IN-PLANE DIMENSIONAL STABILITY OF ORIENTED STRAND PANEL: EFFECT OF PROCESSING VARIABLES[1]

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ABSTRACT

Single-layer oriented strand panels were fabricated under a combination of three alignment levels, four densities, and two resin contents. Flake orientation, density gradient across panel thickness, linear expansion (LE), and bending properties were measured. Flake orientation was characterized with the von Mises distribution using mean flake angle and concentration parameter.

It was shown that the shape of the LE-moisture content change curve varied with alignment level and test direction. The variation was attributed to whether the LE of a panel was controlled by transverse or longitudinal wood swelling along a particular test direction. Total LE from oven-dry to water-soak condition, modulus of elasticity (MOE), and modulus of rupture (MOR) varied significantly with flake orientation distribution and density. Effects of resin content at the levels used on LE, MOE, and MOR was relatively small and was more diversified. The LE, MOE, and MOR were correlated with the concentration parameter, density, resin content, and moisture content using a power form equation. The experimental data form a database of layer properties for modeling three-layer, cross-laminated oriented strandboards (OSBs) manufactured under hot pressing.

Keywords: Flakeboard, linear expansion, modeling, stiffness, strength.

INTRODUCTION

Oriented strandboard (OSB) is a structural reconstituted panel that consists of wood strands glued with an exterior-type, waterproof resin. The physical and mechanical properties of the board are enhanced by layering and alignment of wood flakes. In the last decade, OSB has gained significant growth in the structural wood-based panel market. Oriented strandboard capacity reached about 18.4 million m^3 in 1997, with production at about 15.5 million m^3 (Spelter et al. 1997). It has become a promising substitute for structural plywood.

Oriented strandboard swells significantly when the product is exposed to high relative humidity (RH) conditions and/or in direct contact with water (Geimer 1982; Wu and Suchsland 1996, 1997). In addition to the well-recognized importance of thickness stability, in-plane swelling, known as linear expansion (LE), can be a significant factor in structural applications. This is so because the swelling can greatly affect the state of stress that exists in the material. The in-plane movements can cause high internal stresses due to the restraint offered by fastening such as nails. These stresses may be large enough to cause buckled panels, pushed-out nails, and separation of the panel from the structure (Lang and Loferski 1995; Wu and Suchsland 1996).

The in-plane dimensional change of OSB is a direct result of complex interactions among different layers across panel thickness in a three-layer, cross-laminated board (Bryan 1962; Xu and Suchsland 1997). Many processing parameters affect the dimensional change, the most important being flake orientation, shelling ratio (i.e., flake weight ratio between face layer and core layer), degree of bonding, flake geometry, density, and density

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TABLE 1. *Board fabrication data—single-layer uniform density oriented strand panels.*

Board type[a]	Target board density (g/cm^3)	Resin content[b] (%)	Number of replication	Number of boards made
HAL	0.55, 0.75, 0.95, 1.15	4, 6	2	16
LAL	0.55, 0.75, 0.95, 1.15	4, 6	2	16
RAL	0.55, 0.75, 0.95	4, 6	2	12

[a] HAL = High alignment level; LAL = Low alignment level; RAL = Random alignment level.
[b] Based on oven-dry flake weight.

gradient (Kelly 1977; Geimer 1982). Variation in these variables among different products has led to a large variability of LE values in commercial OSBs (Wu and Suchsland 1996). Efforts to reduce LE in these products require a quantitative understanding of the role each variable plays in controlling the in-plane movement.

The study reported here represents the first part of a comprehensive study aimed at examining dimensional stability and its effect on durability of OSB. The objective of this work was to investigate to what extent in-plane stability of oriented strand panels (single-layer) is related to processing variables, namely, flake alignment level (AL), density, and resin content (RC) at various levels of moisture content (MC). Since the in-plane movement and strength properties are closely related, data on bending modulus of elasticity (MOE) and modulus of rupture (MOR) were also presented and discussed.

MATERIALS AND METHODS

Board fabrication

Forty-four oriented strand panels were manufactured (Table 1) in the USDA Forest Products Laboratory, Madison, Wisconsin. In brief, a number of aspen (*Populus grandidentata*) logs with an average diameter of 45 cm were obtained at a local Wisconsin sawmill. The logs were band-sawn into 13-mm-thick boards, which were ripped to eliminate bark, and crosscut into 152-mm-long blocks. These blocks were oriented with the grain direction parallel to the knives of a disc flaker and cut into flakes measuring 0.645 mm thick × 13 mm wide × 76 mm long. The flakes were then dried to about 5% MC and screened. The boards were pressed to a thickness of 12.7 mm in a cold press and were then heated under pressure until the core temperature passed 104°C. This was done to eliminate vertical density gradient inside the boards (Geimer 1982). All boards were made with liquid phenol-formaldehyde adhesive (solid content = 53%) and 0.5% wax. Table 1 lists RC level and number of board replication used in manufacturing the test panels. Immediately after pressing, the boards were weighed and measured for thickness. They were then placed in a plywood box for thermal equalization. The panel size was 609.6 × 711.2 × 12.7 mm.

Specimen preparation and testing procedure

Flake alignment distribution.—A strip of 50.8 mm was trimmed from the four sides of each panel to reduce the edge effects on test specimens. A clear plastic sheet, marked with a 50.8- × 50.8-mm dot grid, was placed on the top surface of each board. One flake from each grid square was randomly selected, and a line representing the flake was drawn on the plastic film parallel to the long dimension of the flake. The plastic film was then placed on a drafting table, and a protractor was used to measure orientation of each line. Flake angles measured varied from −90° to 90° with 0° set along the major alignment direction. A total of 143 flakes were measured for each panel.

