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Bearing properties of engineered wood products I: effects of dowel diameter and loading direction

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Abstract The embedment tests of laminated veneer lumber (LVL) with two moduli of elasticity (MOE; 7.8 GPa and 9.8 GPa), parallel strand lumber (PSL), and laminated strand lumber (LSL) were conducted in accordance with ASTM-D 5764. The load-embedment relation for each of these engineered wood products (EWPs) was established. The directional characteristics of bearing strength (σ_e), initial stiffness (k_e), and effective elastic foundation depth were obtained from the tested results. The effective elastic foundation depth ($\alpha = E/k_e$, E = MOE), based on the theory of a beam on elastic foundation, was obtained from the k_e and MOE. An α of 90° (perpendicular to the grain) was calculated by dividing E_{90} [MOE of 90° from the compression test, but MOE of 0° (E_0), parallel to the grain, obtained from the bending test] by k_{e90}, the initial stiffness of 90°. This study aimed to obtain the bearing characteristics of each EWP, taking into consideration their anisotropic structures, for estimating the fastening strength of a dowel-type fastener. The relations between the bearing coefficients (σ_e, k_e, α) on the loading direction and dowel diameter were established from the load-embedment curves. Based on the results of the embedment test, tested EWPs showed different tendencies in all directions from wood and glued laminated timber.

Key words Engineered wood products · Embedment test · Bearing strength · Initial stiffness · Effective elastic foundation depth

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Introduction

Engineered wood products (EWPs) are increasingly being applied as structural members in wooden constructions. These EWPs include glued laminated timber (GLT), laminated veneer lumber (LVL), parallel strand lumber (PSL), and laminated strand lumber (LSL).

Among these EWPs, GLT (which has been used as a structural member), seems to be the major product with reliable strength properties. Currently, structural design formulas for mechanical joints of wood (sawn lumber) and GLT are assigned by the Architectural Institute of Japan (AIJ).[1] These formulas are mainly based on past experimental data.[2,3] The bearing characteristics of wood and GLT are related to dowel diameters, as illustrated by Eq. (1) and (2).[1–3]

$$k_{e0} = E_0/(3.16 + 10.9d) \quad (1)$$

$$k_{e90} = k_{e0}/3.4 \quad (2)$$

where: d is the dowel diameter (cm); k_{e0} is the initial stiffness loaded parallel to the grain (kgf/cm^3); k_{e90} is the initial stiffness loaded perpendicular to the grain (kgf/cm^3); and E_0 is the modulus of elasticity (MOE) of wood parallel to the grain (kgf/cm^2).

These design formulas were established before the existence of most EWPs other than GLT. In contrast to wood and GLT, the properties of other EWPs vary according to the element size, gluing condition, grain direction, and anisotropic nature of their element. Thus each EWP has its own unique mechanical properties, and it is necessary to investigate the applicability of the present design formulas proposed by AIJ for these products.

When formulating the new structural design formulas, it is difficult to estimate the initial stiffness (bearing constant) perpendicular to the grain, k_{e90}. According to the definition of initial stiffness,[4] k_{e90} should be estimated based on E_{90}, the MOE perpendicular to the grain. However, information on E_{90} is limited. Because the value of E_{90} is considered to be 1/25 of MOE parallel to the grain (E_0) by AIJ,[5] k_{e90} may

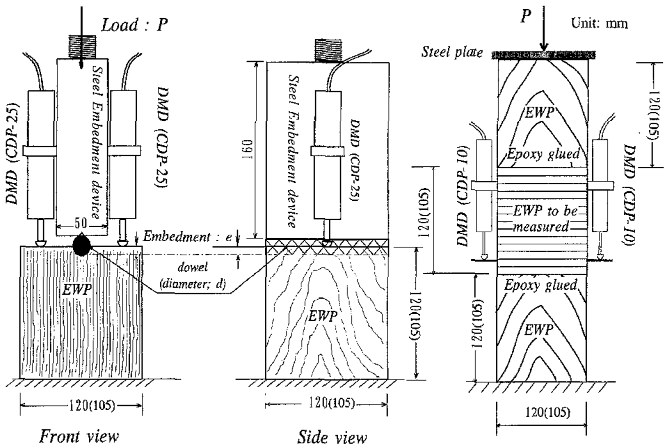

Fig. 1. Embedment test (left, middle) and compression test (right) for modulus of elasticity (MOE) of 90° (E_{90}). *DMD*, deflection measuring device; *EWP*, engineered wood products

alternatively be estimated from Eq. (2), where the k_{e0}/k_{e90} ratio is 3.4. In this study, the E_{90} was estimated using the compression test, the second best method, as it was not possible to prepare the bending test specimens from the test materials available. The E_0 values for the EWPs tested were obtained based on the results of the bending test.

