different finger tip widths as shown in Fig. 1. The orientation of the finger profiles during formation was also divided into 2 directions, horizontal (shaving along the width direction of the lumber, H) and vertical (shaving along the depth direction of the lumber, V) as shown in Fig. 2. Defects such as knots, splits, and wane were avoided at the lumber end used for finger formation. The RPF adhesive was then applied at a rate of 250 g m^{-2} to the finger surfaces. Specimens with a final size of 33 × 81 × 1200 mm were joined longitudinally by a 6100-mm long semi-automatic finger jointer with a maximum 10-ton capacity (KMFJ-400S, Chuan Chier Industrial), which was also equipped with four 1-MPa cylinders for applying vertical pressure during the horizontal assembly process. Pressures applied to the finger joints were 0.74 MPa for Japanese cedar and western hemlock lumber, 1.13 MPa for SPF lumber, 1.87 MPa for Douglas fir, and 2.61 MPa for southern pine based on the

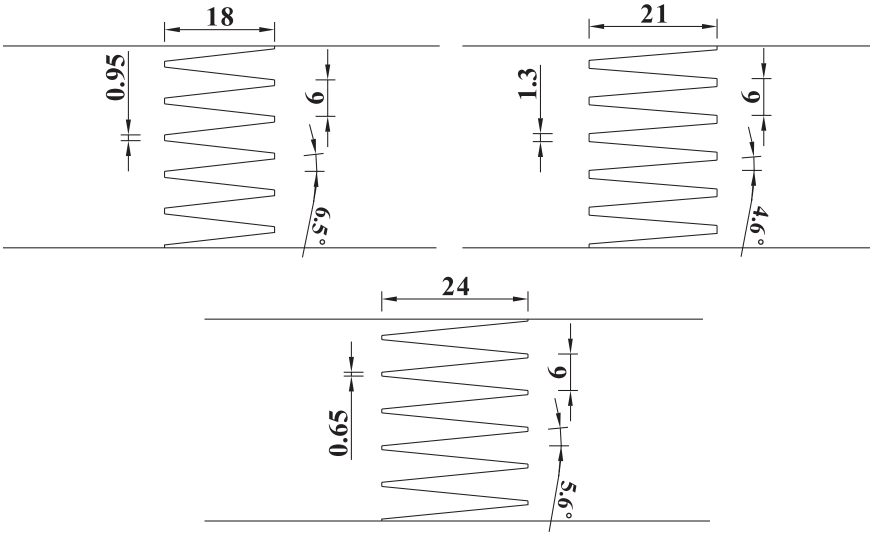


Fig. 1. Profiles of finger joint formation processed using 3 cutter specifications. (units: mm).

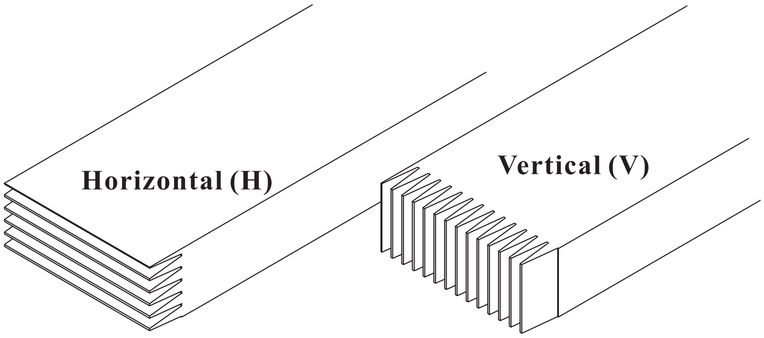


Fig. 2. Orientations of the finger formation of finger-jointed lumber.

cross-sectional area of the lumber specimens. The pressure was set for each wood species based on preliminary test results to prevent splitting during the application process.

