NONDESTRUCTIVE EVALUATION OF MODULUS OF ELASTICITY OF YELLOW-POPLAR LVL: EFFECT OF VENEER-JOINT DESIGN AND RELATIVE HUMIDITY

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ABSTRACT

Two nondestructive testing (NDT) methods, stress-wave propagation and transverse vibration, were employed to evaluate the modulus of elasticity (MOE) of laminated veneer lumber (LVL) fabricated with rotary-peeled yellow-poplar (YP) veneers and phenol-formaldehyde resin. Three groups of LVL specimens, 50 in each group, randomly selected from a very large sample population (over 250), were evaluated in this study. Group I specimens had scarfed veneer-joints; group II had crushed-lap veneer-joints; and group III had no veneer-joints and served as controls. Twenty-five specimens in each group were preconditioned and equilibrated under environmental conditions of 65% relative humidity (RH) and the remainder under 95% RH at 23.9°C (75°F) before the evaluation of nondestructive MOE. Results showed that MOEs of YP-LVL predicted by NDT methods were influenced by the presence of veneer-joints and the difference existed between the NDT methods used. The RH effect was not accurately demonstrated by both NDT methods except in the group without veneer-joints. Significant increase of moisture content (MC) in the LVLs resulted from the increase of RH, but change in densities of LVLs was relatively small. Analysis of correlation between NDT MOEs and the static bending MOE was performed, and poor to fair correlations were observed under the condition of 65% RH.

Keywords: Laminated veneer lumber (LVL), yellow-poplar, nondestructive testing (NDT), stress wave, transverse vibration, veneer joints, static bending, relative humidity.

INTRODUCTION

Several engineered wood composite products have been designed, developed, and used in light- and medium-frame building construction in recent years (Vining 1991). Laminated veneer lumber (LVL) is one of these well-developed engineered wood composite products. In order to have high structural performance, most of these commercial LVL products have usually been fabricated with high quality ro-

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tary-peeled veneers, either of Douglas-fir or southern pine, which are the major structural-use softwood timber species in the United States. Usually they are not fabricated with low-grade softwood veneers or hardwood veneers. Soft hardwood species are seldom used for manufacturing solid sawn lumber and/or plywood for structural applications. Hardwood LVL is commonly recognized and utilized in furniture manufacture as framing components for sofas, beds, and cabinets (Hoover et al. 1984). To better understand the effect of veneer quality/grade and environmental conditions on the short- and long-term structural performance of softwood (loblolly pine) LVLs, and to explore the feasibility of producing structural-use LVLs fabricated with veneers peeled from commercial soft hardwood logs, we have conducted a series of investigations on these LVL products. Reviews of important literature on the development and investigation of structural-use LVLs in the last three decades were made in these studies, and testing results indicated that the static bending properties of southern pine LVLs are highly influenced by the veneer grade (Biblis and Mercado 1991; Biblis 1996; Tang and Pu 1997) and environmental conditions (Tang and Pu 1997). Furthermore, testing results (Tang and Pu 1997) revealed that edgewise bending properties, strength, and stiffness of 13-layered southern pine LVLs fabricated with C and/or D grade veneers, can be substantially improved by substituting two face veneers on both sides of the LVL member with higher (i.e., B) grade veneers, and strength/stiffness performance of members with veneer arrangement of BB-9 $\times$ C-BB is equivalent to those fabricated with all B grade veneers.

In a parallel investigation, structural performance of LVLs fabricated with yellow-poplar veneers was reported in a previous study (Lee et al. 1999). In that report, recent studies on soft hardwood LVLs were reviewed and, in addition, they have indicated that veneer-joint designs have a significant effect on the edgewise static bending properties of yellow-poplar LVLs, and members with crushed-lap veneer-joints performed much better than those with scarf veneer-joints. Furthermore, it was found that under environmental conditions of 65% RH and 75°F, yellow-poplar LVLs with crushed-lap veneer-joints are as stiff and strong as those without veneer-joints, which are equivalent to or higher than that of southern pine (loblolly) LVLs fabricated with all B grade veneers and with C grade veneers but faced with 2-layer B grade veneers as reported in a previous study (Tang and Pu 1997).