Density gradient.—Three 50.8- × 50.8- × 12.7-mm specimens were cut from each panel, totaling 132 specimens for 44 panels. Density profile in the specimen thickness direction was determined on a Quintek Density Profile Model QDP-01X. This equipment is an X-ray-based precision instrument for making density profile measurements in wood composites. The profiler uses an X-ray tube operating in a range of 40 kV to produce a photon beam for density determination.

Linear expansion.—Two samples, 25.4 × 304.8 × 12.7 mm, were cut along each of the two principal directions from each board, totaling 88 samples for each direction. This gave four replications for each combination of density, flake alignment level, and resin content. They were numbered according to board type, test direction (parallel or perpendicular), and replication number. Two holes (1.1 mm in diameter) 254 mm apart were drilled along the long dimension of each specimen, and a small rivet (1.0 mm in diameter), dipped in epoxy glue, was plugged into each of the two holes. After the glue set, one reference cross was carefully cut on the tip of each rivet using a sharp razor blade. The cross facilitated LE measurements with an optical comparator.

All specimens were initially dried in a convection oven at 60°C to reach a constant weight. Measurements including specimen weight, length, width, thickness, and reference dimension between the two rivets of each specimen were made at this initial dry state. The specimens were successively conditioned to reach equilibrium at each of the five RH levels: 35%, 55%, 75%, 85%, and 95%. They were then subjected to a 48 h water-soak (WS) treatment. Finally, all specimens were oven-dried for 24 h at 105°C. The measurements were repeated at each specified RH level, WS, and oven-dry (OD) condition.

Bending test.—Static bending specimens, 76.2 × 355.6 × 12.7 mm, were cut along two principal directions of each panel according to ASTM D1037-96 (ASTM 1996). One parallel and one perpendicular specimen from each panel were prepared, totaling 44 specimens for each direction. This gave two replications for each combination of density, alignment level, and RC. The specimens were conditioned to equilibrium at 45% RH and 25°C. Their weight and size (i.e. length, width, and thickness) were measured before testing. Bending tests were made on a Model 4260 INSTRON machine with a computer-controlled data acquisition system. After breaking, a 50.8- × 76.2-mm section was cut from each end of each sample for further testing in a separate study. The rest of the specimen was weighed and oven-dried to determine its MC on the OD basis.

Data analysis

Flake alignment distribution.—The underlying flake orientation distribution for the test panels is assumed to be the von Mises probability distribution (Harris and Johnson 1982). To obtain the concentration parameter, alignment percent defined by Geimer (1982) and mean flake angle among the number of flakes measured were calculated for each panel. The look-up table published by Shaler (1991) with the alignment percent and mean angle as input was used to obtain the concentration parameter.

Linear expansion, MOE, and MOR.—Linear expansion was calculated as

$$LE = \left[\frac{L_I - L_O}{L_O}\right] \times 100\% \quad (1)$$

where, LE is expressed in % (mm/mm), L_I is the reference dimension at a given RH level (mm), and L_O is the reference dimension at the reference RH level (mm). Linear expansion data were presented in two formats: LE as a function of MC from dry to equilibrium conditions at 35%, 55%, 75%, 85%, and 95% RH; and total LE value from OD to WS condition. Bending MOE and MOR were calculated by the testing program after each test.

The rate of change in LE (from OD to WS), MOE, and MOR per percent change in flake alignment level was calculated as:

$$\text{Property change rate} = \left[\frac{100(P_1 - P_2)/P_1}{(AL_1 - AL_2)}\right] \quad (2)$$

where P_1 and P_2 represent LE (%), MOE (GPa), or MOR (MPa) values at the alignment levels 1 and 2 (AL_1 and AL_2, %). Finally, LE as a function of MC, total LE from OD to WS condition, MOE, and MOR were expressed as a function of processing variables using SAS (SAS Institute 1996) as:

$$P = aRC^b SG^c K^d MC^e \quad (3)$$

where

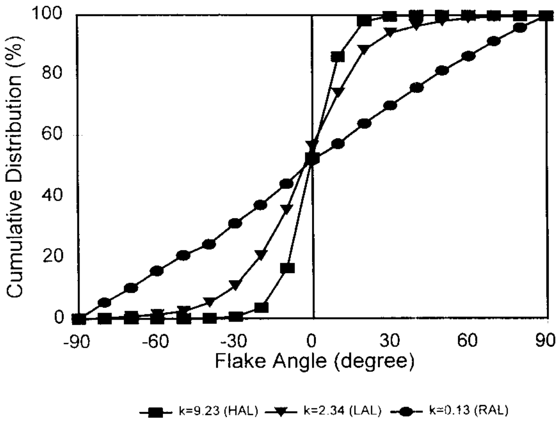

Fig. 1. Measured flake orientation distributions for the test panels at high, low and random alignment levels (HAL, LAL, and RAL).

P = property: LE (%) or MOE (GPa) or MOR (MPa);

RC = resin content (%);

κ = concentration paramenter for the von Mises distribution;

SG = specific gravity;

MC = moisture content (%);

a, b, c, d, and e = regression constants.

In fitting Eq. (3), natural logarithm transformation of both dependent variables (LE, MOE, or MOR) and independent variables (RC, SG, κ, and MC) was first performed. A multilinear regression analysis based on a backward selection procedure was then made with the transformed variables. The backward selection procedure removed insignificant terms at the 0.1000 level from the model.