The dowel-bearing tests (Fig. 1) were conducted on two kinds of LVL, PSL, and LSL to obtain the following basic data. The bearing strength or stress (maximum bearing strength σ_{max}, 2% offset bearing strength $\sigma_{0.02}$, 5% offset bearing strength $\sigma_{0.05}$) was determined based on the bearing load/dowel diameter ratio and the dowel length. Here, the bearing strength is defined as load divided by the projected bearing area. It can be expressed as P/ld, where P is the load, l is the bearing length, and d is the dowel diameter. The initial stiffness (k_e), was calculated from the bearing strength/bearing deformation ratio. The effective elastic foundation depth[4] ($\alpha = E/k_e$, E = MOE), based on the theory of a beam on an elastic foundation, was obtained from the initial stiffness and MOE. An α of 90° was calculated from E_{90} (MOE perpendicular to the grain, obtained from the compression test) divided by k_{e90} (initial stiffness of 90°, perpendicular to the grain). An α of 0° was estimated using E_0 from the bending test. The α of EWPs estimated from the E_0 based on the bending test was compared with those of wood and GLT.

The relation between these bearing properties of EWPs related to the loading direction with reference to element and grain directions and dowel diameter was investigated. The bearing characteristics of each EWP, taking into consideration their anisotropic structure, are important and comprise the preliminary data for estimating the fastening strength of all dowel-type metal fasteners.

Materials and methods

Four types of EWP were used: LVL (radiata pine, *Pinus radiata* D. Don) 80E (this means the MOE is about 7.8 GPa) and 100E (MOE about 9.8 GPa), and PSL (Douglas fir, *Pseudotsuga taxifolia* Poir) 2.0E (MOE about 15.2 GPa), and LSL (Aspen mixed) 90E (MOE about 8.8 GPa). The nominal sizes of the test specimens were 120 × 120 × 120 mm, except LSL, whose size was 105 × 105 × 105 mm. These materials were chosen from commercially distributed products, so the cross-sectional sizes of the specimens were already determined. Four-point bending tests for the E_0 were first conducted by loading long-term allowable bending stress of the specimen's outermost element, followed by determining the dynamic MOE (E) by the transverse vibrating method. The specimens were then cut to the above-mentioned dimensions. The load-embedment relations were obtained in accordance with ASTM-D 5764,[6] and reference was also made to earlier studies.[1,7–9]

Embedment tests were conducted on the cubic specimens with predrilled half-holes, which were 1–2 mm larger than the dowel diameter, using Instron 1125 (98 kN capacity). A reversible load cell (Instron 2511-306, 98 kN capacity) was used, and the loading speed was 2 mm/min. During the embedment test care was taken to prevent the dowel from bending. Figure 1 shows the setups for the embedment test and compression test for measuring E_{90}. The tests were conducted for four types EWPs with three element orientations, two loading directions, and ten dowel diameters (6, 8, 10, 12, 14, 16, 18, 20, 22, 24 mm). The dowel used was a hard steel bar 120 mm long. Six replicates were used for each test, and there were 1440 test specimens.

For the compression test with six replications on each EWP, as shown at the right of Fig. 1, the specimens were prepared with three cubic blocks, where the center cube was protected by two outside cubes, glued with epoxy resin, to maintain pure loading flow using the same materials to determine any effects of the test machine during loading. The loading speed for the compression test was 1 mm/min, using the test machine of Instron 8505 (980 kN capacity) with reversible load cell (Instron 2518-120, 980 kN capacity).

Figure 2 shows the loading direction for the test specimens with reference to their element orientations. As illustrated in Fig. 2, the loading directions in the CH and CV specimens are considered to be 0° (parallel to the grain), and the others 90° (perpendicular to the grain).

Figure 3 shows the determination of 2% and 5% offset bearing strength values from the bearing strength-embedment curve. Based on the curve, a line is drawn through 0.1 and 0.4 points of σ_{max}, and the k_e is obtained as a slope of the line. The $\sigma_{0.02}$ and $\sigma_{0.05}$ can then be deduced from the curve based on 2% and 5% offsets of dowel diameters. Practically, the $\sigma_{0.05}$ could not be obtained in some specimens, as the specimens did not have sufficient data for calculating the 5% offset value. The 2% offset values for the diameter, adopted from past research,[10] were obtained from each EWP for the purpose of comparing it with the 5% offset values. In some specimens (RV and TV specimens in Fig. 2) where the loading direction is perpendicular to the grain, it was difficult to define σ_{max} because the loads of these specimens increased after reaching the yield point.