In recent years, nondestructive testing (NDT) methods have been used extensively by structural engineers and wood scientists to assess the structural performance of individual members of solid wood products, wood composite products, and components in wood structural systems (Gerhards 1982; Jung 1982; Sharp 1985; Ross and Pellerin 1991; Green and McDonald 1993a, b; Ross et al. 1993; Wang et al. 1993). Earlier, the effect of moisture content on the NDT-MOE parallel-to-grain (i.e., E_L) of solid hardwoods was investigated by Tang and Hsu (1972) by testing small-size cantilever beams in transverse (free and forced) vibration. It was reported that values of NDT-E_L of yellow-poplar wood, evaluated from the flat-sawn specimens (i.e., L-T beams), were slightly higher than those obtained from the quarter-sawn specimens (i.e., L-R beams). However, a contradictory result was observed in the specimens of scarlet oak. Obviously, this was attributed to the differences in the degree of anisotropy of the material properties, such as stiffness (MOE), strength (MOR), Poisson's ratio, and moisture expansion (swelling/shrinkage), which are associated with direction and are a function of orientation in anisotropic/orthotropic materials. For example, the data on degrees of anisotropy for solid yellow-poplar wood at 12% moisture content, $E_L/E_T = 23.3$; $E_L/E_R = 10.9$, $\nu_{LR}/\nu_{LT} = 0.81$ and $\nu_{RL}/\nu_{TL} = 1.58$ were reported by USDA (1999). Note that the major input datum for the equation to calculate the MOE-E_L from a transverse vibration of wood beams is the frequency of vibration, which is a function of the damping capacity (coefficient) of the beam and which is known to be affected by the degree of anisotropy of wood and its moisture content (Tang and Hsu 1972). More recently, a study on the NDT of southern pine solid-sawn lumber and LVLs without veneer-joints (Pu and Tang 1997) indicated that LVL's static bending MOE can be predicted with reasonable accuracy by stress-wave propagation tests. Good prediction was made especially in the groups of solid-sawn southern pine lumber specimens.

Engineering applications of LVLs in timber structural systems frequently need members longer than 8 feet or 2.44 m, the approximate maximum length of veneers rotary-peeled from logs in the wood composite industries. Hence, the employment of glued veneer-joints in each ply (such as butt, scarf, crushed-lap) or in the member (finger and scarf) is unavoidable. The effect of end-joints on the tensile strength of 3/4-inch (19.05-mm)-thick LVL, fabricated with 1/10-inch C grade Douglas-fir veneers, was investigated at the USDA Forest Products Laboratory (FPL) (Youngquist et al. 1984). Results indicated that members with a scarf joint (slope: 1:8.3) and a vertical finger joint showed higher tensile strength than those with a horizontal finger joint. In addition, the tensile strength of a nominal 2-inch (i.e., 1.5 in. (38.1 mm)) end-jointed LVL fabricated with 1/10-inch (2.54-mm) C grade Douglas-fir veneers was studied and they concluded that members with two offset (i.e., separated by 6-in. (152.4-mm)) plain scarf joints (slope: 1:8.3) had higher tensile strength than those with one 3-stage (or folded) scarf joint (4.5 in. (114.3 mm) in length and 1:8.3 slope). The effect of lap veneer-joints on the bending properties of LVLs fabricated with 1/8-in. (3.18-mm) aspen veneers was investigated by Hsu (1988), and results indicated that members with lap veneer-joints, distributed 3 in. (76.2 mm) between two adjacent plies, had joint efficiencies of 87.9% and 95.8% for flatwise MOR and edgewise MOR, respectively; and a significant difference was not found between the flatwise MOEs of members without veneer-joints and those with lap veneer-joints. The lap-joint efficiencies reported by Hsu in the 1988 study were higher than those of scarf veneer-joints (72%) reported by Hsu in a 1987 study. A study of the mechanical properties of finger-jointed southern pine LVL members by Biblis (1996) indicated that the existence of finger-joints reduced the strength of members in comparison with those without finger-joints regardless of the orientation of joints in the member. The relationship between the orientation of finger-joints and that of the gluelines plays a very important role in the static bending performance (Biblis and Carino 1993). However, very limited information has been reported on the combined effect of glued veneer-joints and the environmental factors on mechanical properties of LVL members.

The effects of veneer quality (C and D grade) and veneer thickness (3/16-in. (4.47 mm), 1/8 in. (3.18 mm), and 1/10 in. (2.54 mm)) as well as the width (3.50 in. (88.9 mm), 7.25 in. (184.2 mm), and 11.25 in. (285.8 mm)) of testing specimens on the flatwise bending properties of Douglas-fir LVLs were investigated at the FPL (Youngquist et al. 1984). Results indicated that width effect on the flatwise bending properties of LVLs fabricated with different grades of veneer was not observed, but a veneer-grade effect on the flatwise bending MOR and MOE of LVLs was found. However, a significant effect of veneer thickness of LVL's flatwise bending MOR showed in the specimens fabricated either with C or D grade Douglas-fir veneers, but such an effect was not observed in the data of MOE. Effects of wood species, veneer thickness, and member size of LVLs were also studied by Hsu (1988). Results indicated that for aspen LVLs made from thin (0.111-in. (2.82-mm)) lap-jointed veneers, flatwise MOR tended to be equal to or higher than the edgewise MOR, and in contrast, for members made from thick (0.144-in. (3.66-mm)) lap-jointed veneers, edgewise MOR was significantly higher than flatwise MOR. He attributed this fact to the improvement in strength due to the surface densification in face veneers offset by a decrease in the resistance to interply cleavage.