Tensile test of the finger-jointed lumber

The tensile strength of solid wood lumber for each wood species was first evaluated based on CNS 11031 (Bureau of Standards, Metrology, and Inspection, 2006) for tension in longitudinal wood grain as the reference. The actual size of the lamina specimen was 30 (thickness)×80 (width)×1200 (length) mm with a curve that narrowed down to 30 mm in the middle portion of the width. A tensile testing machine with a maximum 50-ton capacity containing 2 sets of hydraulic pressure clamping jigs was developed for this project (Fig. 3). For finger-jointed specimens, 300 mm at both ends of the lumber was clamped by the jigs, and the test span was set to 600 mm long with the finger joint at the center. The average loading speed was < 10 MPa • min^{-1} when the tension load was applied. Both the maximum load as a the specimen failed and the failure modes were recorded for further calculation and analysis. Small clear wood specimens were also tested in tension based on the CNS

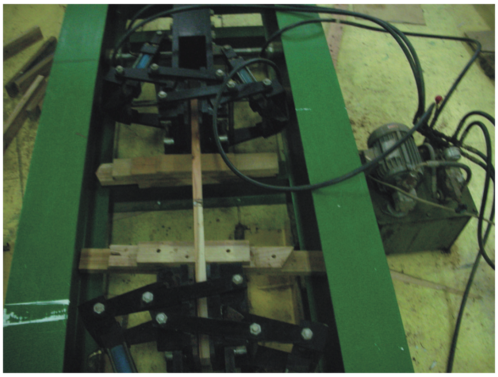


Fig. 3. Tensile testing machine.

456 standard (Bureau of Standards, Metrology, and Inspection, 2005) with a 10-ton universal testing machine (Gotech Testing Machines, Tainan, Taiwan). The size of specimens was 20×15×390 mm with a curve that narrowed down to 5 mm in the middle portion of the width. Each test condition had 12 replications.

RESULTS AND DISCUSSION

Basic properties of the solid wood

Table 1 presents the tensile strength results evaluated using both full-size and small clear solid wood specimens of 5 commercial softwood species. Southern pine had the highest tensile strength based on the small clear specimens, which was 33.7~60.0% higher than those of other wood species, followed by Douglas fir. It is noted that the order of tensile strength for each wood species had a similar trend to that of wood density. In general, the full-sized tensile strength evaluated from full-sized lumber was only 62.4 (Japanese fir)~81.6% (SPF) those of the small clear specimens except for hemlock lumber. It was found that hemlock lumber had good strength while showing the lowest tensile strength in small clear wood specimens. This might have been due to the even and dense annual rings in hemlock wood which showed no further reduction in characteristic mechanical properties as the lumber size changed.

Failure of the finger-jointed lumber

The failure modes of the finger-jointed lumber subjected to the tensile test were placed into 2 categories in the study. The major failure mode occurred at the finger joint which was further classified into 2 types depending on the density of the wood species as shown in Table 2. The broken fingers, 52% in total, were always found in wood species of low density such as Douglas fir and Japanese cedar (Fig. 4), while failure at the glue lines accompanying certain wood failure (7%) was found in southern pine, especially when the finger was formed from the earlywood portion. The remaining failures were on the lumber itself due to knots (23%), an inclined wood grain orientation (5%), and fibers broken in tension (12%) (Fig. 5).

It was also noted that finger-jointed lumber failed in tension with different modes depending on the wood species. There were

