ANISOTROPY CHARACTERIZATION OF STRUCTURAL FLAKEBOARDS WITH ULTRASONIC METHODS

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ABSTRACT

The aim of this research was to study the anisotropic behavior of structural flakeboards using ultrasonic velocity and acoustic emission methods. One full-size board (3,050 × 1,850 × 19 mm) was analyzed for which the orthotropic model was assumed. Ultrasonic velocities of longitudinal and transversal bulk waves were used to estimate the nine stiffnesses. The measurements were performed on specimens of standard size cut from the board. Surface wave velocities were measured on the full-size board along and across the flake alignment direction. Furthermore an acoustic emission technique of breaking 0.5 mm pencil lead on the surface of the specimens was employed. Several parameters of acoustic emission were measured (duration, count number, energy, peak amplitude, rise time) on specimens cut parallel and perpendicular to the direction of flake alignment. The anisotropy was estimated as the ratio of velocities of bulk and surface waves and of acoustic invariants, as well as the ratio of acoustic emission parameters.

Keywords: Structural flakeboards, ultrasound, elastic constants, anisotropy, acoustic emission.

NOTATION

1, 2, 3: principal anisotropic directions of the board, corresponding respectively to the direction of the flake alignment, to the perpendicular direction to the flake alignment and to the thickness of the board.

Γ_{ik}: Christoffel's stiffness, also called propagation tensor, a function of stiffness matrix C_{ij} and of components of unit-wave normal vector $\vec{n}(n_1, n_2, n_3)$

i, j — used as indices, integer taking the values 1, 2, 3, 4, 5, 6
v — velocity of wave propagation
ρ — density
Θ — angle of wave vector orientation $n_1 = \cos\Theta$
v_{ii} — velocity of longitudinal waves (m/s)
v_{ij} — velocity of shear waves (m/s)
V_{QL} — velocity of a quasi-longitudinal wave
V_{QT} — velocity of a quasi-transverse wave
ϑ_{ij} — Poisson's ratios
$[S_{ij}]$ — terms of compliance matrix, or $[S_{ij}] = [C_{ij}]^{-1}$
E_i — modulus of elasticity (10^8 N/m^2)
I_{ij} — acoustic invariant, e.g., in the 1,2-plane the acoustic invariant is given by: $I_{12} = \frac{1}{2}(V^2_{11} + V^2_{22} + 2V^2_{66})^{1/2}$ I-ratio — ratio of acoustic invariants $= I_{23}/0.5(I_{12} + I_{13})$

INTRODUCTION

Different acoustic techniques have been used with varying degrees of success in predicting the quality of wood-based composites. Tests employing the frequency resonance method (Geimer 1986; Greubel and Merkel 1987; Mehlhorn and Merkel 1986; Paraschiv et al. 1977), the ultrasonic velocity method (Burmester 1968; Dunlop 1980; Szabo 1978; Bucur et al. 1991), the stress wave method (Pellerin 1989) and the acoustic emission method (Morgner et al. 1980; Beall 1985, 1986a, b; Lemaster and Dornfeld 1988) assessed the structural and functional integrity of several types of wood-based composites.

The aim of this research was to study with the ultrasonic velocity method, using bulk and surface waves, and with the acoustic emission technique the anisotropic behavior of structural flakeboards of 19-mm thickness, manufactured from softwood flakes ($2 \times 4 \times 0.3$ cm of *Pinus* spp.) bonded with urea-formaldehyde resin.

THEORETICAL CONSIDERATIONS

It is well known that the Christoffel equation gives the relationships between elastic constants and ultrasonic velocities (Musgrave 1970). For an orthotropic solid, nine constants must be determined as:

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & & & \\ & C_{22} & C_{23} & & & \\ & & C_{33} & & & \\ & & & C_{44} & & \\ & & & & C_{55} & \\ & & & & & C_{66} \end{bmatrix} \quad (1)$$

The relations between the terms of the stiffness matrix (Eq. 1) and the ultrasonic velocities are:

$$[\Gamma_{ik} - \rho v^2 \delta_{ik}] = 0 \quad (2)$$

If this equation is solved for the wave propagation directions along the symmetry axes of an orthotropic solid, we get three solutions each of which shows that along every axis it is possible to have three types of waves: one longitudinal and two transverse.

