NONDESTRUCTIVE EVALUATION OF MODULUS OF ELASTICITY OF SOUTHERN PINE LVL: EFFECT OF VENEER GRADE AND RELATIVE HUMIDITY[1]

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ABSTRACT

Nondestructive testing (NDT) methods, stress-wave propagation, and transverse vibration were used to evaluate the modulus of elasticity (MOE) of laminated veneer lumber (LVL). Five types of LVL, fabricated with southern pine veneers of B, C, and D grades and liquid phenolic formaldehyde adhesive, were tested flatwise at environmental conditions of 65% and 95% relative humidity (RH) and 75°F (23.9°C) to examine the influence of veneer grade and RH on some nondestructive mechanical properties of LVL. All LVLs, 1.5 in. (3.81 cm) thick × 3.5 in. (8.89 cm) high × 96 in. (243.84 cm) long, consisted of 13 plies of southern pine veneer, and their structural designs were: (I) all B grade veneers, (II) 2 plies of B grade veneer on both faces and all C grade veneers in the core plies, (III) 2 plies of B grade veneer on both faces and all D grade veneer in the core plies, (IV) all C grade veneers, and (V) all D grade veneers. Results indicated that MOE of LVL predicted by NDT was influenced by the veneer grade, and specimens fabricated with better grade veneers showed a higher value of MOE. A significant decrease in the MOE determined by both NDT methods was found when RH increased from 65% to 95% at 23.9°C (75°F). The MOE measured by the stress-wave method was found to be more sensitive to the RH change than that determined by the transverse-vibration method. A lognormal distribution accurately described the distributions of MOEs determined by both nondestructive methods at both RH levels. As expected, a significant increase in moisture content (MC) in the LVL resulted from increasing RH levels. However, changes in densities of the tested materials due to the RH changes were found to be smaller. Results also indicated that regardless of the RH level, MOE determined from the stress-wave test was consistently higher than that obtained from the transverse-vibration test. For comparison, the results of tests on southern pine No. 1 and No. 2 grade lumber, commonly used in light-frame construction, are also presented. Analysis of the correlation between the static bending and NDT MOEs was made and results suggested that edgewise static bending MOE of LVL can be predicted with reasonable accuracy by the stress-wave testing. Good correlations were not observed between the edgewise static bending MOE and the nondestructive MOE evaluated by flatwise transverse vibration. However, excellent correlations between static bending and both NDT MOEs were observed in southern pine dimension lumber. Correlations between the MOEs evaluated by both nondestructive methods were found to be fair for LVL specimens.

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INTRODUCTION

In recent years, a number of engineered wood composite panels have been developed and used in light- and medium-frame building construction (Vining 1991). Laminated veneer lumber (LVL) is one of these well-developed engineered wood composite products. The production of LVL in North America was 649 $\times$ 10^3 m^3 (275 million board feet) in 1992 and projections indicated that production may reach 2.34 $\times$ 10^6 m^3 (1000 million board feet) in the year 2002 (Vlosky et al. 1994). Such a projection seems rational because of high strength (MOR: modulus of rupture), uniform stiffness (MOE: modulus of elasticity), and availability in virtually unlimited lengths and/or sizes for LVL (Moody and Peters 1972; Nelson 1972; FPL 1972 and 1977; Echols and Currier 1973; Koch 1973; Bohlen 1974 and 1975; Kunesh 1978; Stump et al. 1981; Biblis and Mercado 1991; Kretchmann et al. 1993; Tang et al. 1975). This potential marketing opportunity would be a challenge to the wood structural products industries.

It is known that mechanical/physical properties and engineering performance of LVL are affected by many factors, such as wood species, veneer thickness and quality, veneer-joint type and lay up, processing variables, member size, in-service environments, and loading types and histories. Most reported studies on LVL have been focused on the modulus of rupture (MOR) and modulus of elasticity (MOE) properties, as determined by static tests including bending, tension, and shear. It was reported by Stump et al. (1981) that structural grade LVL can be produced from mixed species of small, low quality plantation-grown conifers, and a strong correlation between MOR and MOE was found for these LVLs. Recently, Biblis and Mercado (1991) studied the effect of timber management practices on the mechanical properties of LVL and showed that the members made from 40-year-old natural southern pine stands had higher bending strengths and stiffness than those using veneers cut from 20-year-old southern pine plantation stands. More recently, the effect of veneer grade and relative humidity (RH) on the structural performance of southern pine LVL was investigated (Tang et al. 1995) and results indicated that veneer grade had a significant effect on the edgewise bending strength and stiffness, and that these properties were substantially reduced if RH was increased from 65% to 95% at 23.9°C (75°F).

Considerable interest in the use of nondestructive testing (NDT) for assessing the engineering performance of individual members of solid wood products, wood composite products, and components in a wood structural system has developed in recent years. In addition, NDT techniques for assessing wood member performance have been extensively reviewed by Ross et al. (1993) and Ross and Pellerin (1994). The most frequently used techniques for nondestructively evaluating wood-based materials are low load static bending (i.e. machine stress rating (MSR)), transverse vibration, and stress-wave propagation (Ross and Pellerin 1994).

Stress-wave techniques have been extensively used in the evaluation of MOE of clear wood/lumber specimens (Bell et al. 1954; Galligan and Courteau 1965; Porter et al. 1972; Pellerin and Galligan 1973; Galligan et al. 1977; Gerhards 1982; Ross and Pellerin 1991; Wang et al. 1993) and veneer sheets/laminated veneers (Koch and Woodson 1968; Pellerin and Galligan 1973; McAlister 1976; Jung 1979 and 1982; Sharp 1985). All of these studies indicated the existence of a high correlation between the static bending MOE and stress-wave-evaluated MOE in clear wood/lumber, and between tension MOE and stress-wave-evaluated MOE in veneer and laminated veneers. However, poor correlations were reported between the static bending strength (MOR) and stress-wave-evaluated MOE in laminated Douglas-fir veneers (Jung 1982).

Good correlations were found, however, between the MOR and MOE of solid softwood lumber tested in flatwise bending while slightly lower correlations were observed if the members were tested in edgewise bending (Hoyle 1964 and 1968, Pellerin 1963). However, information concerning the evaluation of evaluated MOE by stress-wave on softwood LVL fabricated with different grade veneers is limited.