Table 1. Basic property of the wood species

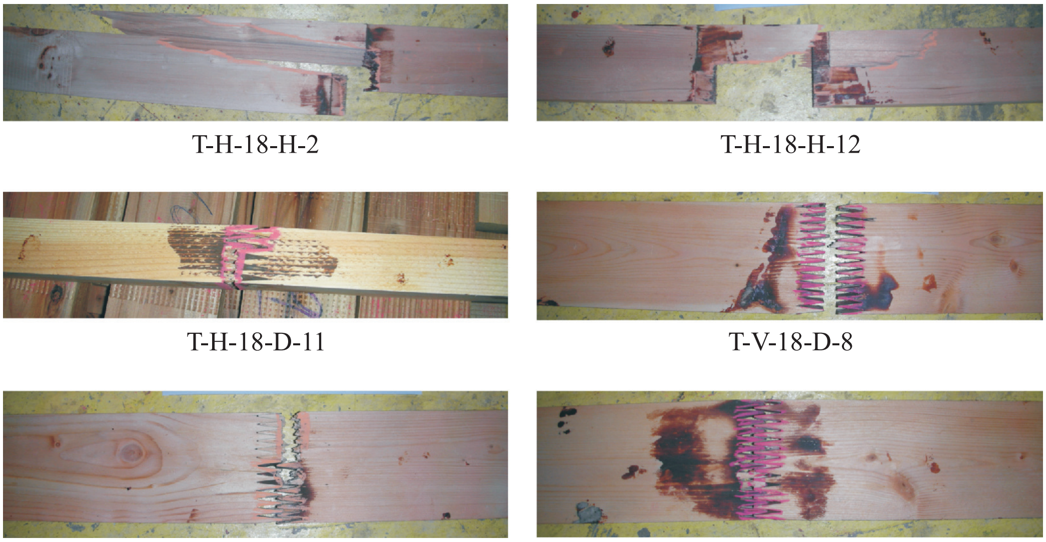
Species	Moisture content (%)	Density (g cm^{-3})	Width of annual rings (mm)	F_t (MPa) (full size)	F_t (MPa) (CNS 456)
Japanese cedar	14.5±0.1	0.48±0.07	4.89±1.39	42.6±8.3^{d}	68.3±12.2^{bc}
Hemlock	12.6±0.2	0.49±0.07	1.59±1.06	70.3±16.9^{b}	52.6±28.2^{c}
Spruce-pine-fir	13.3±0.1	0.49±0.06	2.36±0.48	53.7±13.4^{c}	65.8±27.8^{bc}
Douglas fir	14.3±0.2	0.52±0.62	2.11±0.65	55.1±17.0^{c}	87.1±20.6^{b}
Southern pine	13.6±0.1	0.65±0.06	3.48±1.00	92.7±14.6^{a}	131.4±20.4^{a}

Table 2. Failure occurrence of finger-jointed lumber subjected to a tensile test

Wood species	Joint type	Finger broken (%)	Glue line failure (%)	Failure at a knot (%)	Oriented wood grain (%)	Fiber tension failure (%)
Japanese cedar	H-18	92	-	8	-	-
	V-18	84	-	8	-	8
	H-21	84	-	8	-	8
	V-21	92	-	-	-	8
	H-24	92	-	-	8	-
	V-24	75	-	-	-	25
Hemlock	H-18	33	-	17	17	33
	V-18	33	17	33	8	8
	H-21	33	17	33	-	17
	V-21	58	-	17	17	8
	H-24	42	8	17	8	25
	V-24	17	8	33	8	33
Spruce-pine-fir	H-18	42	17	33	-	8
	V-18	17	-	58	-	25
	H-21	42	8	42	-	8
	V-21	25	25	50	-	-
	H-24	33	-	50	-	17
	V-24	25	-	67	-	8
Douglas fir	H-18	33	-	58	8	-
	V-18	75	8	17	-	-
	H-21	50	8	42	-	-
	V-21	67	-	33	-	-
	H-24	8	-	50	-	42
	V-24	36	-	27	9	27
Southern pine	H-18	83	-	-	8	8
	V-18	36	55	-	-	9
	H-21	50	8	-	8	33
	V-21	58	25	-	8	8
	H-24	67	8	-	25	-
	V-24	75	-	-	25	-

H, horizontal; V, vertical; 18, 21, and 24, 18-, 21-, and 24-mm-long finger profiles.