RESULTS AND DISCUSSION

Flake alignment distribution

Figure 1 shows measured flake orientation for boards at the three alignment levels. The mean angle for all panels was within ±5°. An assumption of a 0° mean angle was thus made to look up the concentration parameter (Shaler 1991).

The concentration parameter, κ, averaged 9.23, 2.34, and 0.13 for the boards with high, low, and random alignment levels, respectively (Table 2). The corresponding alignment percent (Geimer 1982) was 82.3%, 61.3%, and 5.2%. There was a large drop in κ value between 82.3% and 61.3% alignment levels. This was due to the nature of the von Mises distribution itself (Harris and Johnson 1982). As the alignment level further increases, κ increases sharply and becomes infinite at the 100% alignment level. Also shown, random boards were not completely random (i.e., κ was not equal to zero), according to the measured flake orientation distribution.

As the value of κ decreases, flake orientation changes from a perfectly aligned distribution toward a completely random distribution. This quantity can thus be used to correlate both physical and mechanical properties of the panel with flake orientation distribution. The fact that the cumulative distribution curves for flake alignment follow a common mathematical rule is of special significance in comparing analytical expressions of OSBs properties with experimental results.

Density gradient

Figure 2 shows measured density distribution across board thickness for boards at various density levels. As shown, vertical density gradient was effectively eliminated by using a cold press at closing. Subsequent heating after press closure did not cause a significant density gradient inside the panel. Absence of density variation across board thickness allows the study of effects of board density alone on both physical and mechanical properties. From this, layer properties as a function of density can be established to simulate individual layers in three-layer boards with vertical density gradient.

Relationship between LE and MC change

The shape of LE-MC change curve depends on alignment level and test direction (Fig. 3). For the high alignment boards shown (κ = 11.5), LE in the perpendicular direction fol-

TABLE 2. *Summary of LE data from oven-dry to water soak condition.*

Board Type[a]	Alignment level Percent[b]	Alignment level κ[c]	Parallel Density[d] (g/cm³)	Parallel LE (%)	Perpendicular Density (g/cm³)	Perpendicular LE (%)	LE ratio[e]
			4% Resin content				
HAL	84.6	11.52	0.51 (0.02)	0.20 (0.04)	0.58 (0.03)	2.12 (1.05)	10.60
	82.5	9.69	0.76 (0.02)	0.13 (0.05)	0.75 (0.02)	3.30 (0.40)	25.38
	82.1	9.04	0.96 (0.02)	0.15 (0.04)	0.98 (0.03)	3.17 (0.74)	21.13
	81.8	8.66	1.18 (0.03)	0.12 (0.08)	1.21 (0.04)	3.23 (1.23)	26.92
LAL	61.2	2.33	0.59 (0.02)	0.22 (0.08)	0.61 (0.01)	0.83 (0.10)	3.77
	63.1	2.49	0.75 (0.04)	0.22 (0.04)	0.79 (0.02)	0.87 (0.11)	3.95
	60.8	2.29	0.97 (0.02)	0.20 (0.06)	0.89 (0.04)	0.98 (0.18)	4.90
	62.3	2.42	1.13 (0.02)	0.16 (0.02)	1.18 (0.02)	1.28 (0.48)	8.00
RAL	5.86	0.15	0.52 (0.03)	0.39 (0.03)	0.59 (0.03)	0.30 (0.13)	0.77
	8.35	0.21	0.71 (0.01)	0.31 (0.11)	0.79 (0.02)	0.28 (0.07)	0.90
	6.21	0.15	0.90 (0.01)	0.35 (0.09)	0.93 (0.03)	0.41 (0.07)	1.17
			6% Resin content				
HAL	82.8	9.69	0.54 (0.02)	0.21 (0.04)	0.54 (0.01)	2.88 (0.74)	13.72
	82.6	9.73	0.76 (0.04)	0.16 (0.05)	0.84 (0.01)	3.07 (0.56)	19.19
	81.6	8.49	0.97 (0.06)	0.12 (0.06)	0.99 (0.02)	2.96 (0.55)	24.67
	80.2	7.05	1.19 (0.04)	0.11 (0.12)	1.16 (0.02)	3.33 (0.93)	30.27
LAL	59.5	2.18	0.61 (0.02)	0.21 (0.07)	0.60 (0.02)	0.87 (0.19)	4.14
	61.7	2.36	0.78 (0.01)	0.23 (0.04)	0.76 (0.03)	0.89 (0.08)	3.87
	60.9	2.29	0.96 (0.02)	0.20 (0.05)	1.00 (0.03)	1.13 (0.41)	5.65
	60.8	2.33	1.11 (0.08)	0.17 (0.08)	1.09 (0.06)	1.15 (0.36)	6.76
RAL	3.97	0.10	0.53 (0.02)	0.42 (0.03)	0.56 (0.01)	0.44 (0.14)	1.05
	5.25	0.13	0.70 (0.03)	0.37 (0.06)	0.73 (0.02)	0.32 (0.11)	0.86
	1.49	0.04	0.95 (0.05)	0.36 (0.05)	0.91 (0.03)	0.35 (0.13)	0.97

[a] HAL = High alignment level; LAL = Low alignment level; RAL = Random alignment level.
[b] Alignment percent follows the definition by Geimer 1982.
[c] κ = Concentration parameter of the flake orientation distribution.
[d] Density—based on the oven-dry weight and volume at about 2% MC.
[e] LE ratio = LE in the perpendicular direction divided by LE in the parallel direction.

lowed a nearly linear relationship with MC change (Fig. 3a). This relationship agrees with well-established linear MC-shrinkage or swelling relationships in the transverse directions for solid wood. The swelling coefficient, % swelling/%MC change, of the high aligned boards averaged 0.12 in the perpendicular direction. This value compares well with the published radial shrinkage or swelling coefficient of 0.11 for aspen based on a total radial shrinkage or swelling of 3.4% and a fiber saturation point of 30% (USDA Forest Service 1987). Linear expansion in the parallel direction followed a curvilinear relationship with MC change (Fig. 3b). Over a given MC change, LE change in the parallel direction was larger at lower MC levels. Thus the swelling rate decreased as MC levels increased such that the LE-MC curve gradually approached an asymptote parallel to the MC axis. The small magnitude of LE in the parallel direction and its curvilinear relationship with MC change reflected the true longitudinal wood swelling (Sadoh and Christensen 1964).