Several investigations have been made on the application of transverse vibration techniques to evaluate the MOE of clear hardwood (Tang and Hsu 1972) and softwood dimensional lumber (Pellerin 1965; O'Halloran 1969; Ross and Pellerin 1991; Wang et al. 1993), with high correlations between static bending MOE and transverse vibration evaluated MOE. More recently, Green and McDonald (1993a, 1993b) reported high correlations between static bending MOR and MOE evaluated by transverse vibration for red oak and maple structural lumber. However, information is lacking on the application of transverse vibration techniques for the evaluation of MOE of LVL products fabricated with different grade veneers and exposed to different environmental conditions.

In this study, two NDT techniques, stress-wave and transverse vibration, were applied to the investigation of engineering performance of LVL members fabricated with different grades of visually graded southern pine veneers. Also, this study quantified correlations between static edgewise bending MOE (EBE) and stress-wave predicted MOE (SWE), and between EBE and transverse vibration determined MOE (TVE), as well as between SWE and TVE. The resulting data along with those determined by edgewise bending tests were used as references for the selection of load level for the on-going duration of load (DOL) behavior (edgewise) study for southern pine LVL. Moreover, the results of correlations among the MOEs of LVL products fabricated with different grade veneers and evaluated with different testing methods may provide useful information to LVL products industries for developing effective product quality control programs and to timber structures designers for better application of LVLs as components in structural systems. In addition, the effect of relative humidity (moisture content) on these mechanical properties, EBE, SWE, and TVE, as determined by different testing methods was investigated. Furthermore, data for solid southern pine dimension lumber members, No. 1 and No. 2 grade, with identical dimensions to the LVL specimens were presented for comparative purposes.

MATERIALS AND METHODS

Randomly selected southern pine (loblolly pine: *Pinus taeda* L.) logs from an Alabama plantation were commercially peeled into 0.3175-cm (1/8-in.)-thick veneers, 132 cm (52 in.) wide and 254 cm (100 in.) long. All veneers were kiln-dried to approximately 7% moisture content (MC) and then sorted into grade B, C, and D groups following the Voluntary Products Standard PSI-95 (NIST 1995). Ultrasonic grading methods were not used to sort the veneers because such equipment was not available in the plywood mill that fabricated the LVL billets. Thirteen-ply LVL panels, 3.81 cm (1.5 in.) thick × 211 cm (4 ft) wide × 244 cm (8 ft) long, were fabricated with commercial liquid phenol-formaldehyde (PF) adhesive in a southern pine plywood mill. The processing variables used were:

(1) Resin amount: single line, 21.97 g/1000 cm^2 (45 lb/1000 ft^2);
(2) Press temperature: 160°C (320°F);
(3) Press time: 1000 seconds (16.67 min); and
(4) Press cycle: 1000 s. → 120 s. (880 sec) 1379 kpa (200 psi) and 120 s. → 0 s. (120 sec) 1034.25 kpa (150 psi).

Five types of LVL panels, with 17 billets in each type, were fabricated with twelve 0.3175-cm (1/8-in.)-thick veneers of various grades, single or mixed, with one 0.254-cm (1/10-in.)-thick veneer placed in the center of the panel (7th ply). None of the plies contained glue joints (i.e. all veneers were full size visually graded sheets). The design of these 5 types of LVL is as follows:

I. All B grade veneers: 13 × B (BbB)
II. Nine C grade veneers in the core and two plies of B grade veneers on both faces: 2 × B + 9 × C + 2 × B (BcB)
III. Nine D grade veneers in the core and two plies of B grade veneers on both faces: 2 × B + 9 × D + 2 × B (BdB)
IV. All C grade veneers: 13 × C (CcC)
V. All D grade veneers: 13 × D (DdD)

Twelve LVL testing specimens, 3.81 cm (1.5 in.) thick × 8.89 cm (3.5 in.) high × 244 cm (8 ft) long, were cut from each LVL billet. A total of 1020 LVL members were prepared for the nondestructive tests (stress-wave propagation and transverse-vibration methods), destructive edgewise bending, and duration of load (DOL) tests. The resulting data from the NDT and edgewise bending tests were used as references for the selection of load level for the on-going DOL behavior (edgewise) study of LVL. In this report, the results of NDT for 25 randomly selected specimens in each LVL type and RH group were collected and conditioned to equilibrium under constant 65% RH and 95% RH at 23.9°C (75°F). In addition, 25 specimens No. 1 and No. 2 grade solid southern pine 2 by 4 lumber were randomly selected from each grade group with a sample size of 300 and tested for comparison. The Metriguard Model 239A Stress Wave Timer Tester was used to perform the flatwise stress-wave propagation tests and the Metriguard Model 340 E-Computer was used for the flatwise transverse-vibration tests. These two pieces of equipment are commonly used by the wood products manufacturing industries for quality control. After both nondestructive tests, all specimens were destructively tested in edgewise bending according to the ASTM Standard D-198 (ASTM 1994) and data of MOE were collected. Then MC sample blocks were cut from each LVL specimen 6 inches away from the end and oven-dried for MC determination. Statistical analyses were performed on the distribution of resulting MOE as a function of veneer grade and RH level (MC), and correlations between these values were determined.

RESULTS AND DISCUSSIONS

Effect of veneer grades

The results of NDT MOEs determined by using the stress-wave technique (SWE) and transverse-vibration technique (TVE) of all five types of southern pine LVL and No. 1 and No. 2 grade solid southern pine lumber (SYP-1 and SYP-2) under environmental conditions of constant 65% RH and 95% RH at 23.9°C (75°F) are shown in Figs. 1–4 including their density (DN) and moisture content (MC). In addition, the Duncan's Multiple Range Test (α = 0.05) was performed to determine if there were significant differences among the NDT MOEs of southern pine LVL and solid lumber under environmental conditions of 65% RH and 23.9°C (75°F). The results are summarized in Table 1.

As shown in Fig. 1, under the environmental conditions of 65% RH and 23.9°C (75°F), as expected, the LVL specimens, regardless of their veneer grades as determined by visual grading methods, had densities (Mean: 0.636 g/cm^3 (39.705 pcf)) higher than those of the No. 1 (SYP-1) and No. 2 (SYP-2) solid southern pine lumber (Mean: 0.529 g/cm^3 (33.025 pcf)). The density (based on the weight and volume measured immediately after the bending tests) of LVL members was observed to decrease with decreasing veneer grade. Specimens fabricated with all B grade veneers (LVL-I:BbB) had a mean density of 0.654 g/cm^3 (40.829 pcf), while members fabricated with all C grade veneers (LVL-IV:CcC) and all D grade veneers (LVL-V:DdD) had slightly lower densities of 0.641 g/cm^3 (40.018 pcf) and 0.601 g/cm^3 (37.520 pcf), respectively.