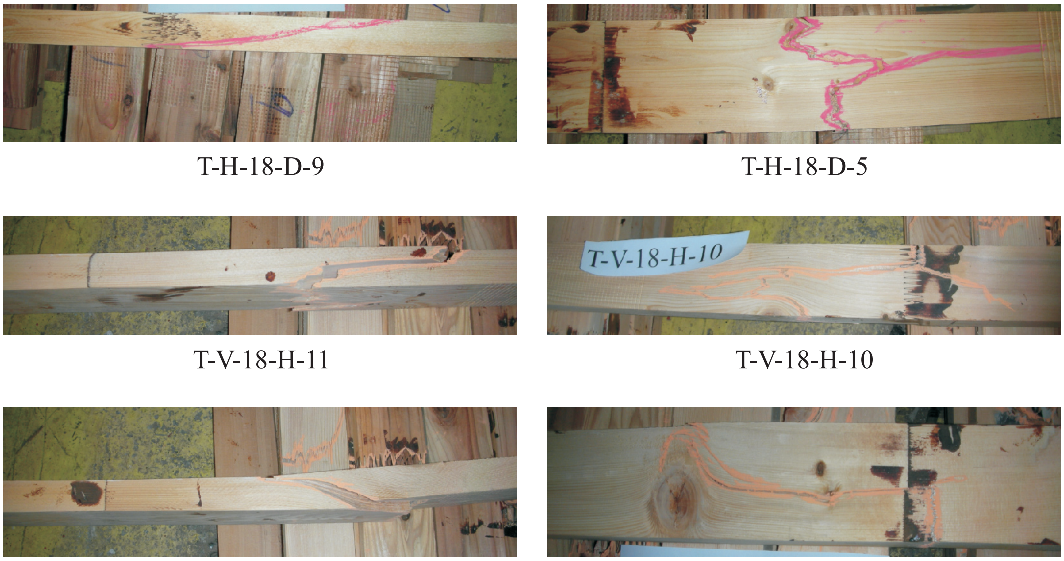
86% of finger-jointed specimens that failed due to broken fingers for Japanese cedar followed by 60% of southern pine and 45% of Douglas fir specimens as shown in Fig. 6. Morita et al. (2003) reported that all failures occurred at the finger joints of Japanese cedar and mostly at the base of 25-mm fingers with a lower Young's modulus, which are similar to results of this study. On the other hand, 50% of the SPF finger-jointed lumber failed due to the existence of knots. The major reasons for failure of Douglas fir finger-jointed lumber were broken fingers (45%) and knots (38%). Hemlock finger-jointed lumber failed due to the fibers broken in tension in addition to the 2 major causes mentioned above.


T-H-18-H-2 T-H-18-H-12

T-H-18-D-11 T-V-18-D-8

T-V-18-D-3 T-V-18-D-2

Fig. 4. Failure at the fingers and glue lines of finger-jointed lumber in tensile testing.



T-H-18-D-9 T-H-18-D-5

T-V-18-H-11 T-V-18-H-10

T-V-18-H-11 T-H-18-H-11

Fig. 5. Failure due to knots and the grain slope of finger-jointed lumber in tensile testing.

For the case of the broken-finger failure mode, overall there was no difference between horizontal and vertical joint formation of finger-jointed lumber. But for the SPF group, 64% of specimens failed in the horizontal joint formation and 36% in the vertical treatment case as indicated in Table 2. On the other hand, 32% of Douglas fir specimens failed in the horizontal joint formation and 68% in the vertical treatment case. This

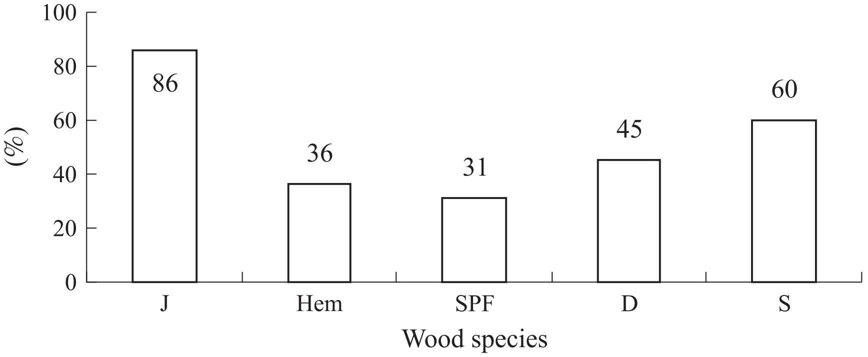


Fig. 6. Percentage of broken finger failure of finger-jointed lumber of various wood species subjected to the tensile test. J, Japaness cedar; Hem, hemlock; SPF, spine-pine-fir; D, Douglas fir; S, southern pine.