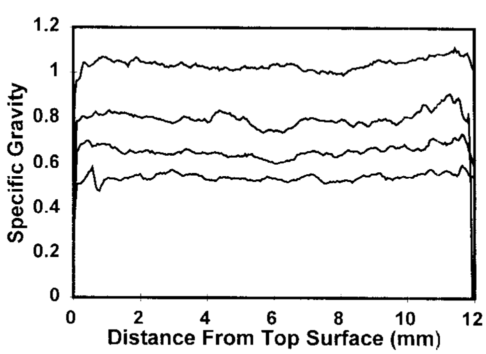

Fig. 2. Measured density profiles across board thickness for the test panels at various density levels.

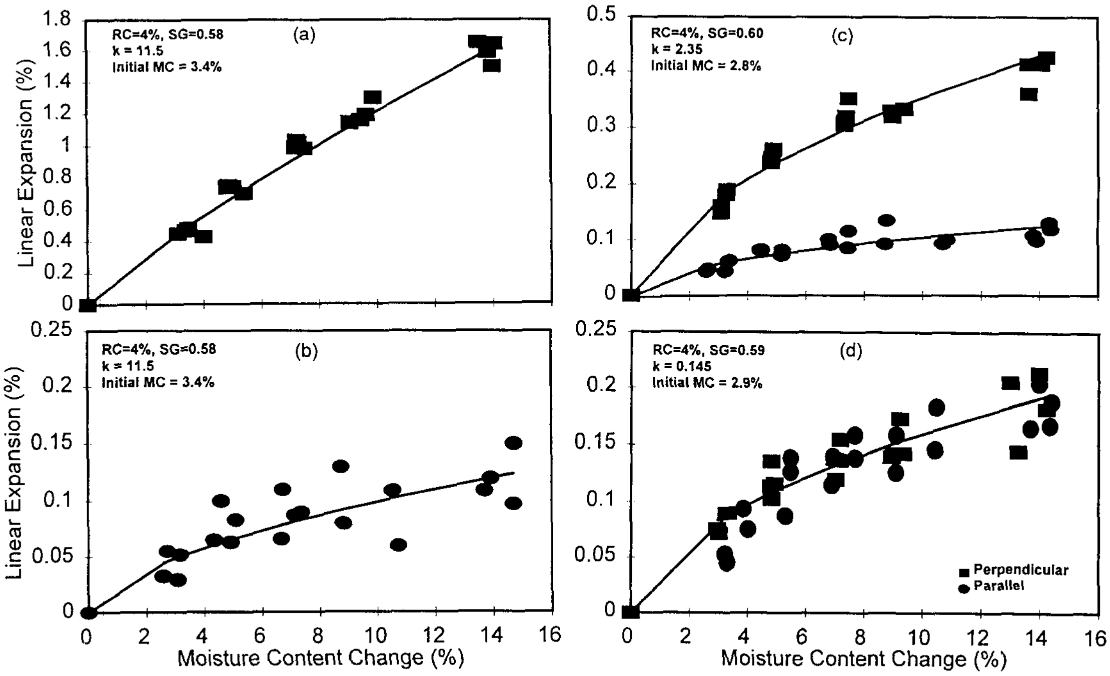

Fig. 3. Typical LE-MC change relationships for the test panels. a) high alignment boards in the perpendicular direction, b) high alignment boards in the parallel direction, c) low alignment boards, and d) random alignment boards.

Therefore, high alignment boards swelled in the plane of the panel much like solid wood.

As the flake alignment level decreased, LE decreased greatly in the perpendicular direction and increased slightly in the parallel direction (Fig. 3c for $\kappa = 2.35$). This was due to an increased percentage of flakes turning away from the major alignment direction as compared to the high alignment boards. In the perpendicular direction, wood longitudinal swelling from the flakes oriented toward the perpendicular direction restricted the transverse swelling of the flakes oriented toward the parallel direction. This resulted in a reduced amount of panel swelling in the perpendicular direction. In the parallel direction, the transverse wood swelling of the flakes oriented toward the perpendicular direction contributed to the increased panel swelling in the parallel direction. However, the extent of LE increase in the parallel direction was much smaller as compared to the LE decrease in the perpendicular direction. Due to the contribution of longitudinal wood swelling, the LE-MC relationship in the perpendicular direction became curvilinear. This change in the shape of the swelling curve clearly demonstrated the dominant effect of longitudinal wood swelling. The swelling not only changed the magnitude of panel swelling, but also changed the shape of the swelling curve. This provides more clear evidence that longitudinal wood swelling controls in-plane movement of wood composite panels.

For the random boards (Fig. 3d for $\kappa = 0.145$), LE curves from both directions overlapped indicating more uniform in-plane swelling properties. Again, a curvilinear relation was observed. Board density and resin content had little effect on the shape of the swelling curve.