Such solutions enable us to calculate the six diagonal terms of the stiffness matrix, having the general form

$$C_{ii} = v_{ii}{}^2 \rho \quad (3)$$

The three off-diagonal stiffness components can be calculated using the general equation:

$$C_{ij} = \Gamma_{ij}/n_k n_l - C_{ii} \quad (4)$$

giving for example, for the constants in the 2,3-plane:

$$C_{23} = \Gamma_{23}/n_2 n_3 - C_{44} \quad (5)$$

where Γ_{23} is computed from Christoffel's equation as:

$$\Gamma_{23} = [(\Gamma_{22} - \rho V^2)([\Gamma_{33} - \rho v^2)]^{1/2}$$

$$\Gamma_{22} = C_{22} n_{22}{}^2 + C_{44} n_{33}{}^2$$

$$\Gamma_{33} = C_{33} n_{33}{}^2 + C_{44} n_{22}{}^2 \quad (6)$$

For the elastical model of the boards in this study we assume orthotropic symmetry. The overall elastic properties are defined in terms of a homogeneous equivalent material.

Γ_{ij} can be calculated from quasi-longitudinal or quasi-transverse waves propagating at the angle Θ of the wave orientation vector. In our case the quasi-longitudinal velocities were measured on specimens at 45°. The choice of this angle was determined by the very small thickness of the board. More details about the calculation of the nondiagonal terms of the stiffness matrix in wood are given by Bucur (1986) and in composites by Kriz and Stinchomb (1979), by Rokhlin and Wang (1989), or by Castagnede et al. (1990).

The relationships between the Young's moduli and stiffnesses are as follows:

$$E_1 = AC/C_{22} \cdot C_{33} - C^2{}_{23} \quad (7)$$

$$E_2 = AC/C_{33} \cdot C_{11} - C^2{}_{13} \quad (8)$$

$$E_3 = AC/C_{11} \cdot C_{22} - C^2{}_{12} \quad (9)$$

$$AC = C_{11}C_{22}C_{33} + 2C_{13}C_{23}C_{13} - - C^2{}_{12}C_{33} - C^2{}_{23}C_{11} - C^2{}_{13}C_{22} \quad (10)$$

The Poisson ratios ν_{ij} were calculated from the terms of compliance matrix $[S_{ij}]$ (where $[S_{ij}] = [C_{ij}]^{-1}$) and Young's modulus E_i as:

$$\nu_{ij} = -S_{ij}/E_i \quad (11)$$

From the above parameters, the anisotropy of the studied solid can be deduced as a ratio of velocities, stiffnesses, or the technical constants.

Interest in acoustical invariant calculation for anisotropic solids has been expressed in several references (Hearmon 1961; Fitzgerald and Wright 1967; Musgrave 1986; Bucur and Chivers 1991).

The calculation of acoustic invariants is derived from the classical theory of elasticity. The general equation for the invariant sum of squared velocities deduced for an orthotropic solid for which $C_{11} > C_{22} > C_{33}$ is the following:

$$V^2{}_{QL(\alpha)} + V^2{}_{QT(\alpha)} + V^2{}_{QL(90^\circ-\alpha)} + V^2{}_{QT(90^\circ-\alpha)} = = \text{a constant} \quad (12)$$