As shown in Fig. 2, the groups tested by the stress-wave method, LVL-I:BbB and LVL-II:BcB, had highest average MOE (17.38 GPa and 17.32 GPa (2.521 × 10^6 psi and 2.512 × 10^6 psi)), followed by LVL-IV:CcC (15.78 GPa (2.289 × 10^6 psi)), LVL-III:BdB (15.56

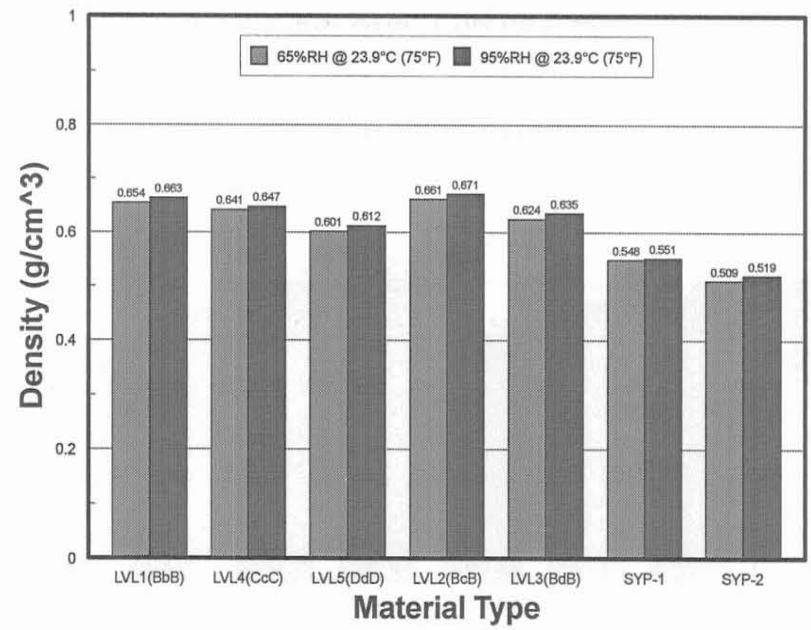

FIG. 1. Density of Southern Pine LVLs and Solid Lumber.

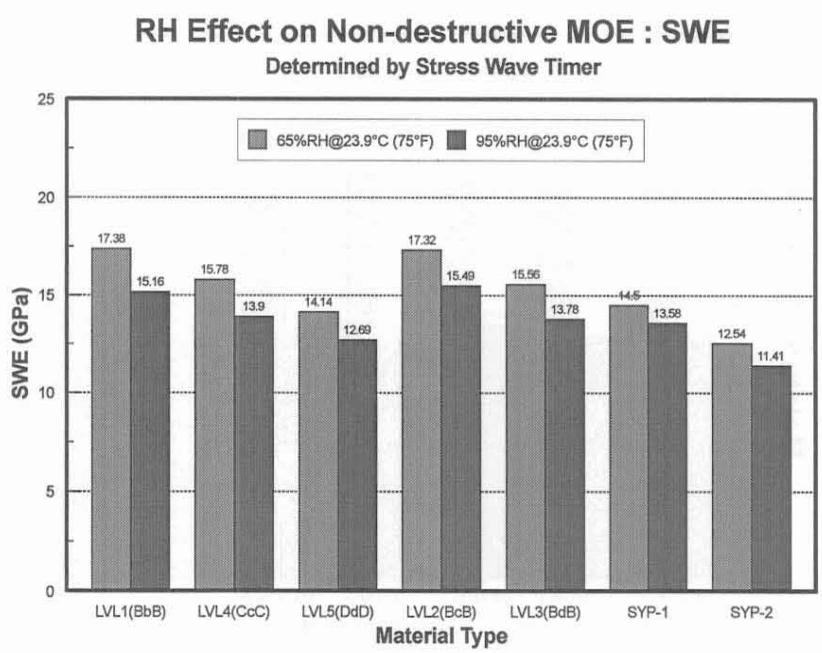

FIG. 2. RH Effect on Nondestructive MOE:SWE.

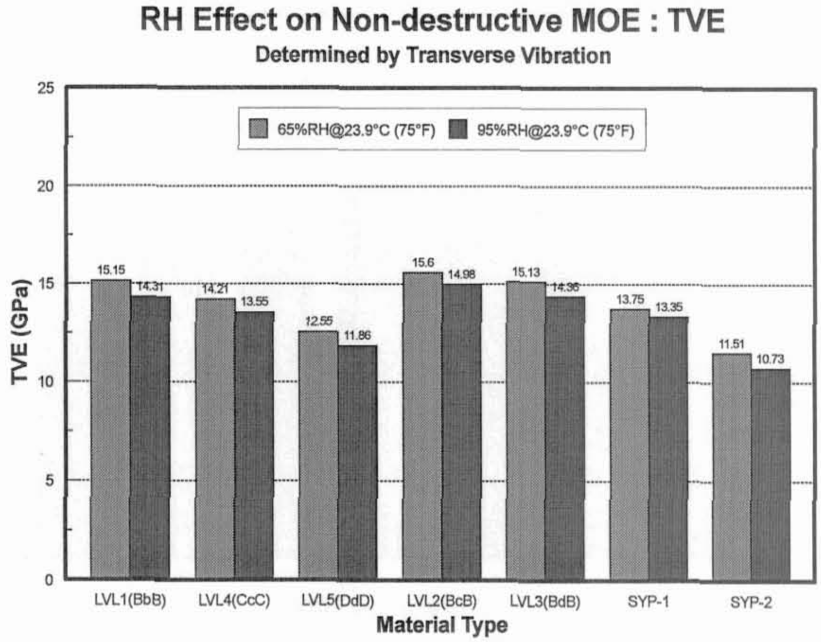

FIG. 3. RH Effect on Nondestructive MOE:TVE.