Also, Hsu indicated that significant differences of edgewise MOE and MOR among LVLs made from aspen, pine, and spruce veneers with lap joints were not observed, but some differences showed in the data of flatwise MOE (pine vs. aspen/spruce) and MOR (spruce vs. pine/aspen). Furthermore, he reported that, with the exception of edgewise MOR, there were no significant differences in bending properties between nominal 2-by 10-in. (38.1-mm × 235-mm) and 2-by 4-in. (38.1-mm × 88.9-mm) aspen LVLs. These findings suggest that the effect of veneer thickness (i.e., from 1/10 in. (2.54 mm) to 3/16 in. (4.76 mm)) on the edgewise bending MOE of LVLs may be very small or negligible.

The effect of veneer orientation or the loading direction on LVL's static bending MOR and MOE was investigated by several wood scientists. Kunesh (1978) reported that a significant difference was not observed on the MOEs obtained from edgewise and flatwise bending tests of 1.5-by 2.3-in. (38.1-mm × 58.4-mm) specimens of LVLs fabricated with 1/8-in.–1/10 in. (3.18-mm–2.54-mm) C and D grade Douglas-fir veneers with crushed-lap joints. Douglas-fir LVLs (size: 1.5 by 3.5 in. (38.1 mm × 88.9 mm)) fabricated with 1/4-in. (6.35-mm)-thick veneers without joints were tested by Jung (1982), and results indicated that a significant difference showed between the MORs obtained from the edgewise and flatwise bending tests, but such a difference was not observed in the MOE data. However, Hsu (1988) reported that flatwise MOE and MOR for aspen, pine, and spruce LVLs made from lap-jointed veneers tended to be slightly higher than those of edgewise MOE and MOR.

Yellow-poplar lumber is recognized by the wood industries as a very important commercial soft hardwood product in the South. Yellow-poplar lumber is commonly used for furniture, interior finish, cabinets, musical instruments, and structural components, and yellow-poplar veneers are generally used for fabricating non-structural-use plywood (USDA 1999). However, a recent study by Green and Evans (1994) at FPL indicated that yellow-poplar LVLs performed structurally as well as Douglas-fir LVLs after 2 years of exposure under constant environmental conditions of 65.6°C (150°F) and 75% RH.

In the current study, LVL specimens, fabricated with rotary-peeled yellow-poplar (*Liriodendron tulipifera*) veneers, were nondestructively tested flatwise and edgewise by using the stress-wave propagation (SW) and transverse vibration (TV) methods under both 65% and 95% RH at 23.9°C (75°F) to evaluate their stiffness (MOE: modulus of elasticity) performance as affected by the design of glued veneer joints and relative humidity (RH) conditions. Also, these LVL specimens were static-bending tested after the NDT and the MOE data for 65% RH conditioned specimens, as reported by Lee et al. (1999) were included in this current study for comparison. The data reported in the current NDT study may provide additional useful information on the assessment of the engineering performance of yellow-poplar LVLs as structural members, especially when they are fabricated with veneers having different types of veneer joints. Furthermore, this current study may provide information on the effectiveness of the NDT methods for the prediction of MOEs of yellow-poplar LVLs with different veneer joints and the relationship between MOEs evaluated by NDT methods and static bending.

MATERIALS AND METHODS

Materials and veneer-joint designs

Rotary-peeled yellow-poplar (*Liriodendron tulipifera*) veneers, 3.18 mm and 4.23 mm (1/8 in. and 1/6 in.) in thickness, 1,320.8 mm (52 in.) in width, and 2,540 mm (100 in.) in length, were used to fabricate the LVL specimens for this study. All veneers were dried to approximately 7% moisture content (MC). D grade veneers were visually sorted out according to the Voluntary Products Standard PS 1-95 (NIST 1995). Then, the remaining B and C grade veneers were randomly mixed and used for the fabrication of LVL billets with commercially produced liquid phenol-formaldehyde resin. The press conditions similar to those used in our previous studies on southern pine and yellow-polar LVLs (Pu and Tang 1997; Tang and Pu 1997; Lee et al. 1999) were used in this study. Note that ultrasonic grading methods for sorting the veneers were not available in the mill where the LVL was fabricated. Three groups of LVL billets were fabricated with different types of veneer joints: Group I had scarfed veneer joints (SJ), Group II had crushed-lap veneer joints (LJ), and Group III had no veneer-joints (NJ). Due to the geometric differences in veneer-joints and limitations in veneer lay-up and feeding operation in a continuous hot-press, three types of yellow-poplar (YP) LVL billets were fabricated. Their dimensions, veneer-joint designs, and hot-press types are as follows:

I. Scarf Veneer Joint (SJ) Group: designated slope: 1/9.
   Veneer dimensions: 4.23 mm (1/6 in.) × 1.32 m (52 in.) × 2.54 m (100 in.)
   Billet dimension: 44.5 mm (1.75 in.) thick × 1.32 m (52 in.) wide
   Continuously hot-pressed, 11 plies of veneer
   Scarf veneer joint in each ply stepwisely distributed 152.4 mm (6 in.) apart in adjacent plies (i.e., scarf veneer-joints are distributed at 2.44 m (8 ft) apart in each ply).

II. Crushed-Lap Veneer Joint (LJ) Group: 38.1 mm (1.5 in.) overlapped.
   Veneer dimension: 3.18 mm (1/8 in.) × 1.32 m (52 in.) × 2.54 m (100 in.)
   Billet dimension: 38.1 mm (1.5 in.) thick × 1.32 m (52 in.) wide
   Continuously hot-pressed, 13 plies of veneer
   Crushed-lap joints in each ply distributed similarly to those in group I but with a cyclic sequence of 152.4 mm–304.8 mm (6 in.–12 in.) arrangement (i.e., crushed-lap veneer-joints in each ply were approximately 2.44 m (8-ft) apart).

III. No Veneer Joint (NJ) Group:
   Veneer dimension: same as group II
   Billet dimension: 38.1 mm (1.5 in.) thick × 1.22 m (4 ft) wide × 2.44 m (8 ft) long
   Conventional multi-opening hot-pressed, 13 plies of veneer

Processing variables for the fabrication of YP LVL are similar to those reported previously on the southern pine LVL (Pu and Tang 1997). LVL specimens, 88.9 mm (3.5 in.) wide × 2.44 m (96 in.) long, were cut from each billet and 25 members for each RH group were randomly selected from a large sample size with over 250 members in each veneer-joint group, and they were preconditioned and equilibrated in a computer-controlled environmental room under a constant RH of 65% and 95% at 23.9°C (75°F). Due to the scarfing process at both ends of each 1.22-× 2.44-m (4-× 8 ft) veneer and the continuous bonding of these scarf joints to produce a continuous 1.22-m (4-ft) wide veneer sheet for billet fabrication under a continuous hot-pressing process, the 12 LVL specimens, ripped from the same 2.44-m (8-ft)-long billet section had identical scarf veneer joints locations. However, members ripped from other 2.44-m (8-ft)-long billet sections would have somewhat different joint positions with reference to the ends of an LVL member because the cross-cut into 2.44-m (8-ft)-long sections from a continuously hot-pressed billet was made without the consideration of joint positions, and hence the testing members were randomly selected from the population of sawn specimens. The LJ LVLs were fabricated, sawn, and sampled in the same manner. Consequently, the positions of veneer joints, either scarf or crushed-lap, with reference to the ends of LVL specimens within the 25-member group were not controlled.

Testing methods

The Metrigard model 239A stress-wave timer tester was used to perform the flatwise stress-wave propagation tests (SW). The Me-

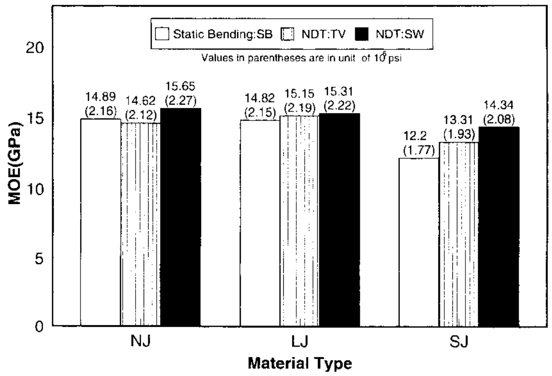

FIG. 1. MOE of yellow-poplar LVL evaluated by different methods under constant 65% RH at 23.9°C (75°F).