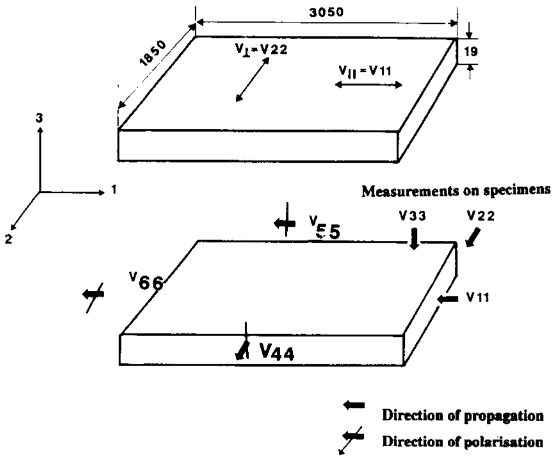

FIG. 1. Velocity measurements on board and specimens.

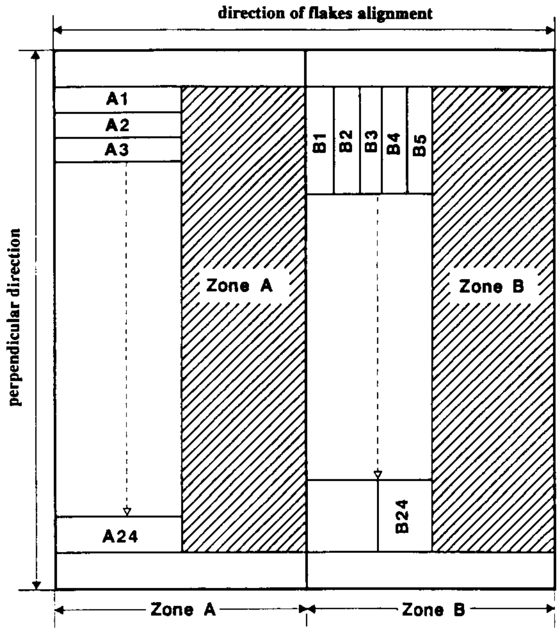

FIG. 2. Sampling strategy. Specimens Type A were cut parallel to the direction of the flake alignment and the specimens Type B were cut perpendicular.

where $V_{QL(\alpha)}$ and $V_{QT(\alpha)}$ are, respectively, the velocities of quasi-longitudinal and quasi-shear waves propagating in n direction, out of principal axes of symmetry. The velocities $V_{QL(\alpha)}$ and $V_{QT(\alpha)}$ lie exterior and interior to an ellipse, which for example in 1,2 plane have the equation:

$$\rho V^2_{ellipse} = \Gamma_{11} + \Gamma_{22} \tag{13}$$

When $\alpha = 0$ the propagation takes place in symmetry axis and

$$\begin{aligned} V^2_{11} + V^2_{22} + 2V^2_{66} &= \text{a constant; in a 1,2-plane} \\ V^2_{11} + V^2_{33} + 2V^2_{55} &= \text{a constant; in a 1,3-plane} \\ V^2_{22} + V^2_{33} + 2V^2_{44} &= \text{a constant; in a 2,3-plane} \end{aligned} \tag{14}$$

While the calculated velocities deduced from the relations (14) have to lie between $V_{QL(\alpha)}$ and $V_{QT(\alpha)}$, we see that:

$$0.5V_{ellipse} = 0.5(V^2_{11} + V^2_{22} + 2V^2_{66})^{1/2} = \text{a constant} = I_{12} \tag{15}$$

The anisotropy of the studied specimen can be expressed as a ratio (I-ratio) of the invariant in transverse plane (I_{23}) to the average of the invariants in planes containing the axis 1, as:

$$I_{ratio} = I_{23}/0.5(I_{12} + I_{13}) \tag{16}$$

EXPERIMENTAL PROCEDURE

One flakeboard of current industrial size (3,050 × 1,850 × 19 mm) was tested. Three ultrasonic techniques were employed for its characterization: surface wave measurements on the whole board, ultrasonic bulk wave (longitudinal and shear) velocity measurements on specimens cut from the board, and acoustic emission parameter measurements, induced by breaking 0.5 mm pencil lead on the surface of the specimens.