Most OSB products have a flake alignment level falling between those of the high alignment and random boards shown above. They all possess a similar curvilinear LE-MC change relationship, provided that they are

TABLE 3. *Summary of test results on bending MOE and MOR.*

		Parallel				Perpendicular				
Board type[a]	κ	MC (%)	SG	MOE (MPa)	MOR (MPa)	MC (%)	SG	MOE (MPa)	MOR (MPa)	MOE ratio[b]
				4% Resin content						
HAL	11.52	5.5	0.50	8,305.5	51.96	5.5	0.60	608.5	5.83	13.65
	9.69	5.7	0.75	13,317.5	82.67	5.6	0.75	1,059.1	8.28	12.57
	9.04	5.7	0.92	15,358.2	114.76	5.9	0.88	1,392.4	12.89	11.03
	8.66	4.6	1.17	19,133.1	141.62	6.1	1.08	2,316.2	19.64	8.26
LAL	2.33	5.2	0.54	7,270.6	45.91	5.2	0.53	1,603.1	13.89	4.54
	2.49	5.1	0.73	9,349.4	61.43	5.1	0.72	2,580.7	26.08	3.63
	2.29	5.6	1.03	13,579.3	102.73	5.8	0.90	3,064.7	31.08	4.43
	2.42	5.2	1.11	14,472.2	106.94	5.8	1.07	3,283.9	36.82	4.41
RAL	0.15	4.7	0.50	3,703.2	23.83	5.0	0.56	4,306.8	31.07	0.86
	0.21	4.8	0.73	5,909.9	42.14	4.7	0.80	6,396.9	45.35	0.92
	0.15	5.1	0.86	6,874.8	49.54	5.8	0.90	6,347.0	51.34	1.08
				6% Resin content						
HAL	9.69	5.3	0.52	8,484.1	48.45	5.4	0.52	722.9	6.88	11.74
	9.73	5.6	0.73	12,141.7	81.64	5.6	0.73	1,256.9	12.22	9.66
	8.49	5.7	0.92	15,134.1	120.18	5.9	0.92	1,662.7	13.23	9.10
	7.05	4.4	1.14	20,032.9	151.55	5.9	1.17	2,454.2	24.24	8.16
LAL	2.18	5.1	0.53	7,327.5	47.89	5.6	0.53	1,821.3	18.29	4.02
	2.36	5.3	0.72	9,607.9	65.54	5.3	0.75	2,072.9	25.49	4.64
	2.29	6.1	0.99	12,000.4	95.84	6.1	0.93	3,070.9	33.82	3.91
	2.33	5.9	1.06	15,764.9	120.35	6.3	1.05	3,673.2	36.27	4.29
RAL	0.10	5.8	0.54	3,744.6	27.54	5.0	0.59	5,043.2	38.48	0.74
	0.13	4.5	0.65	5,448.6	45.38	4.8	0.70	5,975.7	49.09	0.91
	0.04	4.5	0.95	6,874.8	49.54	5.8	0.99	7,270.9	68.19	0.95

[a] HAL = High alignment level; LAL = Low alignment level; RAL = Random alignment level.
[b] MOE ratio = MOE in the parallel direction divided by MOE in the perpendicular direction.

properly made (Wu and Suchsland 1996). As a result, departure in the shape of the curve from the one with a falling rate would reflect some internal structural changes due to moisture-related swelling (Xu and Suchsland 1991). For example, if a panel has an LE-MC curve with a swelling rate increasing with MC as the MC of the panel approaches the fiber saturation point, significant internal adhesive bond damage must have occurred in the panel due to excess thickness swelling. Therefore, the shape of LE-MC curves may provide a way to check the integrity of the panel under swelling conditions.

Effect of flake alignment level on LE, MOE, and MOR

The dependence of LE from OD to WS condition, MOE, and MOR on flake orientation is summarized in Table 2 and Table 3. Figures 4a, 4b, and 4c show, respectively, plots of LE, MOE, and MOR as functions of κ for the panels at the 4% resin content level. The magnitudes of LE, MOE, and MOR were strongly influenced by flake orientation.

With decreases in κ, indicating that flake orientation changes from an aligned distribution toward a random distribution, LE decreased in the perpendicular direction and increased in the parallel direction (Fig. 4a). In contrast to LE, MOE, and MOR increased in the perpendicular direction and decreased in the parallel direction (Fig. 4b and 4c). Thus, there is a close relationship between in-plane movement and strength properties in oriented strand panels. Both LE, MOE, and MOR in the two principal directions reached a similar value for random boards.

To further demonstrate the effect of flake alignment level on LE, MOE, and MOR, Eq.