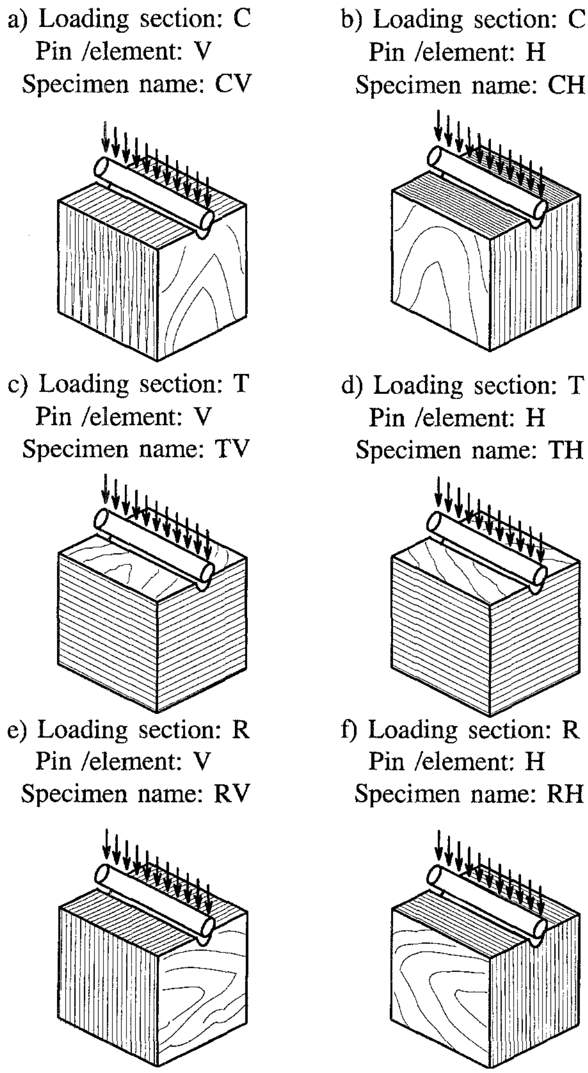

Fig. 2. Specimen names for all structural directions of engineered wood products. *Pin/element*, direction situation between dowel and element; *C*, cross section; *T*, tangential section; *R*, radial direction; *H*, horizontal loading to the element direction; *V*, vertical loading to the element direction

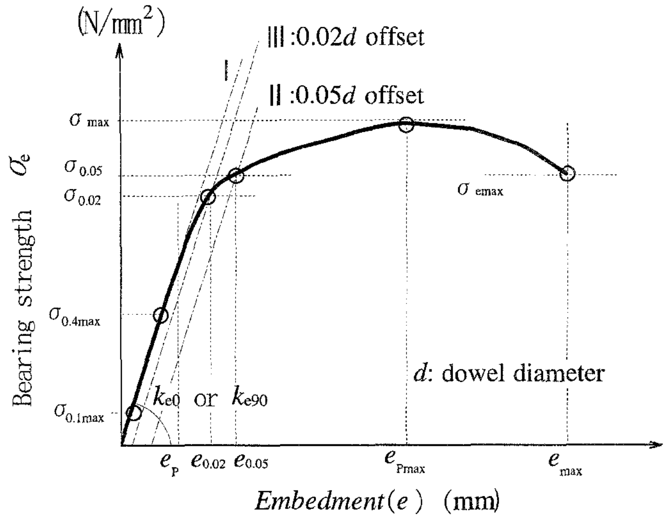

Fig. 3. Method for evaluating bearing strength (σ_e) and initial stiffness (k_e). *I*, initial proportional line through $\sigma_{0.1max}$ and $\sigma_{0.4max}$; *II*, 5% offset line of diameter from line *I*; *III*, 2% offset line of diameter from line *I*; σ_{max}, maximum bearing strength; σ_{emax}, bearing strength at maximum embedment; $\sigma_{0.05}$, 5% offset bearing strength; $\sigma_{0.02}$, 2% offset bearing strength; $\sigma_{0.4max}$, bearing stress at 40% of maximum bearing strength; $\sigma_{0.1max}$, bearing stress at 10% of maximum bearing strength; k_{e0}, initial stiffness parallel to the grain; k_{e90}, initial stiffness perpendicular to the grain; e_p, embedment at proportional strength; $e_{0.02}$, embedment at 2% offset bearing strength; $e_{0.05}$, embedment at 5% offset bearing strength; e_{Pmax}, embedment at maximum bearing strength; e_{max}, maximum embedment