The ultrasonic velocity method was used to measure the velocity of propagation of longitudinal, shear and surface waves, induced by corresponding transducers as indicated in Fig. 1. Specimens (400 × 75 × 12 mm) were cut from the board of commercial size as shown in Fig. 2. Type A specimens are parallel to the direction of flake alignment. Type B specimens were cut perpendicular to the direction of flake alignment.

TABLE 1. *Ultrasonic velocity (m/sec) in flakeboards (19 mm).*

Values	Specimens						Boards		
	Longitudinal waves			Shear waves				Surface waves[1]	
	V_{11}	V_{22}	V_{33}	V_{44}	V_{55}	V_{66}	I-ratio	(1)	(2)
Average	2,379	2,155	704	564	618	1,129	0.77	2,400	2,290
Minimum	2,198	1,966	652	528	574	1,070	0.72	2,242	2,172
Maximum	2,613	2,310	841	622	648	1,239	0.82	2,612	2,372
Coeff (%) variation	4	4	6	3	3	3	4		4

[1] Parallel (1) and prependicular (2) to fake alignment.

The density of the specimens was determined by measuring the dimensions and the mass of specimens of Types A and B.

The specimens were conditioned at constant temperature (20 C) and relative humidity (65%) for 3 weeks.

Ultrasonic measurements on specimens were performed with Panametrics equipment, composed of an AU 5052 analyzer and Panametrics 1 mHz broadband transducers for longitudinal (V105) and shear (V153) waves in the through-transmission method.

The phase velocities were calculated as dimension of the specimen divided by time, deduced as measured delay in the specimen. On the screen of the oscilloscope, the measurement of time delay was taken at the peak amplitude of the received signal.

The next step in nondestructive, in line control of flakeboard production by ultrasound needs to bridge the gap between the description of the elastical parameters of the board and the velocity measurements on full size specimens. For this purpose, we suggest the measurement of surface velocities.

Surface wave velocity measurements on the board were performed with a portable ultrasonic apparatus. Some characteristics of this apparatus are: maximum pulser voltage 250 V; bandwidth 3–300 kHz, bandfilter on receiver 80 kHz, sensitivity 1–1,000 mV cm^{-1}; time-base 30–10,000 μs; repetition rate 20 Hz, and rise-time 3 μs.

The special design of a receiving transducer provided with a wedge set at 45° yielded the reception of surface waves induced by mode conversion of bulk waves launched by a plane transmitter.

The third approach proposed for quality estimation of the flakeboards was the acoustic emission technique. Acoustic emission activity was induced by breaking 0.5-mm pencil lead on the surface of the specimen. Acoustic emission parameters measured were: duration of the acoustic event, count number, peak amplitude, energy, and rise time. These parameters were measured at the surface of the specimen following the two main symmetry directions, either parallel to the flake alignment or perpendicular to it. Measurements were performed with a Dunegan-Locan acoustic emission analyzer, with a frequency response of 1.2 kHz–1.2 mHz. The transducer used was an R15 with a frequency response at 150 kHz. The reference at the transducer was set at 1 μV for 0 dB. The gain was 33 dB. The

TABLE 2. *Ultrasonic stiffnesses (10^8 N/m^2) of specimens.*

Values	Density kg/m^3	Stiffnesses (10^8 N/m^2)					
		Longitudinal waves			Shear waves		
		C_{11}	C_{22}	C_{33}	C_{44}	C_{55}	C_{66}
Average	634	36.2	29.5	3.2	2.2	2.4	8.1
Minimum	602	31.1	23.6	2.6	1.9	2.0	7.0
Maximum	665	45.4	33.1	4.5	2.4	2.7	9.9
Coeff (%) variation	3	9	8	13	6	7	7

TABLE 3. *Off-axis velocities (m/sec) and stiffness deduced from specimens of 611 kg/m³.*

Velocities (m/sec) at 45°			Stiffnesses (10^8N/m²)								
			Off-diagonal			Diagonal terms					
V_{12}	V_{13}	V_{23}	C_{12}	C_{13}	C_{23}	C_{11}	C_{22}	C_{33}	C_{44}	C_{55}	C_{66}
1,900	550	640	3.43	4.27	0.91	36.1	23.6	2.76	2.04	2.39	9.35

transducer was successively located on the specimens at 5, 10, 15 and 20 cm from the source. The source was located at 30 mm from the end of the specimen at mid-width.