means the wood characteristic quality in terms of wood species is highly related to the structural performance of finger-jointed products. Ayarkwa et al. (2000a) demonstrated that open lumens and pores filled with glue of low-density hardwoods achieved high joint efficiency, but when only the wood surface was covered with glue with high-density wood indicating poor penetration, there was low joint efficiency based on a scanning electron microscopic (SEM) examination. Further, there seemed to be no effect of finger lengths of 18~24 mm on the failure mode in the study.

Tensile properties of finger-jointed lumber

The tensile strength results of finger-jointed lumber were statistically analyzed with the analysis of variance (ANOVA) procedure. It showed that the parameters of wood species and finger length had significant effects on the strength properties, while the finger profile orientation did not change the tensile strength of finger-jointed lumber (Table 3). The interaction among these parameters also made a difference in the strength for each treatment combination.

There was a significant difference in tensile strength of finger-jointed lumber among the 5 wood species due to variations in wood density, proportions of earlywood/latewood, and widths of the annual rings, which may have had effects on the structural joint performance. Southern pine finger-jointed lumber showed the highest tensile strength, which was 116.6% higher than that of the lowest Japanese cedar group, followed by Douglas fir group, which was 65.9% higher than that of Japanese cedar group as shown in Fig. 7. The hemlock and SPF groups had similar tensile strengths and also had significantly higher tensile strengths than the Japanese cedar group by 46.8 and 40.7%, respectively. It is noted that the weakest Japanese cedar group still met the requirement of the no. 1 grade in tensile strength as specified by CNS 11031 for structural glulam manufacturing. The efficiency of a finger joint, calculated as the percentage ratio based on the corresponding tensile strength of full-sized solid wood specimens, ranged 48.1~83.5% as shown in Table 4. Douglas fir finger-jointed lumber showed the best joint efficiency, at 74.1%, followed by the SPF group, at 65%, among the 5 wood species (Fig. 8). The finger-jointed lumber of

Table 3. ANOVA analysis of the tensile strength of finger-jointed lumber

Variable	Degrees of freedom	*F* value	Significance
Species (Sp)	4	138.2	0.000[2)]
Finger length (Fl)	2	7.223	0.001[2)]
Finger orientation (Fo)	1	1.291	0.257
Sp×Fl	8	2.578	0.010[1)]
Sp×Fo	4	2.559	0.039[1)]
Fl×Fo	2	4.648	0.010[1)]
Sp×Fl×Fo	8	4.351	0.000[2)]

[1)] Significant at the 5% level.

[2)] Significant at the 1% level.

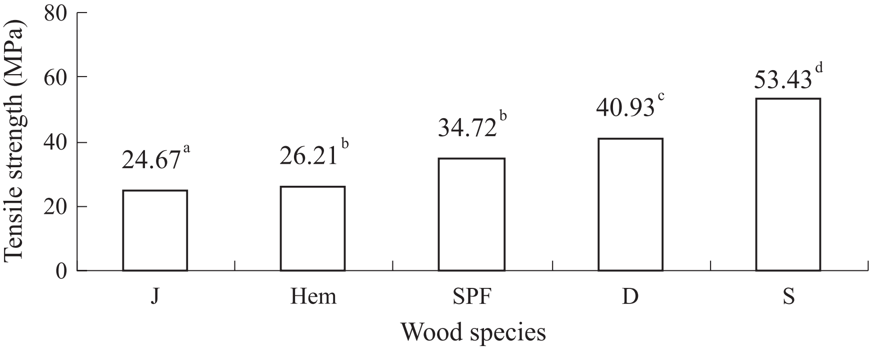


Fig. 7. Tensile strength of finger-jointed lumber among wood species. J, Japaness cedar; Hem, hemlock; SPF, spine-pine-fir; D, Douglas fir; S, southern pine.