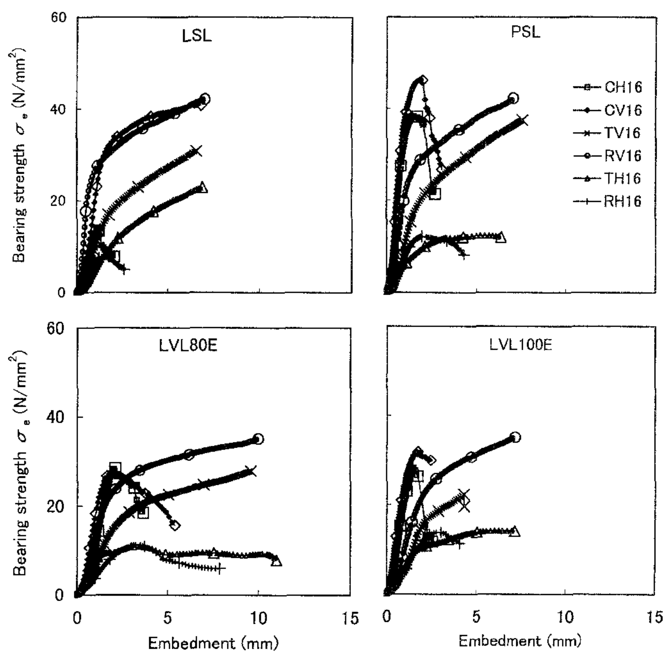

Fig. 4. Typical examples of bearing strength (σ_e) and embedment. The number in the specimen name indicates the dowel diameter (mm)

The effects of dowel diameter and loading direction on the bearing strength, k_e, and a were determined.

Table 1 shows the densities, moisture contents, and static and dynamic Young's moduli (E_0, E_{90}, E') of each EWP. Moisture contents were measured using a high-frequency capacity-type moisture meter, HM520 (MOCO-2, Kett Co.).

Results and discussion

Based on the structure of EWP, the CH and CV specimens in Fig. 2 were loaded parallel to the grain, whereas the TV and RV specimens were loaded perpendicular to the grain. Because it is rare to have the loading in the directions of TH and RH in real-life applications, only the CH-TV and CV-RV relations were investigated in detail in this study. The initial stiffness of some TV and RV specimens were derived based on the line connecting the 0.1 and 0.4 points of σ_{max}, as illustrated in Fig. 3.

Figure 4 shows some typical examples of the relations between the embedment and bearing strengths derived from

Table 1. Moisture content, timber density, and each modulus of elasticity of engineered wood products

EWP	Grade	*TD*, air-dried (kg/m³)	MC (%)		MOE (GPa)					
			Moisture meter	Oven-dried	E_L		E_C		E'	E_{90}
					LR	LT	LR	LT		
LSL	90E	619 (13.89)	13 (1.18)	7 (0.45)	9.5 (0.35)	9.5 (0.24)	11.2 (1.66)	10.9 (1.51)	10.4 (0.34)	0.34 (0.01)
PSL	2.0E	657 (26.83)	12 (1.34)	11 (1.15)	15.1 (1.07)	15.3 (0.98)	18.4 (3.01)	18.5 (3.51)	17.6 (0.96)	0.61 (0.10)
LVL80E	80E	491 (8.54)	11 (1.03)	11 (0.49)	8.0 (0.43)	7.8 (0.37)	9.6 (0.82)	9.4 (0.89)	8.9 (0.48)	1.08 (0.28)
LVL100E	100E	508 (6.45)	11 (0.98)	10 (0.63)	10.1 (0.63)	9.9 (0.36)	12.3 (1.75)	12.3 (1.62)	11.3 (0.33)	1.08 (0.28)

EWP, engineered wood products; *TD*, timber density; MC, moisture content; MOE, modulus of elasticity; E_L, MOE in overall length of the bending test; E_C, MOE in no shear range of the bending test; LR (LT), loading direction parallel to the radial (tangential) direction during the bending test; E', dynamic MOE parallel to the grain; E_{90}, MOE from the compression test; LSL, laminated strand lumber; PSL, parallel strand lumber; LVL, laminated veneer lumber
Numbers in parentheses are standard deviations

the embedment test for various EWPs. It is clear that these EWPs have different bearing strengths, depending on the loading directions with respect to their element orientations.