RESULTS AND DISCUSSION

Wood-based composites can be designed and fabricated to obtain specific mechanical properties for particular uses. The results presented in this article try to prove that ultrasonic techniques can be developed to permit the nondestructive determination of elastic properties and the detection of material inhomogeneities or flaws. The unique aspects related to the implementation of ultrasonic testing of flakeboards are analyzed in terms of the solution of an inverse acoustic problem. With ultrasonic measurements, one seeks to recover from signals the characteristics of the material. For this reason, measurements of ultrasonic velocities are shown in Tables 1 and 2. It should be noted that the highest velocity was measured in the direction of flake alignment, and on the other hand, the lowest velocity was that of shear waves, observed in the transverse plane.

The off-diagonal stiffness constants were deduced from experimental measurements on specimens at 45° to the principal planes (Table 3).

Knowing the full stiffness matrix, it is possible to calculate the velocity surface, or its reciprocal, the slowness curve, and thus to predict the velocity for all directions in the board. In Fig. 3 the velocity surface is given for specimens having a density of 611 kg/m³.

Technical constants are tabulated in Table 4. Young's modulus E_1 deduced from the ultrasonic test is 14% higher than that measured in the static bending test. From ultrasonic tests, we obtained the value of E_2 that is 20% lower then that of E_1 and a very low value of E_3.

As expected we can deduce the Poisson's ratios from ultrasonic tests (Table 5). Sliker (1989) presented Poisson's ratio measurements for solid wood and related these to corresponding compliances deduced from static tests.

Unfortunately, the literature on flakeboards is very scarce in data related to Poisson's ratios, and it is impossible for us to compare our values with those of other publications. To ascertain the validity of the calculated Poisson's ratios, it is therefore natural to consider

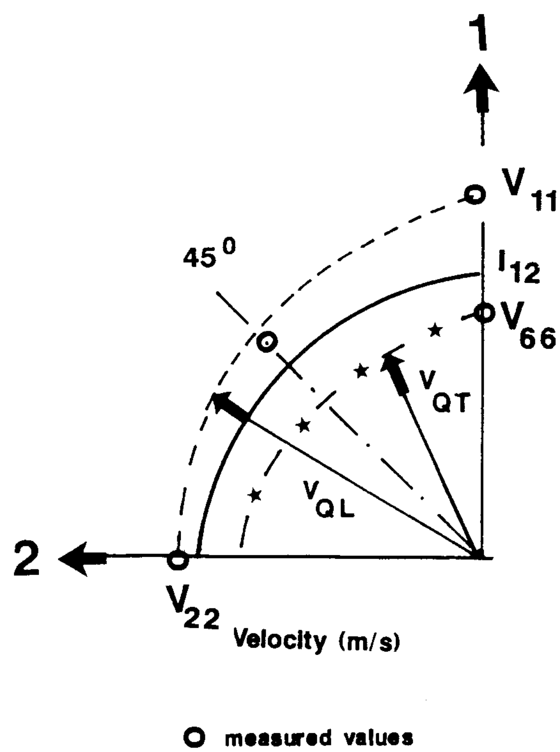

FIG. 3. Velocity surface in the 1,2 plane.