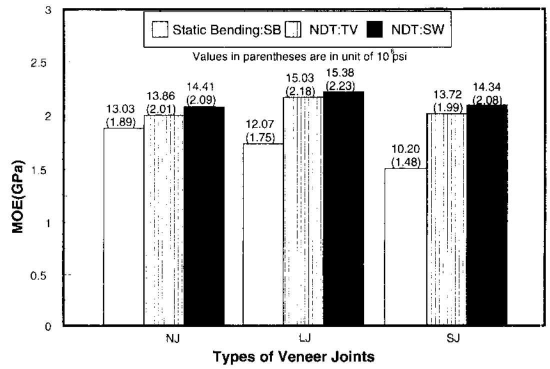

FIG. 2. MOE of yellow-poplar LVL evaluated by different methods under constant 95% RH at 23.9°C (75°F).

trigard Model 340 E-computer was used for the flatwise transverse-vibration tests (TV) similar to those reported on the southern pine LVLs (Pu and Tang 1997). In both tests, each LVL specimen was mounted flatwise (i.e., wider side of LVL members faced upwards) on the testing frame. In the SW tests, the stress time propagation in the LVL specimen was measured at each 304.8 mm (1 ft) and then an average value was used in the determination of MOE. In the TV tests, a 2.13-m (7-ft) span was used in the transverse free vibration by applying a tapping force perpendicular to the veneer face (i.e., the wider side of LVL members). After both NDT evaluations of MOEs, all three groups of specimens were tested destructively under edgewise bending according to the ASTM standard D-198 (ASTM 1994) in which each specimen was subjected to a ramp load on the veneer-edge face at two points 304.8 mm (12 in.) away from the center of the beam with a simply supported span of 2.13 m (84 in. i.e., span/depth ratio = 24) to determine their static bending (SB) MOE and MOR. The MC and the density of specimens from each veneer-joint group were measured using small blocks cut from each specimen 304.8 mm (12 in.) away from the member end. MC calculation was based on the oven-dried weight.

Statistical analyses were performed to determine the effect of veneer-joints, relative humidity, and the type of NDT methods on the MOE. Furthermore, the specific MOEs (ratio of MOE to density), taken for granted worldwide as the index of material efficiency and effectiveness of materials used in structural applications, of each veneer-joint design group were calculated.

RESULTS AND DISCUSSION

Effect of testing methods

Average MOE values determined by three different testing methods including SW, TV, and SB for all types of veneer-joint groups exposed to RHs of 65% and 95% at 23.9°C (75°F) are plotted respectively in Figs. 1 and 2. The MOE data with their coefficients of variation (COV) and density values for each veneer-joint group are summarized in Table 1.

It is evident from Fig. 1 and Table 1 that, regardless of the type of veneer-joints and RH conditions, the MOEs evaluated by SW method were slightly higher than those determined by either TV or SB method. However, the MOE values determined by TV are closer to those evaluated by the SB. The effect of testing methods on the MOEs was statistically analyzed by the Duncan's Multiple Range Test ($\alpha = 0.05$) and results indicated that, as shown in Table 2, a significant effect of testing methods on the MOEs of YP-LVLs under both 65% and 95% RHs does exist in the group with scarf veneer-joints (SJ). For the group with crushed-lap veneer-joints (LJ), such an

TABLE 1. *Average MOEs of YP-LVLs evaluated by Flatwise NDTs (SW and TV) and Edgewise Static Bending Test under 65% and 95% RH at 23.9°C (75°F).*

Type of joints	MC %	Density (kg/m^3)	SW MOE (GPa)/COV*	TV MOE (GPa)/COV	SB MOE (GPa)/COV
			65% RH		
NJ	6.89	586	15.65/0.19	14.62/0.30	14.89/04.1
LJ	8.65	613	15.31/0.28	15.15/0.37	14.82/0.29
SJ	9.57	566	14.34/0.47	13.31/0.42	12.20/0.93
			95% RH		
NJ	17.0	599	14.41/0.25	13.86/0.42	13.03/0.64
LJ	19.3	638	15.38/0.25	15.03/0.25	12.07/0.60
SJ	17.8	582	14.34/0.44	13.72/0.43	10.20/0.73

* COV: Coefficients of Variation and 1 GPa = 145,033 psi.

effect was not observed between the two NDT methods, but difference showed between the results obtained by NDT methods (i.e., SW and TV) and the destructive testing method (i.e., SB).