2% Offset bearing strength and dowel diameter

Figure 5 shows the relation between $\sigma_{0.02}$ and the dowel diameter for various loading directions. Except for the RH specimen of PSL and the CH specimen of LSL, most EWPs did not show a clear correlation between $\sigma_{0.02}$ and dowel diameter. For PSL and LVL, the $\sigma_{0.02}$ of CH and CV specimens was higher than that of TV and RV specimens. For LSL specimens, the strength and trend of variation in $\sigma_{0.02}$ for TV specimens were similar to those of CH; the CV specimen recorded higher strength values than the RV specimens. The $\sigma_{0.02}$ of RH and TH specimens showed a similar trend of variation and mean bearing strength values as the dowel diameter increased; however, these values were generally lower than those for other specimens.

The reason for the small difference between the $\sigma_{0.02}$ in the CH specimen and the $\sigma_{0.02}$ in the TV specimen for LSL is not clear. It may be due to the fact that the thin elements of LSL create a rather directional weakness compared to that of other EWPs, causing many CH and TV specimens to split during loading. Except for the CH and TV specimens of LSL, the results showed that each EWP had a different bearing strength because of its difference in structure.

The $\sigma_{0.02}$ of LVL80E and LVL100E showed similar trends of variation and values when the dowel diameter increased, irrespective of the loading direction. All LVL specimens exhibited similar relations between $\sigma_{0.02}$ and dowel diameter.

For all four of the EWPs studied, lower values were recorded in the RH and TH specimens. This is because the embedding load tends to induce shear failure (split) parallel to the element orientation direction during the embedment test.

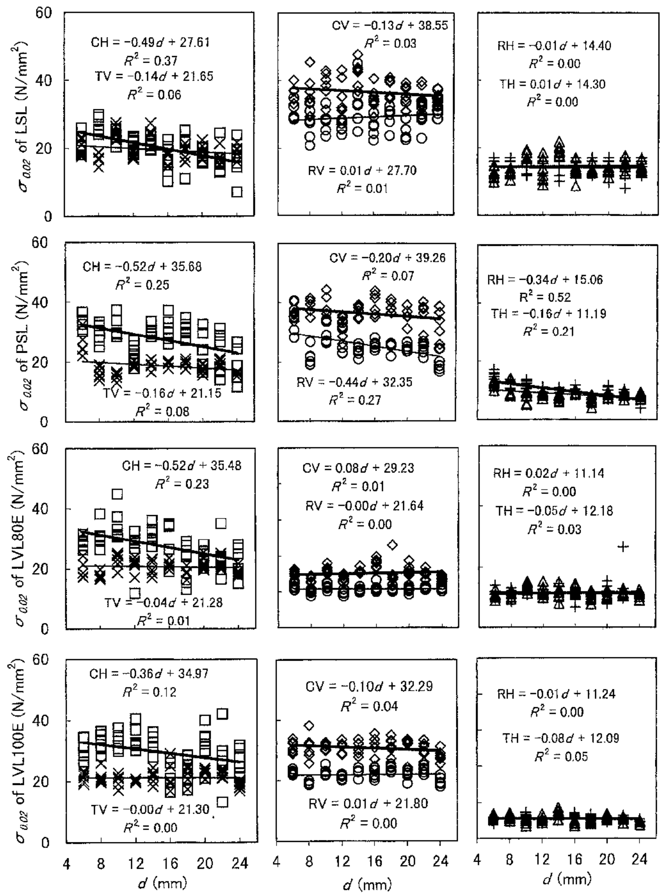

Fig. 5. Relation between 2% offset bearing strength ($\sigma_{0.02}$) and dowel diameter (*d*). *Thick solid lines* express the regression line of the top specimens; *thin solid lines* express that of the bottom specimens; *squares*, CH specimens; *crosses*, TV specimens; *diamonds*, CV specimens; *circles*, RV specimens; *pluses*, RH specimens; *triangles*, TH specimens

5% Offest bearing strength and dowel diameter

When determining $\sigma_{0.05}$ the data for $\sigma_{0.05}$ decreased with increasing dowel diameter. This is because most specimens split before reaching $\sigma_{0.05}$ when the dowel diameter increased. The specimens experienced shear failure in the lateral direction, as the large-diameter dowel induced greater shear in the lateral direction rather than causing failure due to embedment action in the loading direction.