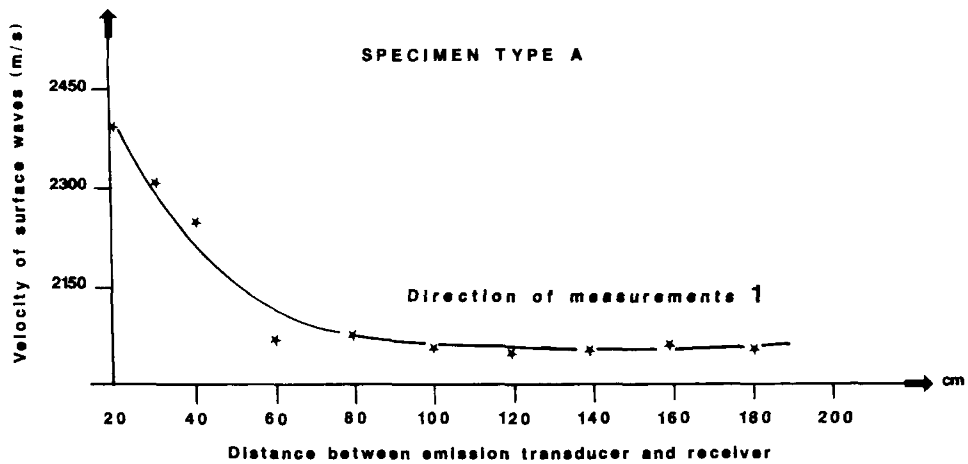

FIG. 4. Variation of surface velocity versus measurement distance.

the conditions imposed on the terms of the stiffness matrix, namely [Cij] > 0. From this condition several restrictions imposed on Poisson's ratios can be deduced as:

$$(1 - \nu_{12}\nu_{21}) > 0$$
$$(1 - \nu_{13}\nu_{31}) > 0$$
$$(1 - \nu_{23}\nu_{32}) > 0 \qquad (17)$$

and the

$$(1 - \nu_{12}\nu_{21} - \nu_{13}\nu_{31} - \nu_{23}\nu_{32} - 2\nu_{21}\nu_{32}\nu_{31}) > 0 \qquad (18)$$

For all our coefficients, these conditions are satisfied, and we can conclude that the coefficients are valid and useful for computer programs related to the analyses of stresses in various structural elements in which the flakeboards of the type tested are used.

The anisotropy of specimens can be expressed by the ratio of density of type A or type B specimens, by the ratio of bulk velocities as for example V_{11}/V_{22}, V_{11}/V_{44}, etc., by the ratio of surface velocities, by the ratio of Young's moduli, or by the ratio of acoustic invarants as given in Table 1.

The second technique used for nondestructive evaluation of the analyzed board was the measurement of propagation velocity of surface waves.

The value of surface velocity depends on the distance of measurement as can be seen in Fig. 4. Surface velocity measured on boards is probably more related to the properties of the skin than to overall properties of the flakeboard. The small difference between this velocity and V_{11} could be considered as a proof of the homogeneity of the board.

The third technique used was acoustic emission. Factors affecting the detectability of acoustic events on flakeboards are: wood species, flake orientation, resin content, moisture content, temperature, and presence of internal defects. We analyze only the influence of flake orientation on acoustic emission parameters.

The results of the acoustic emission technique are shown in Table 6 and Fig. 5. On

TABLE 4. *Young's moduli (10^8 N/m²) from ultrasonic and static tests.*

Ultrasonic test			Static bending test	
E_1	E_2	E_3	E_1	σ_r[1]
29.3	23.2	2.2	25.5	14.3

[1] Modulus of rupture, σ_r, in 10^6 N/m².