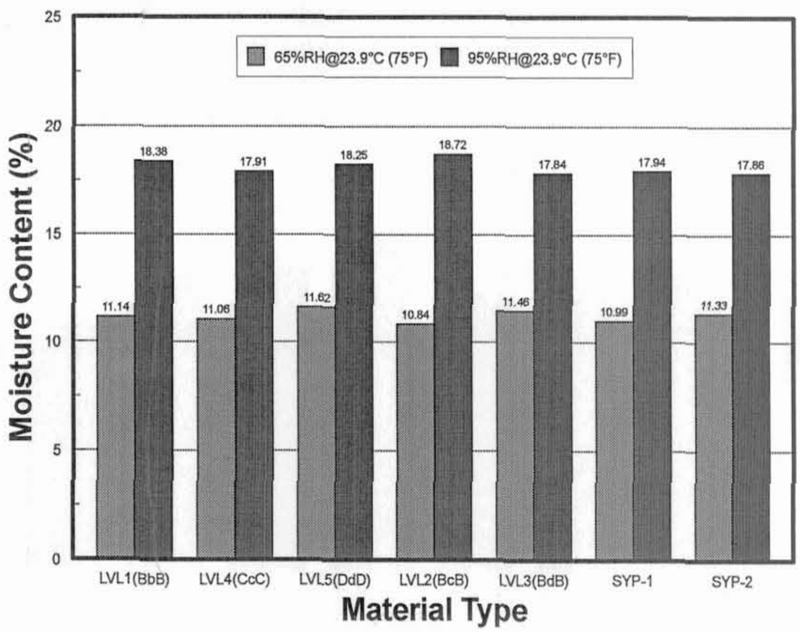

FIG. 4. Moisture Content of Southern Pine LVL and Solid Lumber.

TABLE 1. *Duncan's multiple range test* (α = *0.05) for nondestructive MOEs*[1].

Beam type		Stress wave MOE (SWE)	Transverse vibration MOE (TVE)
LVL-I	(BbB)	A	A
LVL-II	(BcB)	A	A
LVL-III	(BdB)	B	A
LVL-IV	(CcC)	B	B
LVL-V	(DdD)	C	C

[1] Means with the same letter are not significantly different at 0.05 level.

GPa (2.257×10^6 psi)), and LVL-V:DdD had lowest value (14.14 GPa (2.051×10^6 psi)). However, as shown in Table 1, the Duncan's Multiple Range Test ($\alpha = 0.05$) indicated that there were no significant differences between the stress-wave predicted MOE (SWE) of LVL-I:BbB and LVL-II:BcB and between the values of LVL-III:BdB and LVL-IV:CcC. Significant differences did exist among the groups of LVL-I:BbB/LVL-II:BcB, LVL-III:BdB/LVL-IV:CcC, and LVL-V:DdD. The statistical distributions of SWE under different RHs, for the 25 specimens tested in each LVL type and solid lumber grade groups, were plotted in a lognormal fashion in Figs. 5–6, and mathematical models for each LVL type and lumber grade are included. This approach was used in previous studies of the short-term (static) engineering properties of Douglas-fir lumber at Auburn University (Fridley et al. 1992). It is evident from these figures that the lognormal plots adequately described the statistical distributions of MOE probability of southern pine

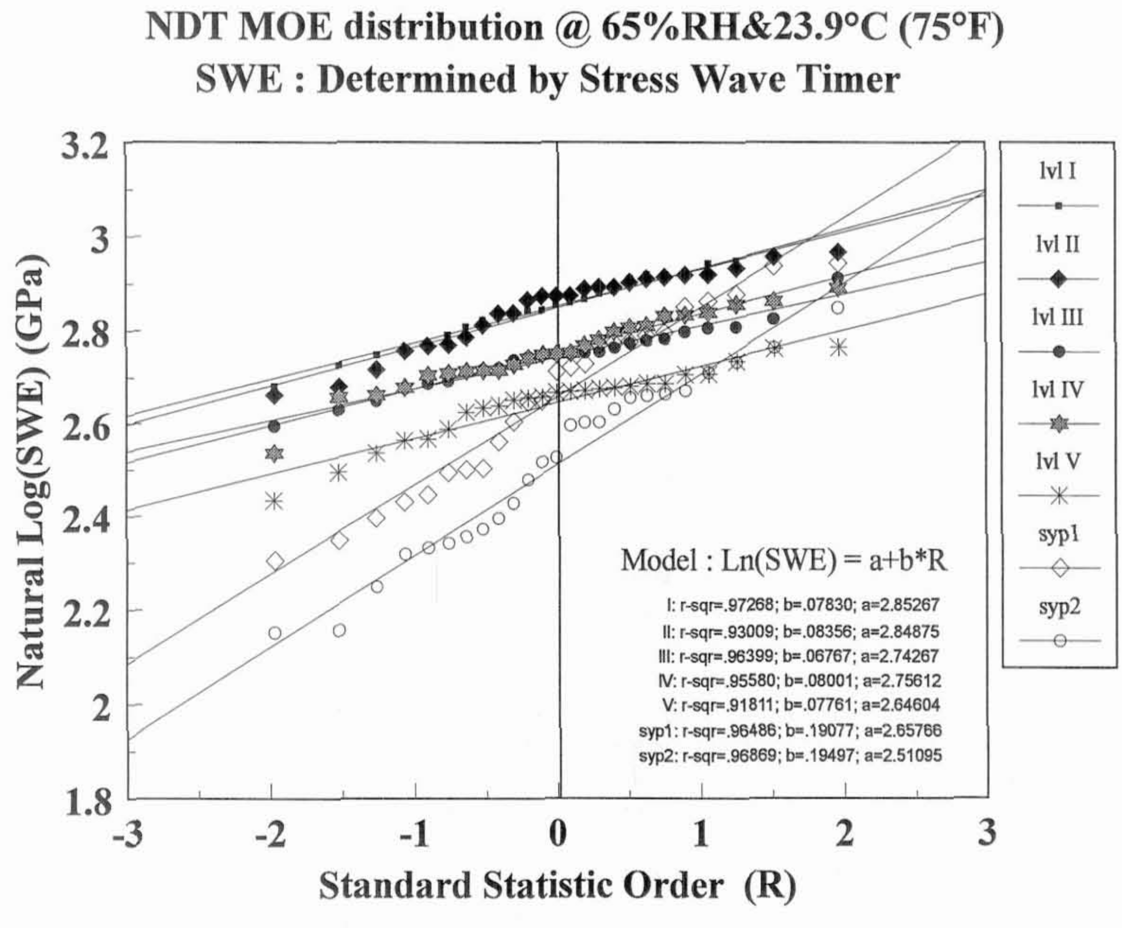

FIG. 5. NDT MOE (SWE) Distribution of LVL & SYP under 65% RH and 23.9°C.