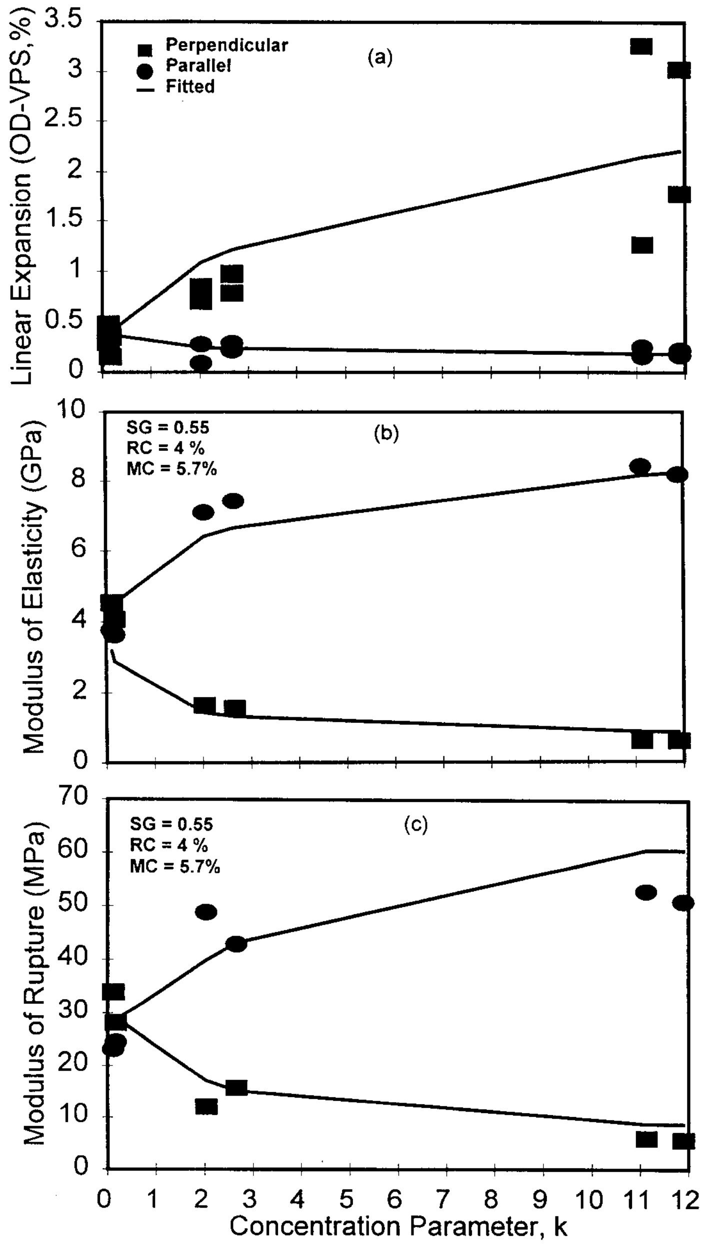

Fig. 4. Dependence of LE from OD to water-soak condition (a), MOE (b), and MOR (c) on the concentration parameter. Lines show fitted values.

(2) and data in Tables 2 and 3 were used to calculate the rate of change in LE, MOE, and MOR in relation to the change in flake alignment level. The rates varied with test direction and degree of alignment (Table 4). As shown, in the parallel direction, the rate of change for each property (LE, MOE, or MOR) was similar for the two given alignment ranges at each of the two RC levels. In the perpendicular direction, however, the rate at the higher align-

TABLE 4. *The rate of property change over the two alignment ranges*[a].

Alignment level		LE[b]		MOE		MOR		
Percent	κ	//	⊥	//	⊥	//	⊥	RC
83% ~ 62%	9.73 ~ 2.38	−2.11	3.23	0.85	−6.78	0.76	−7.85	4%
62% ~ 7%	2.38 ~ 0.17	−1.17	1.15	0.82	−2.57	0.80	−1.59	
82% ~ 61%	8.74 ~ 2.29	−1.75	3.22	1.28	−4.79	0.65	−6.83	6%
61% ~ 4%	2.29 ~ 0.09	−1.46	1.11	0.82	−3.04	0.74	−1.85	

[a] LE, MOE, and MOR data shown are in percent change in the property value per percent alignment level change. The data are means from boards at the first three density levels of each board type (HAL, LAL, and RAL in Tables 2 and 3).
[b] Negative numbers mean a decrease in the property and positive numbers mean an increase in the property.

ment levels (alignment percent > ~60% or κ > ~2.3) was up to three times higher than that at the lower alignment levels (alignment percent < ~60% or κ < ~2.3). This suggested that in the parallel direction, property change occurred more uniformly over the entire alignment range. In the perpendicular direction, however, there was more dramatic change in all three properties at the higher alignment level. The rate of change decreased considerably once the alignment level decreased to about 60% level. These experimental observations in LE agree with the predicted behavior by Xu and Suchsland (1997) for single-layer oriented strand panels.

The large rate increase of LE value in the perpendicular direction for the panels at higher alignment levels may not cause significant problems in three-layer boards. This is because their strength properties decrease at the same time. Under cross-lamination, their large swelling potential will be restricted by the flake layers running perpendicular to them.

Effect of board density on LE, MOE, and MOR

The dependence of the LE, MOE, and MOR on panel density is summarized in Table 2 and Table 3. Data of LE, MOE, and MOR as a function of density are plotted in Fig. 5a, 5b, and 5c, respectively.

For the aligned boards, there was an increase in LE along the perpendicular direction and a decrease in LE along the parallel direction with increases in panel density (Table 2 and Fig. 5a). As a result, LE ratio between perpendicular and parallel directions generally increased with increase in panel density (Table 2). For the random boards, the trend was less obvious. Thus, with single-layer oriented strand panels of uniform density, panel density not only influenced LE value, its effect also varied with test directions.

Earlier works quoted by Kelly (1977) did not show a consistent relationship between LE and density. This may be due to the presence of density gradient and cross-lamination in the study panels manufactured under hot pressing. As shown earlier, density effect on LE varied with test directions. Under cross-lamination, the effects from the two directions cancel each other. Depending on the test direction actually measured and density difference in the face and core layers, LE of the panel may increase or decrease with increased panel density.