TABLE 5. *Poisson's ratios deduced from ultrasonic measurements.*

ν_{12}	ν_{21}	ν_{13}	ν_{31}	ν_{23}	ν_{32}
0.086	0.068	1.52	0.12	0.22	0.02

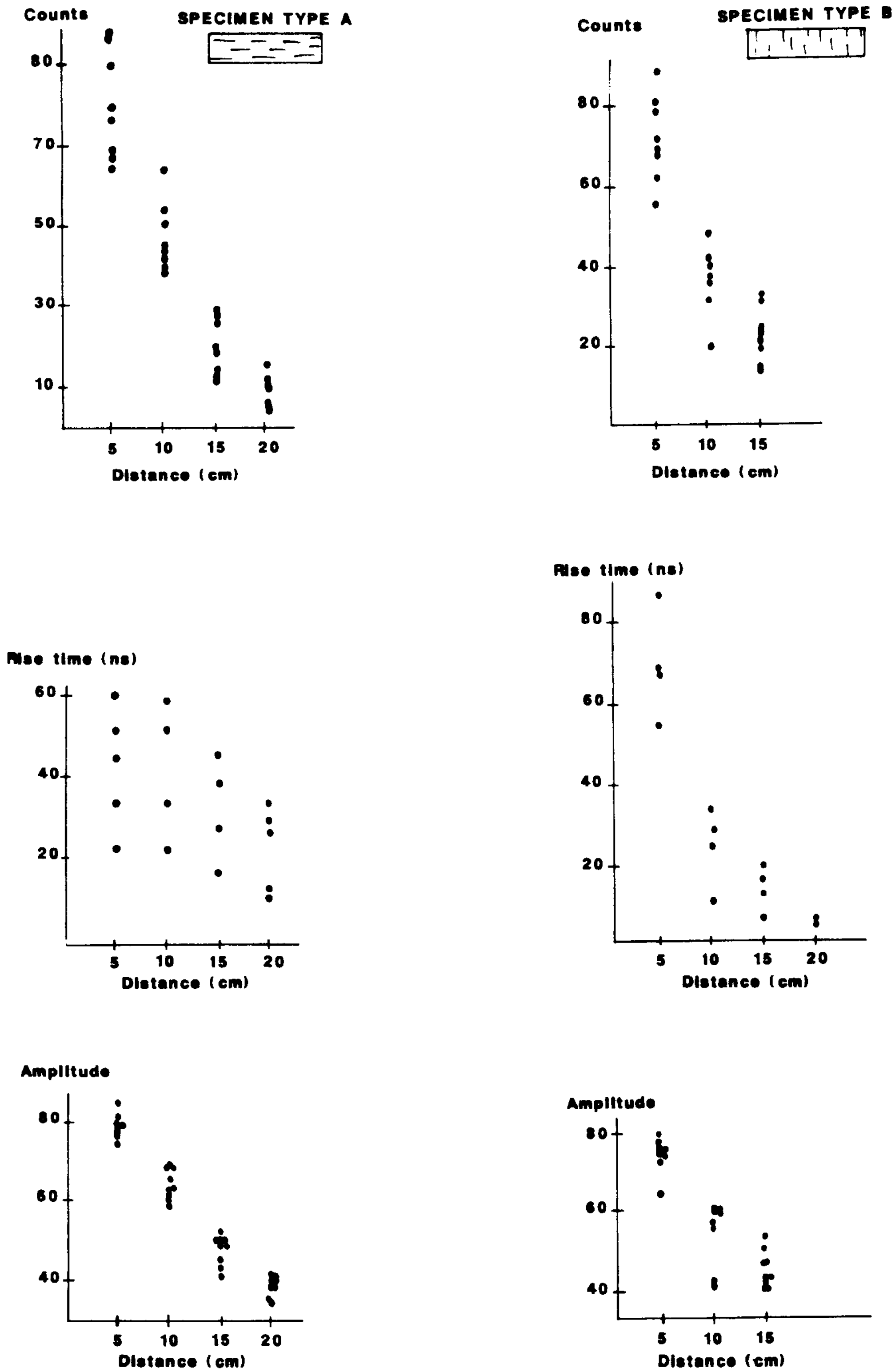

FIG. 5. Acoustic emission parameters measured on Type A and Type B specimens.