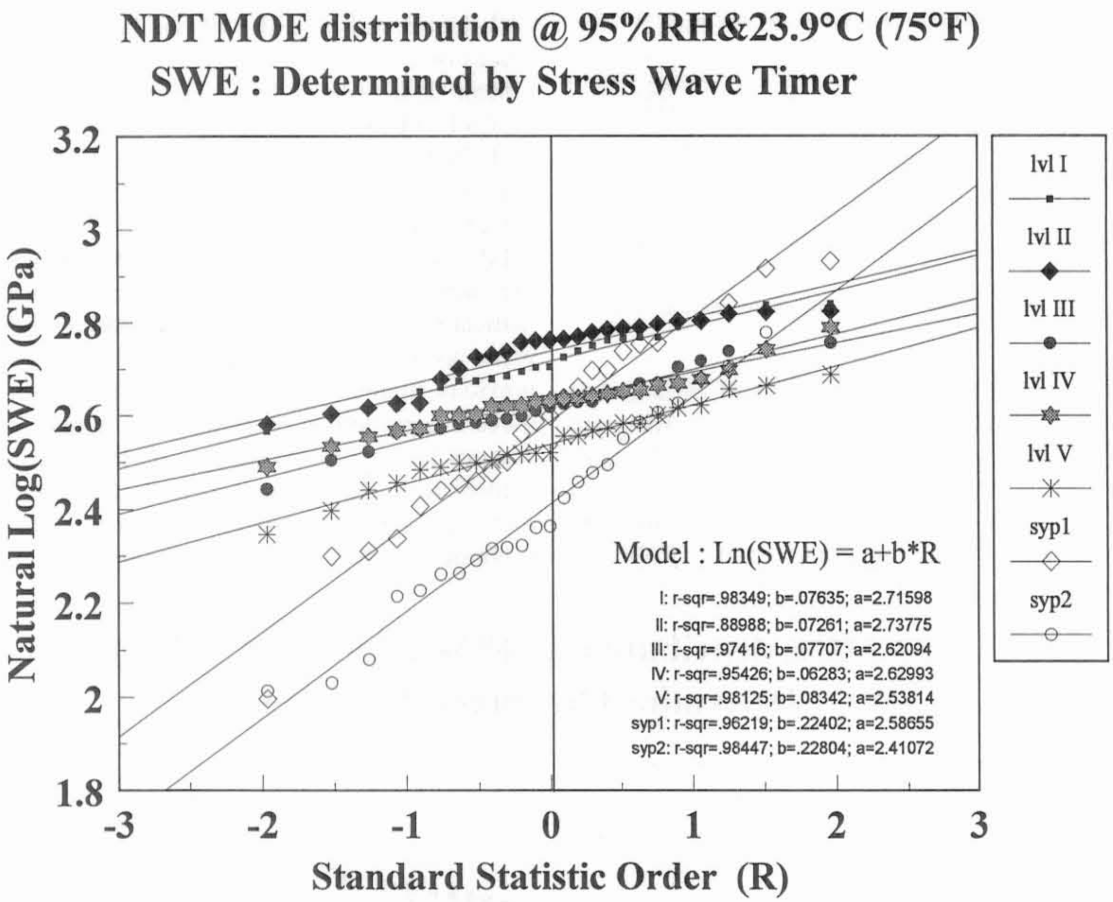

FIG. 6. NDT MOE (SWE) Distribution of LVL & SYP under 95% RH and 23.9°C.

LVLs and the solid southern pine dimension lumber. The general form of mathematical models for LVL and solid lumber as given in Figs. 5 and 6 is: Natural Log of SWE or $Ln(SWE) = a + b \times R$; where R designates the standard statistic order, a and b are constants related to material properties. When R is equal to zero, i.e. $Ln(SWE) = a$, and then $SWE = \exp[a]$ which represents the mean MOE value of that specimen group. The b values in the mathematical model designate the slope of MOE distribution lines and they represent the coefficients of variation. As shown in Figs. 5 and 6, b values for all LVL groups exposed to 65% RH/23.9°C and 95% RH/23.9°C are very small and ranged from 6.767%–8.356% and 6.283%–8.342% respectively. Note that very large b values showed in the solid lumber data (19%–23%) as expected. This finding suggest that veneer sorting using the visual grading method may be adequate for veneer selection in fabrication of LVL products to achieve different levels of MOE.

For the groups tested by the transverse-vibration method, groups of LVL-I:BbB/LVL-II: BcB/LVL-III:BdB tested under environmental condition of 65% RH at 23.9°C showed the highest values of MOE (15.15 GPa (2.197×10^6 psi)/15.60 GPa (2.262×10^6 psi)/15.13 GPa (2.195×10^6 psi)) followed by LVL-IV: CcC (14.21 GPa (2.061×10^6 psi)) and LVL-V:DdD (12.55 GPa (1.820×10^6 psi)) as shown in Fig. 3. Furthermore, significant differences among these groups were confirmed by the Duncan's Multiple Range Test (α =