Figure 6 shows the relation between $\sigma_{0.05}$ and dowel diameter. The $\sigma_{0.05}$ of these EWP specimens became almost

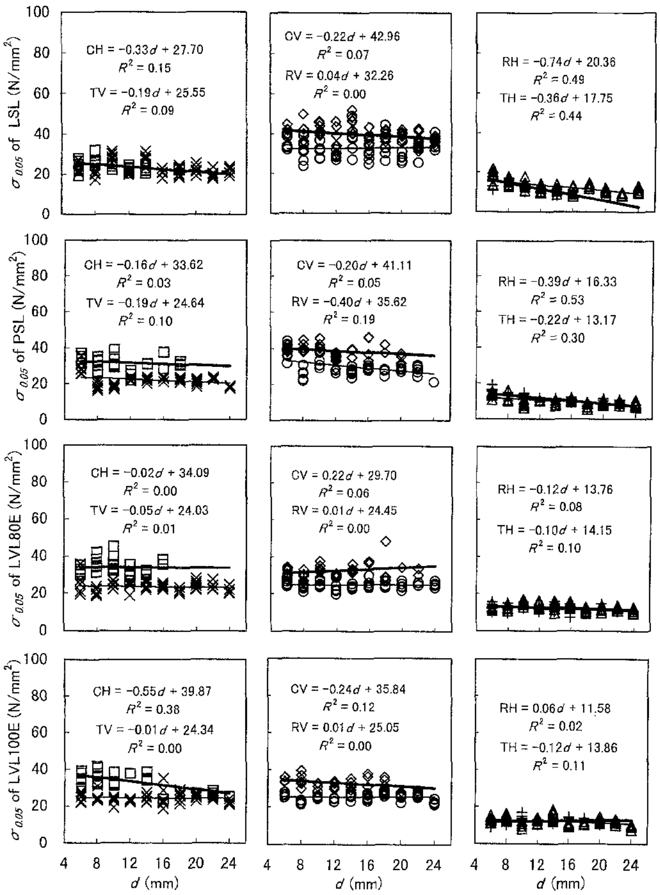

Fig. 6. Relation between 5% offset bearing strength ($\sigma_{0.05}$) and dowel diameter (d). See Fig. 5 for further information

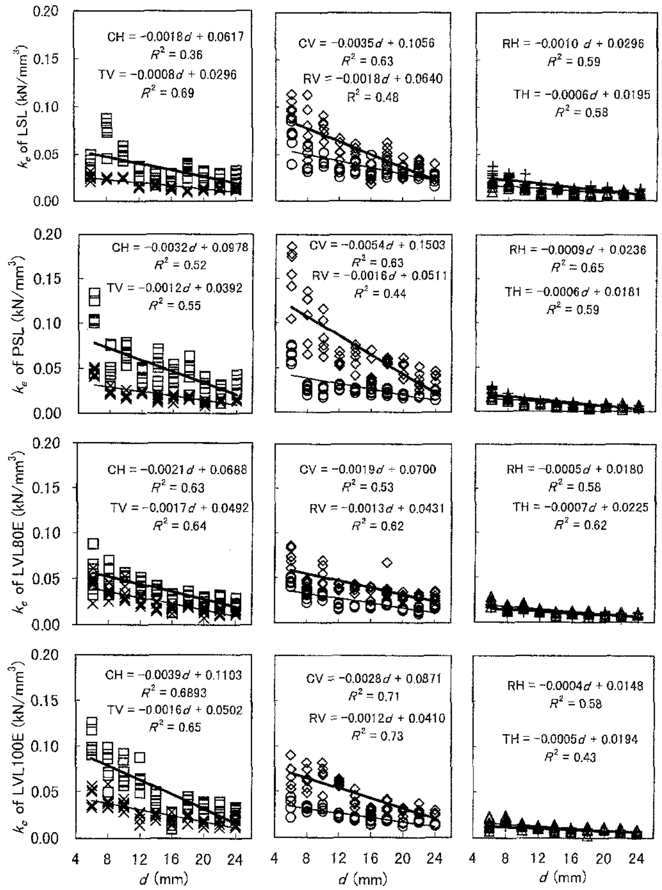

Fig. 7. Relation between initial stiffness (k_e) and dowel diameter (d). See Fig. 5 for further information

constant as the dowel diameter increased. In most of the specimens, $\sigma_{0.05}$ seems to be proportional to $\sigma_{0.02}$.

The CH specimen of LSL had fewer data than the TV specimen. In particular, no $\sigma_{0.05}$ data could be obtained for the RH specimen of LSL for dowel diameters ranging from 16 to 24mm. Based on the results obtained, $\sigma_{0.02}$ is recommended to be used as the characteristic bearing strength for these EWP.