The correlations between the MOEs of YP LVL fabricated with different veneer-joints and determined by different tests, including SB, TV, and SW, were statistically analyzed by using SB-MOE as a dependent variable. The resulting Coefficient of Determination (r^2) of linear correlations for both RHs are given in Table 3. Furthermore, the correlations between TV-MOE and SW-MOE were analyzed by using TV-MOE as a dependent variable with results for both RHs given in Table 4. It is evident from Table 3 that very poor to fair correlations between edgewise static bending MOE (SB-MOE) and NDT MOE (TV-MOE and SW-MOE) existed in the YP-LVL groups with different veneer-joints tested under both RH levels. Under the environmental conditions of 65% RH and 23.9°C (75°F), r^2 = 0.2335/0.0715, 0.2480/0.5532, and 0.4390/0.5329 respectively for the NJ, LJ, and SJ groups evaluated by TV/SW were observed, while very poor correlations (i.e., very low r^2 values: 0.0004–0.0695) were observed under 95% RH as expected. These findings suggest that the edgewise static bending MOE of YP-LVLs with veneer-joints can be fairly predicted by SW test under 65% RH. Furthermore, poor to fair correlations were found in YP-LVLs between TV-MOE (dependent variable) and SW-MOE (r^2 = 0.4616 (NJ), 0.3355 (LJ) and 0.5096 (SJ)) for members tested under 65% RH as shown in Table 4.

Statistical distributions of NDT MOEs for NJ, LJ, and SJ groups are plotted in a lognormal fashion in Fig. 3 for both TV and SW tests under constant environmental condition of 65% RH at 23.9°C (75°F), and mathematical models for each groups were developed. It is evident that lognormal plots adequately described the probability distributions of NDT MOEs of YP-LVLs. The general form of the mathematical model in Fig. 3 can be expressed as follows:

$$\text{Logn(MOE)} = a + b \times R \qquad (1)$$

Where a is the mean MOE of the group, b is the coefficients of variation (COV) of MOE in

TABLE 2. *Duncan's multiple range test (α = 0.05) of MOEs for YP-LVL (effect of testing methods).*

Testing methods	65% RH			95% RH		
	NJ	LJ	SJ	NJ	LJ	SJ
SW (Flatwise)	A	A	A	A	A	A
TV (Flatwise)	B	A	B	A	A	B
SB (Edgewise)	B	B	C	B	B	C

* Means with same characters are not significantly different at 0.05 level.

TABLE 3. *Coefficients of determination (r^2) of linear correlations between SB-MOE, TV-MOE and SW-MOE; independent variable: SB-MOE.*

Test methods	65% RH			95% RH		
	NJ	LJ	SJ	NJ	LJ	SJ
TV	0.2335	0.2480	0.4390	0.0004	0.0267	0.0695
SW	0.0715	0.5532	0.5329	0.0012	0.0071	0.0298

this group, and R designates the standard statistic order (rank). As shown in Fig. 3, values of b in the models for NJ/LJ/SJ are 4.38%/5.34%/6.09% and 2.79%/4.08%/6.80% for specimens tested by TV and SW methods respectively. This suggests that the YP-LVLs tested in this study have uniform stiffness despite the differences in the types of veneer-joints present. Note that in general, b values for structural-use solid-sawn southern pine lumber are larger than 20% (Tang and Pu 1997).

Effect of relative humidity

The MC of LVL specimens conditioned under 65% RH were 6.89%, 8.65%, and 9.57% respectively, for NJ, LJ, and SJ groups and they were substantially increased to 17.10%, 19.21%, and 17.88%, respectively, in those conditioned under 95% RH as shown in Table 1. However, changes of NDT MOEs due to the increase of MC were very little as shown in Table 1. But large reductions were observed in the groups of NJ (12.5%), LJ (18.7%), and SJ (16.3%) which were tested by SB. In Duncan's Multiple Range Test (α = 0.05) results, as shown in Table 5, there was a significant difference between MOEs of all NJ, LJ, and SJ groups tested in SB under both 65% RH and 95% RH conditions. However, such a difference was not observed in the groups tested by TV and SW method except in the NJ specimens tested by SW. The statistical distributions of NDT MOEs evaluated under 95% RH at 23.9°C (75°F) are also plotted in a lognormal fashion in Fig. 4, and mathematical models for each group were developed.