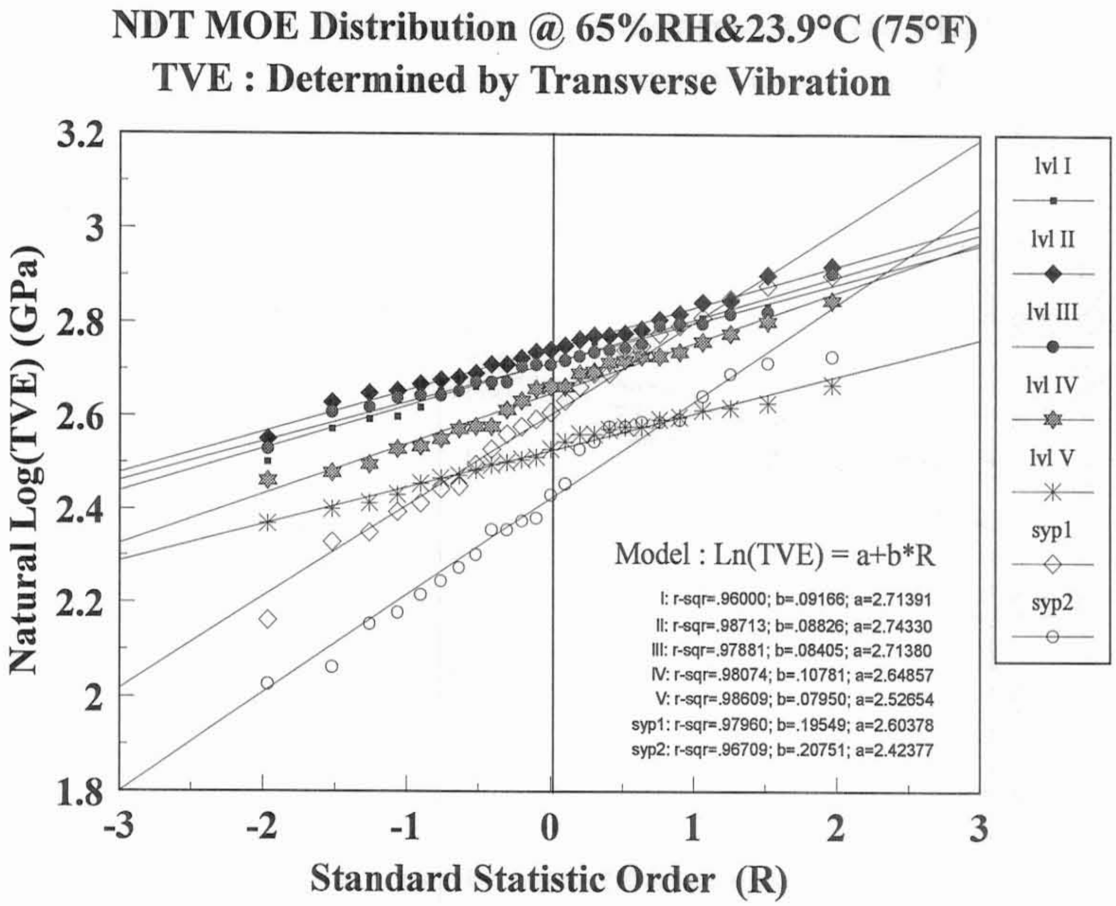

FIG. 7. NDT MOE (TVE) Distribution of LVL and SYP under 65% RH and 23.9°C.

0.05) as indicated in Table 1. These findings strongly suggest that the LVL's MOE is highly influenced by the visually determined veneer grades and it can be improved if a few plies of high grade veneers are placed on both surfaces of the LVL members fabricated with low grade veneers. In this study, two plies of B grade veneer were placed on both surfaces of the members fabricated with C grade veneer (i.e. LVL-II:BcB) and D grade veneer (i.e. LVL-III:BdB). Note that substitution of only one surface ply of low grade veneer with high grade veneer on both sides of the LVL members may not achieve such an improvement in MOE as indicated by a trial test in a previous study (Tang et al. 1995). Like the groups tested by the stress-wave method, transverse vibration MOE (TVE) values evaluated at environmental conditions of 65% and 95% RH levels were also plotted in a lognormal distribution as shown in Figs. 7 and 8. Again, low b values (i.e. coefficients of variation) for MOEs resulted from the transverse-vibration tests and they ranged from 7.950% − 10.781% and 7.879% − 10.539%, respectively, for the groups exposed to 65% RH/23.9°C and 95% RH/23.9°C. However, as expected, much larger values, 19.549% − 23.007% were found in solid southern pine lumber groups.

Effect of testing methods

The values of MOE evaluated by the transverse-vibration method (TVE) for both southern pine LVL and solid lumber groups under both RH levels were slightly lower than those

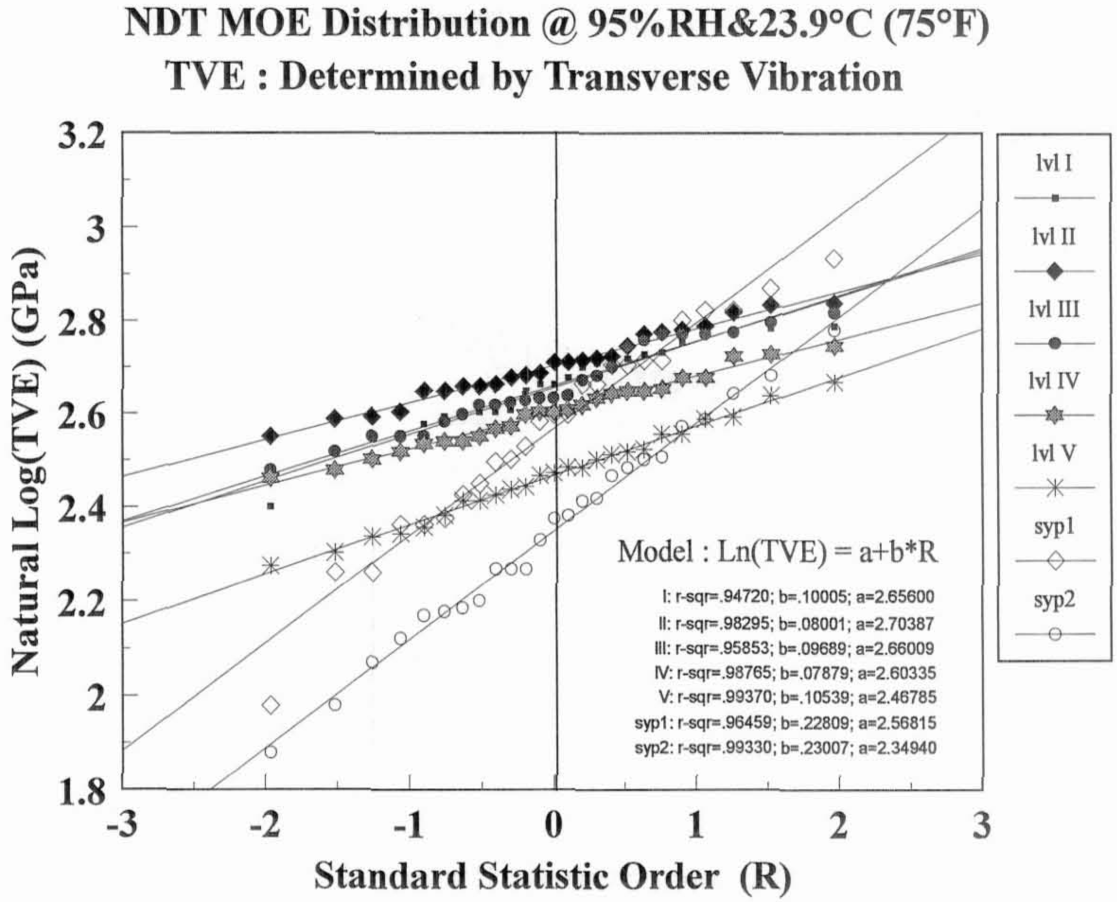

FIG. 8. NDT MOE (TVE) Distribution of LVL and SYP under 95% RH and 23.9°C.

determined from the stress-wave method (SWE) as shown in Figs. 9 (65% RH at 23.9°C) and 10 (95% RH at 23.9°C). However, the MOEs determined by destructive edgewise bending (EBE) were considerably lower than those predicted by the stress-wave method.