Initial stiffness and dowel diameter

Figure 7 shows the relations between the initial stiffness (k_e) and dowel diameter (d) for all the specimens. As shown in the graphs, there was a reduction in k_e with increasing dowel diameter. The relation between k_e and dowel diameter could be established when loading parallel to the grain (CH, CV) or perpendicular to the grain (TV, RV, TH, RH). However, the regression coefficients of these relations were different for each EWP, which could be attributed to the differences in the structure and size of the elements in these EWPs. As mentioned above for the 2% offset bearing strength, the variation in k_e may be due to the characteristics of each EWP, such as the lathe checks in LVL, voids in PSL, and the thin element in LSL.

For LVL80E and LVL100E, the values of k_e decreased with increasing dowel diameter, irrespective of the loading direction. However, the slopes of the regression lines in CH and CV directions of LVL100E were greater than that of LVL80E. This shows that despite having the same composite structure a material with a higher MOE could result in a different correlation between k_e and the dowel diameter.

The PSL had a higher k_e value than did LSL and LVL, but it registered a markedly high variance in the value of k_e in all loading directions. For PSL, LSL, and LVL, the loading directions of CH and CV had the highest k_e followed by the TV and RV specimens. RH and TH specimens, which had similar k_e values, were the lowest among all the loading directions.

Effective elastic foundation depth and dowel diameter

According to the Harada,[4] it is possible to calculate the effective elastic foundation depth α based on the values of k_e and MOE. This means that the α is higher conception than k_e because it is evaluated by the effects of both MOE and k_e. The α increased with increasing dowel diameter d and was affected by the value of k_e to a greater extent than

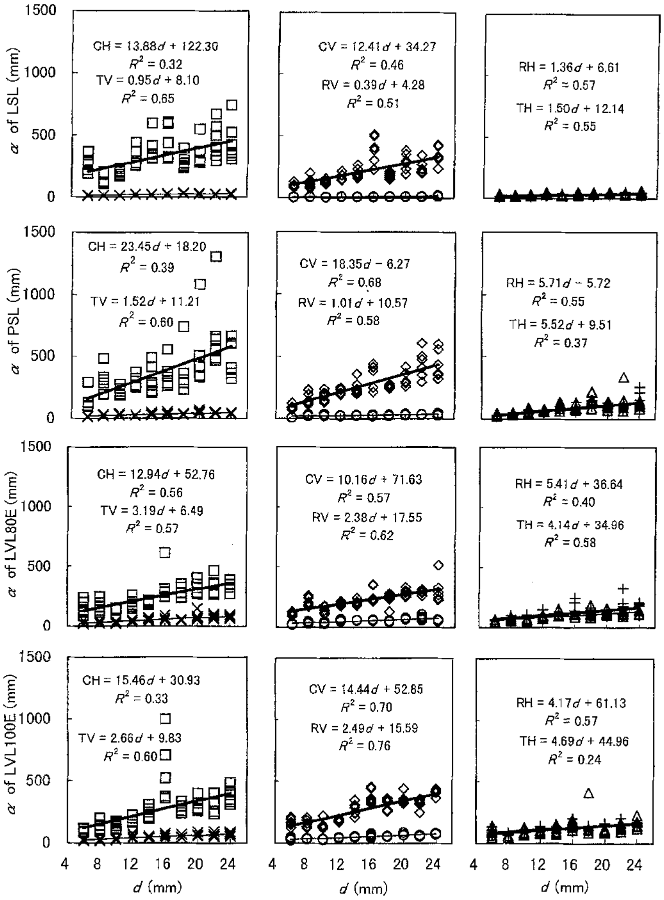

Fig. 8. Relation between effective elastic foundation depth (α) and dowel diameter (d). See Fig. 5 for further information

by the MOE of the material because the MOE was the same for each EWP. Because the structures of LVL, PSL, and LSL are quite different from those of solid wood and GLT, their α was used as a major factor to indicate their bearing properties.

In previous studies[8] the α values for wood and GLT were obtained using Eq. (1) based on the experimental data. The α was calculated only in the case of loading parallel to the grain, as it was difficult to obtain the MOE when loading perpendicular to the grain. In this study, α was evaluated by employing their individual MOEs (E_0, E_{90}) from Table 1.

As shown in Fig. 8, the α generally increased as the dowel diameter increased, with a little variation. Compared to the earlier study on GLT, for all four types of EWP examined the CH and CV specimens showed a greater increase in α than the TV and RV specimens as the dowel diameter increased.