The peculiar behavior of LE in relation to panel density for the test panels may be explained at the cellular level. Under pressure and heat as used in hot pressing, cell lumina and/or vessels in hardwoods would collapse, and fractures in cell walls would develop. As a result of densification, the amount of wood material and wood-to-wood (or flake-to-flake) contact in the plane of a panel would increase. This process is likely to occur at an increased intensity with increased panel density. Because of large transverse swelling potential of wood, the increased amount of wood material in the plane of the panel would lead to a larger swelling in the perpendicular direction, which explains why the perpendicular LE increased with panel density. Since wood is much stronger and swells much less in the longitudinal direction, relative movement between flakes

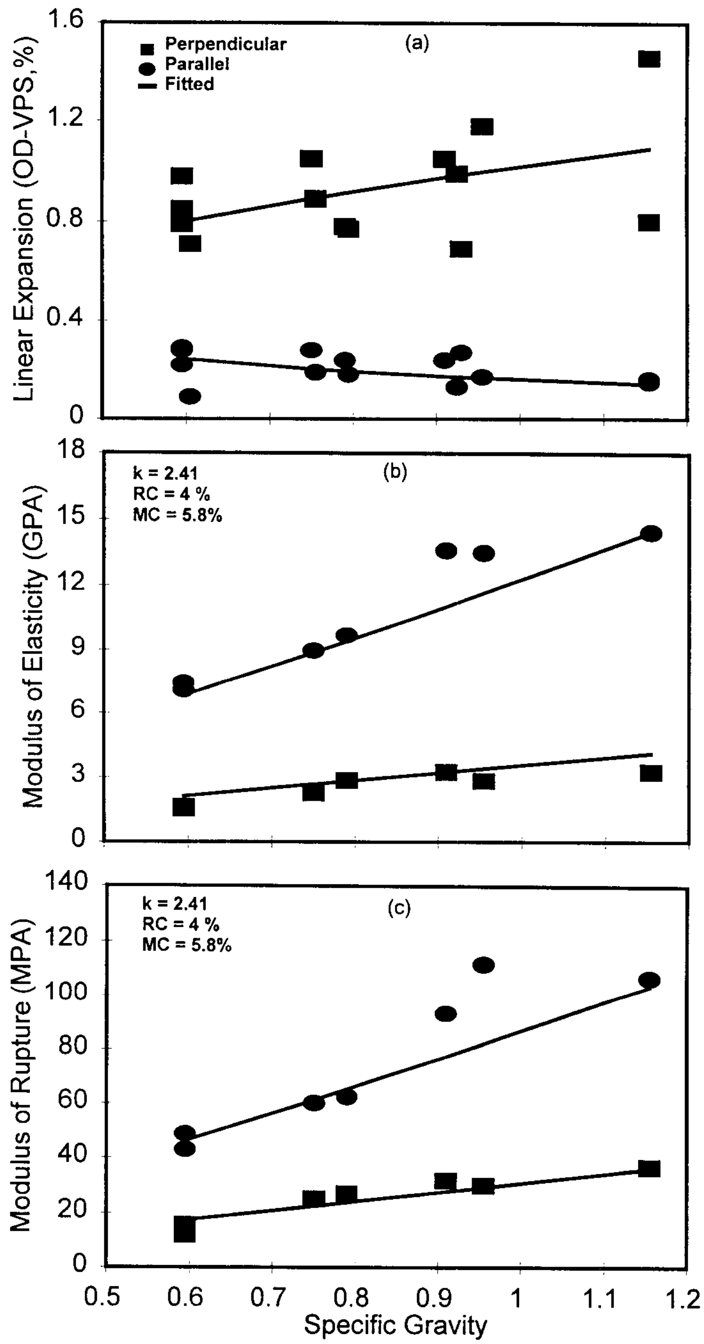

Fig. 5. Dependence of LE from OD to water-soak condition (a), MOE (b), and MOR (c) on panel density. Lines show fitted values.

becomes important in controlling the LE in the parallel direction of the panel. Under the swelling condition, the effect of increased wood-to-wood (or flake-to-flake) contact (leading to better bonding and less movement) outweighed the effect of increased wood material in the plane. As a result, LE decreased with panel density in the parallel direction. It should be pointed out that for a three-layer panel, effect of cross-lamination plays a significant role in controlling the LE of the panel.

As expected, MOE and MOR in both parallel and perpendicular directions increased linearly with specific gravity. The result agrees with earlier research results in the field (Geimer 1982; Kelly 1977). This is commonly attributed to the increase of wood material for a given board volume at higher density levels.

Effect of resin content on LE, MOE, and MOR

Resin content is often believed to play a key role in helping stabilize the panel under the swelling condition. However, for the two resin content levels used in the study, the effect of resin content on LE was relatively small and diversified. Under the high humidity exposure conditions, RC had significant effects on LE. However, total LE from OD to WS was not affected by the resin content. The general impression was that RC did not influence LE greatly at the RC levels used (Fig. 6a and 6d). This seems to agree with the earlier finding (Kelly 1977) that except at extremely low resin contents where LE is substantially increased, above a resin content high enough to adequately bond the particles, further resin addition is of little benefit to this property.

For MOE and MOR, resin content had only significant effects on MOR in the parallel direction (Fig. 6b, 6c, 6e, and 6f). Thus, effects of RC on both MOE and MOR seem to level off at the given RC range, similar to LE data. Further experiments are underway to examine effects of resin content on the long-term strength retention behaviors of these products under cyclic MC change conditions.