The correlations between the MOE determined by different tests, including EBE (destructive edgewise bending, TVE (transverse vibration), and SWE (stress-wave), were statistically analyzed by using EBE as a dependent variable. The resulting Coefficients of Determination (r^2) of Linear Correlations are given in Table 2. Furthermore the correlations between TVE and SWE were analyzed by using TVE as a dependent variable with results given in Table 3. It is evident from Table 2 that high correlation between the edgewise bending MOE (EBE) and NDT MOE (TVE or SWE) existed in the solid southern pine lumber tested under both RH levels (r^2 = 0.81–0.90 for SYP1 and 0.74–0.91 for SYP2). However, very poor to poor correlations were found in LVLs between TVE and EBE (r^2 = 0.15–0.56) with much better correlations observed between SWE and EBE (r^2 = 0.41–0.78). Note that in the stress-wave evaluation, the measured wave velocity in the specimen is the major input for the determination of MOE, while in the transverse-vibration tests the vibration frequency of the specimen is the major input (measurements are taken automatically as resonant vibration decays in the specimens) as adapted in both pieces of Metriguard equipment's design and elastic principles for solid isotropic materials are used. Because the MOE

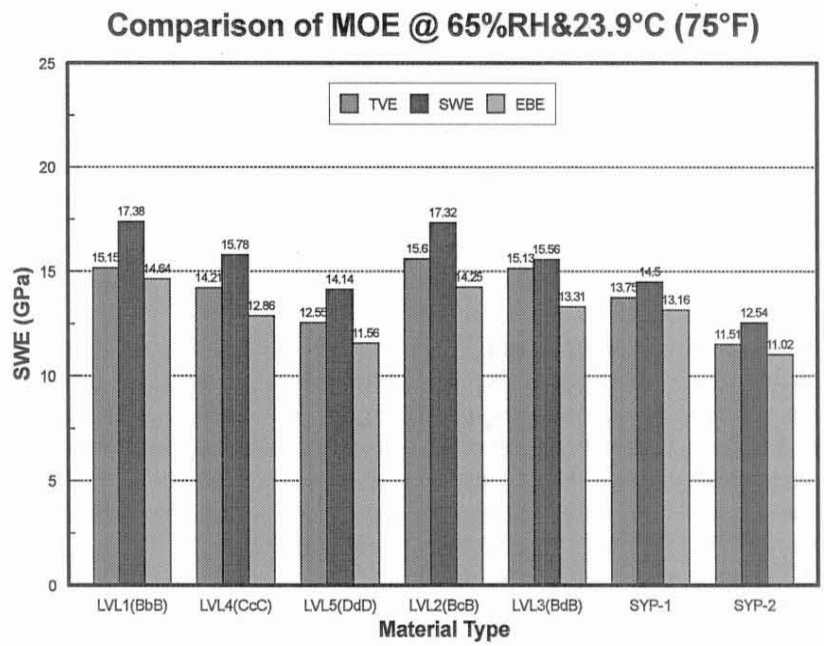

FIG. 9. Comparison of MOEs determined under 65% RH and 23.9°C by different testing methods.

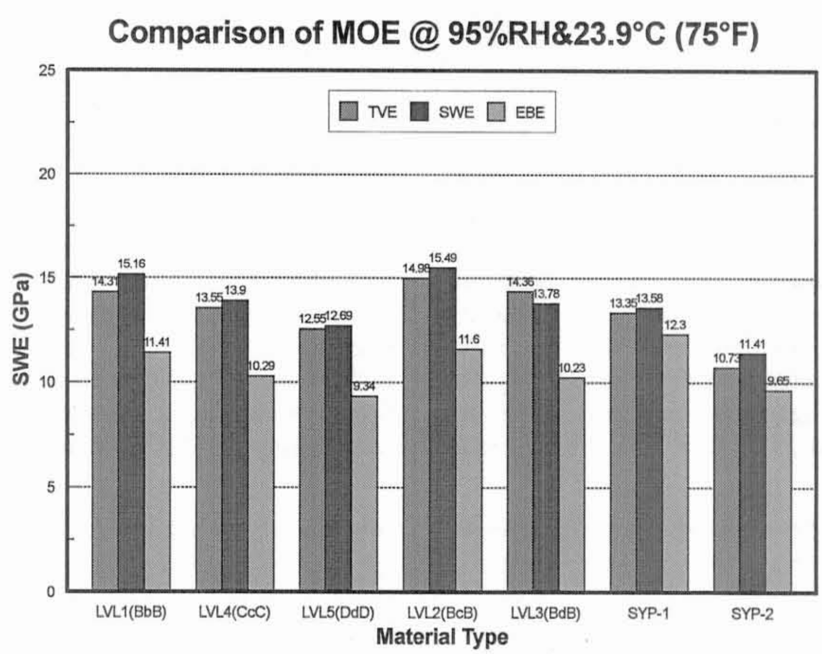

FIG. 10. Comparison of MOEs determined under 95% RH and 23.9°C by different testing methods.

TABLE 2. *Coefficients of determination (r^2) of linear correlations between EBE, TVE, and SWE dependent variable: EBE (edgewise bending MOE).*

ND-MOE	RH	Material type						
		LVL-1	LVL-2	LVL-3	LVL-4	LVL-5	SYP-1	SYP-2
TVE	65	0.3381	0.2482	0.1520	0.4194	0.5615	0.8614	0.8711
	95	0.4273	0.5492	0.4568	0.2708	0.4465	0.8940	0.9108
SWE	65	0.6089	0.7838	0.4808	0.7745	0.6203	0.8066	0.7384
	95	0.6623	0.7551	0.6666	0.5807	0.4107	0.8967	0.8847

is known to be frequency dependent and LVL is a layered anisotropic/orthotropic body, resonant vibration of each veneer may be somewhat different and hence corrections for shear deformation and rotatory inertia may be needed if highly accurate MOE data are sought (Read and Dean 1978). To verify this, further testings on LVL specimens fabricated with different number of plies of veneers, supported with different suspensions and vibrated at different modes, other than the "free-free" beam vibration used in this investigation, as designed by Metriguard, are recommended in the future NDT experiments.