Almost all of the EWPs had higher coefficients of regression between the α and dowel diameter than GLT,[2,3] indicating a greater effect of the dowel diameter on α in these EWPs, especially PSL. This could be due to the presence of more voids among the elements in PSL. As the predrilled hole size (dowel diameter) increases, these voids tend to reduce the value of k_e. Therefore the α had a high value from Eq. (1) because the MOEs of PSL are almost all

Table 2. Results of initial stiffness and effective elastic foundation depth

EWP	CH (0°)		CV (0°)		TV (90°)		RV (90°)		0°/90° Ratio		RH (90°)		TH (90°)	
	C_0	C_1	C_0	C_1	C_0	C_1	C_0	C_1	CH/TV	CV/RV	C_0	C_1	C_0	C_1
LSL														
k_e	−0.0018	0.0617	−0.0035	0.1056	−0.0008	0.0296	−0.0018	0.0640	2.25	1.94	−0.0010	0.0195	−0.0006	0.0195
α	13.88	122.30	12.41	34.27	0.95	8.10	0.39	4.28	14.61	31.82	1.36	6.61	1.50	12.14
PSL														
k_e	−0.0032	0.0978	−0.0054	0.1503	−0.0012	0.0392	−0.0016	0.0511	2.67	3.38	−0.0009	0.0236	−0.0006	0.0181
α	23.45	18.20	18.35	-6.27	1.52	11.21	1.01	10.57	15.43	18.17	5.71	-5.72	5.52	9.51
LVL80E														
k_e	−0.0021	0.0688	−0.0019	0.0700	−0.0017	0.0492	−0.0013	0.0431	1.24	1.46	−0.0005	0.0180	−0.0007	0.0225
α	12.94	52.76	10.16	71.63	3.19	6.49	2.38	17.55	4.06	4.27	5.41	36.64	4.14	34.96
LVL100E														
k_e	−0.0039	0.1103	−0.0028	0.0871	−0.0016	0.0502	−0.0012	0.041	2.44	2.33	−0.0004	0.0148	−0.0005	0.0194
α	15.46	30.93	14.44	52.85	2.66	9.83	2.49	15.59	5.81	5.80	4.17	61.13	4.69	44.96
GLT and wood														
k_e	–	–	–	–	–	–	–	–	3.4	3.4	–	–	–	–
α	10.9	3.16	10.9	3.16	–	–	–	–	0.29[a]	0.29[a]	–	–	–	–

EWP, engineered wood products; LSL, laminated strand lumber; PSL, parallel strand lumber; LVL, laminated veneer lumber; GLT, glued laminated timber; k_e, initial stiffness; α, effective elastic foundation depth; CH, TV, CV, RV, TH, and RH, directions of specimen (refer to Fig. 1)

C_0 means the slope and C_1 the intercept from the regression line in Figs. 7 and 8

[a]The value was calculated from 1/3.4

the same. The α of these EWPs showed slightly different trends of correlation with the dowel diameter, but these differences are not statistically significant at the 95% significance level.

In full-sized structure, the k_{e0} in the loading directions of CH and CV are always given more consideration. In the case of k_{e90}, RV is related to CV and TV is related to CH. The CH/TV and CV/RV ratios are also expressed as k_{e0}/k_{e90}. These EWPs exhibited different performances due to their anisotropic properties. These four EWPs also had higher k_{e0}/k_{e90} values than GLT (3.4).[2,3]

As shown in Table 2, the α values for LSL and PSL are apparently different from those of LVL and GLT and wood; but as noted above, there was no statistical significance. In real-life application, it is therefore necessary to take into consideration the α of each EWP based on its respective structure. Although there was no statistical significance, the trends of the mean values in these EWP specimens according to the dowel diameter increments showed different changes for GLT.

The results obtained showed that LVL, PSL, and LSL had bearing characteristics different from those of GLT and solid wood. It is therefore necessary to derive their bearing capabilities based on different equations, taking into consideration the loading direction. In addition to the existing EWPs, many other new and environmentally friendly EWPs will be manufactured to meet current demands. To ensure the optimum application of these EWPs, it is necessary to formulate new structural design formulas based on their individual bearing properties, as each has a fundamentally different structure.

Conclusions

The bearing properties of four EWPs were investigated. In contrast to wood and GLT, the bearing properties of these EWPs are more dependent on their elemental structures. The results are summarized as follows. (1) Except in a few cases, none of the four EWPs showed a clear relation between the bearing strength ($\sigma_{0.05}$, $\sigma_{0.02}$) and dowel diameter, irrespective of loading direction. (2) The initial stiffness (k_e) of these EWPs decreased with increasing dowel diameter (d). (3) The effective elastic foundation depths (α) of LVL, PSL, and LSL were larger than those of GLT or wood. PSL had a higher α value owing to the decrement of k_e by the presence of numerous voids in its structure. (4) The bearing strength and initial stiffness of each EWP should be used for estimating the deformation and strength of the joints.

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