Fitting the data

The regression results on the relationships between LE, MOE, MOR and various processing variables are summarized in Table 5. Typical plots of fitted lines based on the regression equations in Table 5 are shown in Figs. 4 and 5. In general, the power form relationship fitted MOE and MOR data better compared with the LE data. This can be seen from Table 5 as the coefficients of determination of the regression models for MOE and MOR models are higher than those for LE. Generally, a larger variability in LE data exists in OSB (Wu and Suchsland 1996). This is so because a slight change in flake orientation (within a panel and between replication panels) makes a large difference in the LE values. The analytical functions established provide a means to relate various properties to processing variables for modeling three-layer panels manufactured under hot pressing.

SUMMARY AND CONCLUSIONS

Linear expansion in OSB occurs as a result of complex interactions between various processing variables and MC increases. Excess movement in the plane of a panel can cause high internal stresses when it is totally or partially restrained. The study described here investigates effects of flake orientation distribution, density, resin content, and MC levels on LE, MOE, and MOR of single-layer oriented strand panels.

It was found that the shape of the LE-MC change curve varied with alignment level and material directions. The variation was attributed to the difference in the controlling mechanism for LE in various panels. Linear expansion from OD to WS condition, MOE, and MOR were found to vary significantly with flake orientation distribution and density. Effect of RC on LE, MOE, and MOR was relatively small and more diversified. The LE, MOE, and MOR were correlated with flake orientation distribution, density, resin content, and moisture content through a power form equation. Future publications will discuss in-

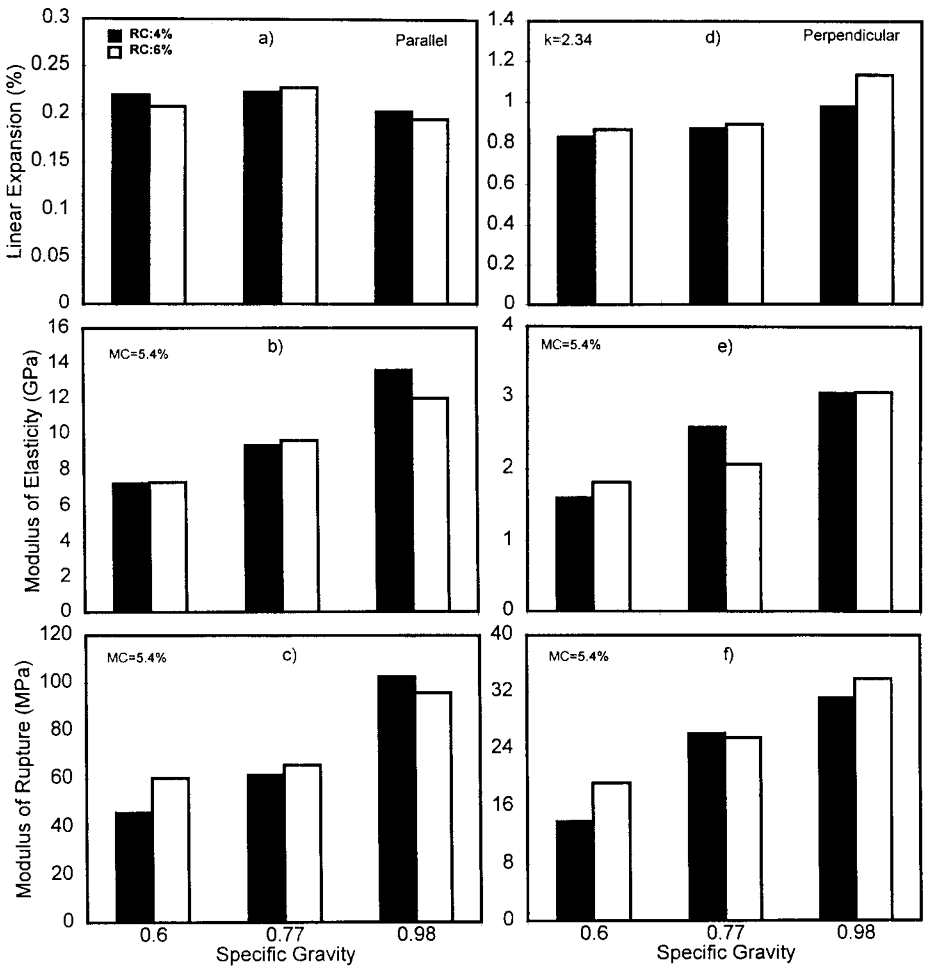

Fig. 6. Dependence of LE from OD to water-soak condition (a, d), MOE (b, e), and MOR (c, f) on resin content.

TABLE 5. *Regression results on the relationships between LE, MOE or MOR and panel manufacturing variables. Model: LE, MOE, or MOR = a RC^b SG^c κ^d MC^e.*

Material direction	Properties	Regression constants a	b	c	d	e	r^2
Parallel	LE (%)	0.02837	−0.1877	−0.7706	−0.1616	0.5890	0.80
	LE (OD-WS, %)	0.1743	/[a]	−0.7883	−0.1679	—	0.54
	MOE (GPa)	12.1314	/[a]	1.1589	0.1411	—	0.96
	MOR (MPa)	57.3969	0.2827	1.2675	0.1358	—	0.95
Perpendicular	LE(%)	0.0500	0.4839	0.62855	0.3281	0.7215	0.80
	LE (OD-WS, %)	0.4078	0.5451	0.4395	0.3994	—	0.75
	MOE (GPa)	3.6324	/[a]	1.1544	−0.2842	—	0.85
	MOR (MPa)	33.4678	/[a]	1.2477	−0.2585	—	0.80

[a] Terms removed by the backward selection procedure (i.e., significant at the 0.1000 level).

plane stability of three-layer, cross-laminated OSBs with vertical density gradient.

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