these 2 wood species contained knot defects which consequently caused a key failure in tension, and might be one of the reasons it reached a high percentage of tensile strength of the solid wood. Both Japanese cedar and southern pine finger-jointed lumber had lower joint efficiencies due to the weak finger profiles which caused early failure in tension. In fact, Selbo (1975) suggested that the tensile strength of a typical finger-jointed connection would have about 70% of the efficiency of clear wood. This may show the adequacy of the finger geometry for Douglas fir and SPF in this study. Further, Janowiak et al. (1993) indicated that the joint efficiency based on the flexural strength for 3 commercial hardwoods assembled with resorcinol formaldehyde resin was 84.5%, which showed better efficiency than that estimated based on the tensile strength, of 73.4%. Yeh et al. (2009) also reported a finger-joint efficiency of 77.7% based on the flexural strength for 5 softwood species. Only 61.8% joint efficiency estimated based on the tensile strength was found in that study, which overall indicates a better finger geometry is required to improve the structural performance of finger-jointed lumber.

In general, the tensile strength of lumber jointed with the 21-mm-long finger profile showed a significantly lower value than those of the 18- and 24-mm finger profile groups by 11.3 and 8.5%, respectively. Ayarkwa et al. (2000a) pointed out that the slope between the pitch and finger length of about 1 in 7 could reduce the joint strength until about a zero slope when the strength becomes almost negligible. On the other hand, finger tips constitute a series of butt joints and can be accorded zero strength. The width of the finger tip further represents a reduction in the cross section when considering the related glue line area at the joint. In this study, 21-mm finger joints with a tip of 1.3 mm wide were larger than those of 18- and 24-mm finger joint groups. The stress concentration may develop due to the existence of wide finger tips. Hernandez (1998) pointed out that the tip width is the geometric parameter that most significantly influences the strength of finger joints and suggested a tip width of no more than 0.5~0.7 mm. The cross-section reduction factor is the ratio of the tip width to the pitch according to DIN 68140 (German Institution for Standard 1971). Consequently, values of the cross-section reduction factor were 15.9, 21.7, and 10.9% for the 18-, 21-, and 24-mm finger profiles, respectively. This might explain why the 21-mm finger-jointed lumber had a lower tensile strength. It was noted that the finger slopes were 1 in 8.8 (18-mm finger), 1 in 12.4 (21-mm finger), and 1 in 10.2 (24-mm finger). And, the joint efficiencies were 63.2, 57.6, and 64.5% for the 18-, 21-, and 24-mm finger-jointed lumber, respectively, also indicating the poor finger profile for the 21-mm finger joint group.

Table 4. Duncan's multiple-range analysis of the tensile strength of finger-jointed lumber

Treatment	Tensile strength (MPa)	Finger joint efficiency (%)
J-H-21	22.09 1 A	51.9
J-V-21	24.04 1 A	56.4
J-H-18	24.17 1 A	56.7
J-H-24	25.24 1 A	59.2
J-V-24	26.18 1 A	61.5
J-V-18	26.48 1 A	62.2
SPF-H-21	28.50 1 AB	53.1
SPF-V-21	33.29 1 BC	62.0
SPF-V-18	33.66 1 BCD	62.7
Hem-V-24	33.83 1 BCD	48.1
Hem-V-18	34.05 1 BCD	48.4
Hem-V-21	34.74 1 BCDE	49.4
SPF-H-24	35.39 1 BCDEF	65.9
D-V-21	35.71 1 CDEF	64.8
Hem-H-18	36.14 1 CDEF	51.4
D-H-24	36.33 1 CDEF	65.9
Hem-H-21	37.26 1 CDEF	53.0
SPF-H-18	37.40 1 CDEF	69.6
D-H-18	39.31 1 CDEFG	71.3
SPF-V-24	41.04 1 DEFG	76.4
Hem-H-24	41.93 1 EFG	76.1
D-H-21	42.66 1 FG	77.4
D-V-24	44.99 1 G	81.7
S-V-21	45.60 1 G	49.2
S-H-24	45.81 1 G	49.4
D-V-18	46.01 1 G	83.5
S-H-21	54.92 1 H	59.2
S-H-18	56.19 1 H	60.6
S-V-24	56.49 1 H	60.9
S-V-18	61.01 1 H	65.8