As shown in Table 3, very high correlations between TVE and SWE were found in the solid lumber groups tested under both RH levels (r^2 = 0.90–0.96 for SYP1 and 0.91–0.92 for SYP2). The correlation between TVE and SWE in the LVL groups were much weaker than those of the lumber group and r^2 values ranged from 0.43–0.59 with the exception of LVL-IV:CcC tested under 95% RH at 23.9°C (r^2 = 0.23). These findings suggest that edgewise bending MOE of solid lumber members can be adequately predicted by NDT techniques, either using stress-wave propagation or transverse vibration, and those observations are in agreement with those reported by other studies (Galligan and Courteau 1965; Pellerin and Galligan 1973; Gerhards 1982; Ross and Pellerin 1991). However, predictions of the edgewise bending MOE in LVL members using NDT techniques were not as good as for solid lumber. It appears that MOE predictions based on the stress-wave method are better than that using the transverse vibration as shown in Table 2.

LVL vs. solid lumber

As shown in Figs. 9 and 10, the values of MOEs (EBE: 13.16 GPa (1.909 $\times$ 10^6 psi), SWE: 14.50 GPa (2.103 $\times$ 10^6 psi), TVE: 13.75 GPa (1.994 $\times$ 10^6 psi)) for No. 1 grade southern pine solid lumber tested under environmental conditions of 65% RH at 23.9°C are approximately equal to those of LVL-IV:CcC (EBE: 12.86 GPa (1.865 $\times$ 10^6 psi), SWE: 15.78 GPa (2.289 $\times$ 10^6 psi), TVE: 14.21 GPa (2.061 $\times$ 10^6 psi), but are relatively lower than those of LVL-I:BbB, LVL-II:BcB and LVL-III:BdB. However, the values of MOEs (EBE, TVE, and SWE) for the No. 2 grade southern pine solid lumber, commonly used for light-frame constructions, are lower than those of LVL-V:DdD which had lowest MOEs among the LVLs, determined either by destructive edgewise bending or by NDT. These findings indicate that LVL products, with proper selection of veneer lay-up designs, will have better performance in MOE than a solid lumber

TABLE 3. *Coefficients of determination (r^2) of linear correlations between TVE and SWE dependent variable: TVE.*

RH (%)	Material type						
	LVL-1	LVL-2	LVL-3	LVL-4	LVL-5	SYP-1	SYP-2
65	0.5272	0.4287	0.5875	0.4894	0.4406	0.8986	0.9149
95	0.4835	0.4691	0.5648	0.2324	0.5153	0.9627	0.9087

member. Furthermore, Figs. 5–6 demonstrate that southern pine LVL specimens had a more uniform MOE distribution than the solid southern pine lumber, as indicated by the slope of distribution lines and by the b values (i.e. COV: coefficients of variation) in the MOE (determined by stress wave method) models for each LVL type and lumber grade. For example, as shown in Figs. 5–6, the COV for LVL specimens ranged from 6.77%–8.00% and 6.28%–8.34%, respectively, for the 65% RH/23.9°C and 95% RH/23.9°C groups while the corresponding lumber groups had much larger b values, 19% and 22%, respectively. Again, more uniform distribution of transverse vibration MOE was exhibited by the LVL groups than those of solid lumber, as indicated by the slope of the distribution lines and by the magnitude of b values in the MOE models as shown in Figs. 7 and 8. The ranges of COV are about the same as those observed in the stress-wave tests.

Effect of relative humidity

The variation of MC in all the LVL and solid lumber tested was very small, as shown in Fig. 4. It ranged from 10.84% to 11.62% and 17.84% to 18.72%, respectively, for the environmental conditions of 65% RH/23.9°C and 95% RH/23.9°C. Increase of MC due to the change of RH from 65% to 95% at 23.9°C had a moderate (SWE) or slight (TVE) weakening effect on the NDT MOE properties of southern pine LVL (Figs. 2–3). The RH effect was, however, substantially increased in the LVL groups tested under destructive edgewise bending (Figs. 9–10).

The reductions of MOEs due to the increase of MC (RH) and the difference of testing methods for all LVL and solid lumber groups are summarized in Table 4. The reduction of LVLs MOE evaluated by stress-wave tests ranged from 10.3% (LVL-V:DdD) to 12.8% (LVL-I:BbB) when RH was increased from 65% to 95%, while the reduction values for transverse vibration tested groups were much lower and ranged from 4.0% (LVL-II:BcB) to 5.5% (LVL-I:BbB/LVL-V:DdD). However, large reductions in MOE resulted in the LVL groups tested in edgewise destructive bending and it ranged from 18.6% (LVL-II:BcB) to 23.1% (LVL-III:BdB). For solid lumber groups, the reductions of MOEs due to the increase in MC are relatively lower than those of LVLs regardless of the testing methods as indicated in Table 4. These findings may be useful to structural engineers for consideration in the use of MOE data for LVL products in the design of timber structural systems to be constructed in high humidity regions.

TABLE 4. *Reduction (%) of MOEs due to the increase of RH from 65% to 95% at 23.9°C.*

	Testing methods		
Specimens	Stress-wave	Transverse vibration	Destructive bending
LVL-I	12.8	5.5	22.1
LVL-II	10.6	4.0	18.6
LVL-III	11.4	5.1	23.1
LVL-IV	11.9	4.6	20.0
LVL-V	10.3	5.5	18.9
SYP-1	6.3	2.9	6.5
SYP-2	9.0	6.8	12.4

CONCLUSIONS AND REMARKS

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

1. There is a significant effect of veneer grade on the MOE properties of southern pine LVL, with LVLs fabricated from higher grade veneers being much stiffer than those made of lower grade veneer.
2. Improvement in MOE of LVL fabricated from low grade veneers can be achieved by substituting 2 face veneers on both sides of the member with higher grade veneers.
3. Regardless of RH levels, MOEs determined from NDT are higher than those obtained from destructive edgewise bending. Furthermore, MOE values determined from stress-wave tests are, in general, slightly higher than those predicted by the transverse-vibration method.
4. Excellent correlations between the MOEs

evaluated by the destructive edgewise bending and those determined by NDT (stress-wave propagation or transverse vibration) exist in the solid southern pine lumber and hence bending stiffness of solid lumber can be well predicted by using the NDT techniques. However, such predictions for LVL products are less accurate and reliable, especially by using the transverse-vibration method.

5. A lognormal distribution adequately describes the statistical distribution of MOEs of the southern pine LVL and solid lumber. Based on these distributions, it appears that LVL had more uniform stiffness than the solid sawn lumber.
6. Relative humidity (moisture content) had a great effect on the MOEs in the southern pine LVL that are determined by edgewise bending, but such effect was much less in the solid southern pine lumber. However, the effect of relative humidity on the MOE determined by NDT methods was small, especially on those determined by using the transverse vibration.

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