TABLE 4. *Coefficients of determination (r^2) of linear correlations between TV-MOE and SW-MOE; independent variable: TV-MOE.*

RH	Type of veneer-joints		
	NJ	LJ	SJ
65% RH	0.4616	0.3355	0.5096
95% RH	0.3058	0.3989	0.0209

Density

Under the equilibrated condition of 65% RH at 23.9°C (75°F), LVL specimens with SJs had lowest average density, 566 kg/m^3 (35.34 pcf), than those with LJs and those without veneer-joints. Furthermore, average density of members with LJs, 613 kg/m^3 (38.27 pcf), was slightly higher than that of NJ LVLs, 586 kg/m^3 (36.58 pcf), which was due to the densification at the regions where veneer-ends were overlapped under compression. Density was greatest at the 38.1-mm (1.5-in.) overlapping zone, and it decreased gradually away from the tip of joints until it reached the value same as the section without veneer-joints. However, the density increases due to the increase of

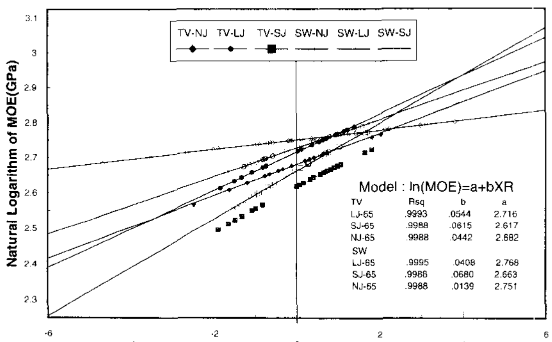

FIG. 3. Distribution of NDT MOEs (Transverse Vibration and Stress-Wave) of yellow-poplar LVL under Constant 65% RH at 23.9°C (75°F).

TABLE 5. *Duncan's multiple range test (α = 0.05) of MOEs of YP-LVL (effect of RH).*

RH level	SB			TV			SW		
	NJ	LJ	SJ	NJ	LJ	SJ	NJ	LJ	SJ
65%	A	A	A	A	A	A	A	A	A
95%	B	B	B	A	A	A	B	A	A

* Means with same characters are not significantly different at 0.05 level.

MC in each specimen as the result of increasing RH from 65% to 95%, were small, as indicated in Table 1.

Effect of veneer-joint designs

As shown in Figs. 1 and 2, MOE values of YP-LVLs without veneer-joints and those with crushed-lap veneer-joints are very close, while those of the specimens with scarf veneer-joints are substantially lower at both RH levels. The effect of veneer-joints on the MOE was statistically analyzed, as shown in Table 6. Duncan's Multiple Range Test (α = 0.05) results indicate that there were significant differences among the NDT (i.e., TV and SW) predicted MOEs of specimens with different veneer-joints (i.e., LJ and SJ) conditioned and tested under 65% RH at 23.9°C. This may be attributed to the densification of overlapped veneer-joints in the NJ members, while discontinuity of wood fibers occurred at the scarf veneer-joints in the SJ group. Note the decreasing of scarf slope from 1/9, as chosen in this study, to 1/10–1/12, may substantially increase the MOR in the YP-LVLs with scarf veneer-joints, but its effect on the improvement of NDT MOE would be very limited. Furthermore, a significant effect of veneer thickness (4.23 mm (1/6 in.) for SJ group vs. 3.18 mm (1/8 in.) for NJ group) on YP-LVL's NDT-MOE in this current study is not expected as analogous to the previous studies of Douglas-fir LVL (Youngquist et al. 1984) and aspen LVL (Hsu 1988). However, regardless of the testing method used, significant difference between the MOEs of NJ and LJ groups was not observed. This suggests that the weakening effect of crushed-lap veneer joints on mechanical properties may be offset by the densification of overlapped joints which increased the density in the NJ members. Note the value of density in each specimen is the second major input to be used in the equation for determining NDT MOE either using TV or SW method. Under the 95% RH condition, significant differences were observed among the MOEs of NJ, LJ, and SJ groups regardless of the testing methods used.

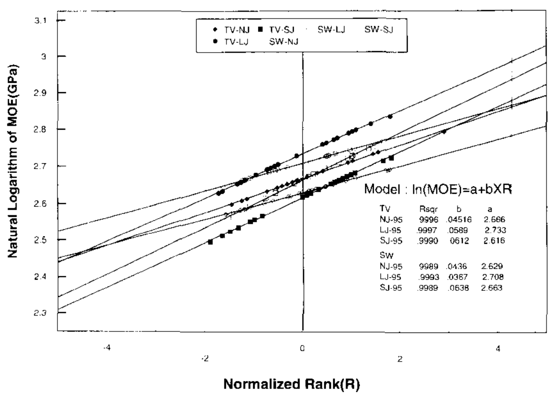

FIG. 4. Distribution of NDT MOEs (Transverse Vibration and Stress-Wave) of yellow-poplar LVL under 95% RH at 23.9°C (75°F).