Finger joint efficiency (%) = F_t (jointed member) / F_t (full size).

Values with different letters significantly differ at $p < 0.05$.

J, Japanese cedar; SPF, spruce-pine-fir; Hem, hemlock; D, Douglas fir; S, southern yellow pine.

There was no significant difference in tensile strength of finger-jointed lumber between those with horizontal and vertical finger formation. With the exception of the 21-mm finger-jointed group, slightly higher (7%) tensile strengths for the 18- and 24-mm finger length groups with vertical finger-joints were also obtained, compared to that with horizontal joints. An 11.5% higher bending strength was obtained for a vertically jointed lumber compared to horizontally jointed lumber by Yeh et al. (2009). Janowiak et al. (1993)

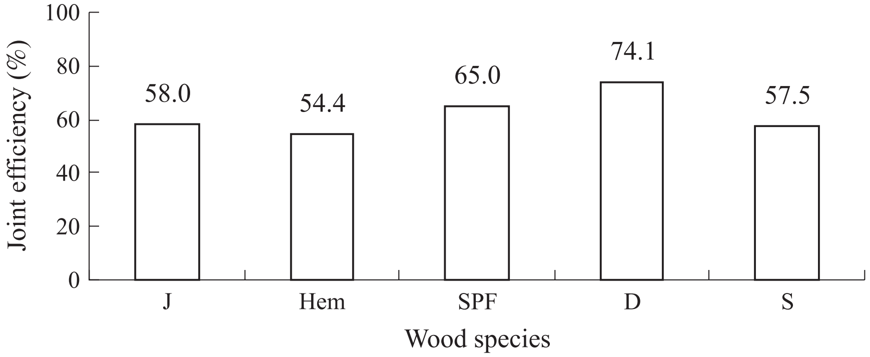


Fig. 8. Finger joint efficiency of the tensile performance among wood species. J, Japaness cedar; Hem, hemlock; SPF, spine-pine-fir; D, Douglas fir; S, southern pine.

also found that bending strength values were slightly higher for all wood species fabricated with vertical finger-joints using resorcinol formaldehyde resin, but higher tensile strengths were found for red maple and yellow poplar fabricated with horizontal finger-joints, but not red oak. It seems that the tensile strength of finger-jointed lumber is more sensitive to the characteristics of the wood species. In this study, the tensile strength of horizontally jointed hemlock lumber was 12.3% higher than that of vertically jointed lumber, which had a different tendency from the other 4 wood species.

CONCLUSIONS

The following general conclusions can be drawn from this study. The major failure mode of the structural finger-jointed lumber of 5 softwood species subjected to a tensile test was mainly due to weak finger-joints, followed by knot defects. The cause for failure in tension is highly dependent on the growth characteristics of the wood species. Southern pine finger-jointed lumber showed the highest tensile strength followed by Douglas fir, hemlock, and SPF, while the lowest was the Japanese cedar group, which followed the tendency of wood density. Douglas fir and SPF finger-jointed lumber showed adequate joint efficiency among the 5 wood species. It is suggested that an adequate finger profile or geometry is necessary to improve the structural performance of the finger-jointed lumber of the 3 other species. The tensile strength of lumber jointed with a 21-mm long finger profile showed a lower value than those of the 18- and 24-mm finger profile groups due to the higher ratio of tip width to pitch. No significant difference in the tensile strength of finger-jointed lumber was found between horizontal and vertical finger formation.

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