Specific stiffness

The specific mechanical properties like specific stiffness (MOE/density), which are generally considered in the engineering field to be

TABLE 6. *Duncan's multiple range tests of MOEs (α = 0.05) for YP LVL (effect of veneer-joints).*

Type of joints	65% RH			95% RH		
	SB	TV	SW	SB	TV	SW
NJ	A	A	A	A	B	C
LJ	A	A	A	B	A	A
SJ	B	B	B	C	C	B

* Means with the same characters are not significantly different at 0.05 level.

TABLE 7. *Specific stiffness (MOE/density:Mm) of YP-LVLs evaluated by different testing methods under two RH levels (65% and 95%) at 23.9°C (75°F).*

LVL type	65% RH			95% RH		
	SB	TV	SW	SB	TV	SW
Yellow-Poplar LVL: (Randomly Mixed of B & C veneers)						
NJ	2.59	2.53	2.72	2.17	2.41	2.32
LJ	2.46	2.31	2.49	1.89	2.41	2.35
SJ	2.20	2.29	2.59	1.76	2.36	2.47
Southern Pine LVL*: (No veneer-joints)						
All B grade veneers	2.28	2.32	2.66	1.75	2.16	2.29
All C grade veneers	2.05	2.22	2.46	1.62	2.09	2.15

* Tang and Pu 1997, and Pu and Tang 1997.

indices of the efficiency and effectiveness of materials used in structural applications (Zahn 1981), were calculated and are tabulated in Table 7. For comparative purposes, the values for southern pine LVLs, without veneer-joints, as reported in the previous studies (Tang and Pu 1997; Pu and Tang 1997) were included in this table. Duncan's Multiple Range Test results, as shown in Table 8, indicate that significant differences among the specific SB MOEs of groups with different veneer-joints and tested at the condition of 65% RH at 23.9°C exist. Such a difference was not observed between LJ and SJ groups that were tested by either SW or TV methods, and this suggests that YP-LVLs with SJs are comparable to those with LJs in material efficiency and effectiveness on stiffness properties. Likewise, under 95% RH condition at 23.9°C, specific stiffness of all LVL groups tested by SB showed significant difference, but such a difference between NDT MOEs of NJ and LJ group tested by SW method was not observed.

Table 9 shows the statistical test results of the effect of testing methods on the specific MOR of tested LVLs at both RH levels. Significant differences among the specific MOEs obtained by three different testing methods were observed in the SJ group. However, for NJ and LJ groups, such a difference was found only between those tested in SB and by TV or SW. Those groups tested under 95% RH at 23.9°C condition showed significant difference of specific MOEs between SJ group and NJ or LJ group by all three testing methods.

CONCLUSIONS

Based on the results of this study, the following conclusions may be drawn:

1. Significant effect of veneer-joint designs on the NDT MOE of YP-LVLs exists. LVLs with crushed-lap veneer-joints showed much higher MOE than those with scarf veneer-joints. However, the group with crushed-lap veneer-joints performed structurally equivalent to those without veneer-joints.

TABLE 8. *Duncan's multiple range tests of specific MOE of YP-LVL (α = 0.05) (effect of veneer-joints).*

Type of joints	65% RH			95% RH		
	SB	TV	SW	SB	TV	SW
NJ	A	A	A	A	A	B
LJ	B	B	B	B	B	B
SJ	C	B	B	C	B	A

* Means with same characters are not significantly different at 0.05 level.

TABLE 9. *Duncan's multiple range tests of specific MOE of YP-LVL (α = 0.05) (effect of test methods).*

Testing methods	65% RH			95% RH		
	NJ	LJ	SJ	NJ	LJ	SJ
SW	B	B	A	B	C	C
TV	B	B	B	A	A	B
SB	A	A	C	C	B	A

* Means with same characters are not significantly different at 0.05 level.

2. The effect of relative humidity on the MOE properties of YP-LVLs was not clearly demonstrated by the NDT methods, while a significant effect of RH on MOE was observed in the results of static bending test.
3. A lognormal distribution adequately describes the statistical distribution of MOEs on the YP-LVL tested under 65% and 95% RH at 23.9°C (75°F). Based on these distributions, it appears that LVL tested in this study had a uniform stiffness.
4. NDT methods had a significant effect on the apparent MOE of YP-LVLs with scarfed veneer-joints or without veneer-joints, but such an effect was not observed in the crushed-lap veneer-joint group under 65% RH at 23.9°C. MOEs determined by stress-wave method are slightly higher than those obtained from the transverse vibration and the static bending tests. However, regardless of their veneer-joint types, analysis of linear correlations indicated the MOE predictions based on the stress-wave method are better correlated with those determined by static bending tests.
5. YP-LVLs with scarf veneer-joints are comparable to those with crushed-up veneer joints in material efficiency and effectiveness on specific stiffness properties.

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