TABLE 6. *Acoustic emission parameters measured on specimens parallel (Type A) and perpendicular (Type B) to the direction of flake alignment.*

Source position	Duration μs	Counts No.	Energy	Amplitude mV	Rise time μs
	Specimen Type A, 607 kg/m³				
Emission	1,809	222	363	99	32
5 cm	555	69	67	74	33
10 cm	324	42	2	63	34
15 cm	143	15	0	45	29
20 cm	29	5	0	35	29
	Specimen Type B, 654 kg/m³				
Emission	1,599	211	299	97	15
5 cm	442	56	49	73	67
10 cm	220	31	0	60	10
15 cm	166	21	0	40	25
20 cm	undetected signal				

specimens with parallel flake alignment (Type A), the acoustic emission parameters (duration, count number, energy, amplitude and rise time) are slightly greater than on specimens cut perpendicular to the flake alignment (Type B). The effects caused by variations in structural properties of specimen Types A and B are more evident in the rise time measured at 5 cm from the source. For other parameters, the differences are less pronounced, probably because of less precise signal processing on specimens exhibiting relatively low variability.

TABLE 7. *Correlation coefficients between ultrasonic and static parameters.*

Parameters X	Parameters Y	Correlation coefficient[1] (r)
σ_r	V_{11} (bulk waves)	0.555***
$V_{surface\ 11}$	E_1 static	0.476*
$V_{surface\ 11}$	σ_r	0.465*
$V_{surface\ 11}$	Amplitude	0.483*
$V_{surface\ 11}$	Density	−0.570***
Density	E_1 static	−0.772***
Density	C_{55}	0.578**

[1] * and *** indicate the level of significance of r as 5 and 0.1%, respectively.

Having in mind that nondestructive testing may assist production line monitoring and complement the existing static control testing, several experimental correlations were established (Table 7). Longitudinal velocity V_{11} is correlated with the modulus of rupture. Interlaminar shear stiffness C_{55} is correlated with density. Surface velocity is correlated with Young's modulus and strength. It should be noted that all the reported data are obtained from one flakeboard. Probably, with more specimens produced from more boards, exhibiting more variability, it might be expected that the correlation coefficients could be im-

TABLE 8. *Manufacturing characteristics of flakeboards (19 mm) and acoustic parameters.*

Characteristics	Ratio of symbols		Values minim	Values maxim
Flake alignment	ultrasonic parameters		minim	maxim
	—longitudinal velocities	V_{11}/V_{22}	1.11	1.13
	—surface velocities	(dir. 1)/(dir. 2)	1.03	1.10
	—acoustic invariants	I_{12}/I_{13}	1.32	1.46
Skin damage (axis 1/axis 2)	acoustic emission at 5 cm			
	—rise time		1.07	1.10
	—peak amplitude		1.04	1.08
	—duration		1.18	0.80
	—count		0.15	0.11
	—energy		1.72	1.68
Interlaminar heterogeneity	shear velocity			
	—in planes 12 and 13	V_{66}/V_{55}	1.86	1.91
	—in planes 12 and 23	V_{66}/V_{44}	1.87	1.99
Global board anisotropy	acoustic invariants	I-ratio	0.72	0.82

proved for the benefit of the predicting power of nondestructive testing for quality assessment.

Recently Geimer (1986) suggested the measurement of flake alignment as a ratio of parallel and perpendicular velocities and noted that the "modulus of rupture does not respond to alignment in the same manner as Young's modulus." Velocity ratios as opposed to static parameters "measure alignment independent of the predicted physical properties of the board."

In Table 8 we complete this idea with other ultrasonic parameters (the ratio of surface velocity, the ratio of acoustic invariants in the 1,2, and 1,3 planes), and with parameters of acoustic emission more related to the alignment of flakes in the skin. The internal bond and the shear behavior of layers related to the thickness interlaminar heterogeneity could be tied to the ratio of measured shear velocities V_{66}/V_{55} or V_{66}/V_{44}, or to the acoustic invariants. The global board anisotropy could also be expressed by the ratio of acoustic invariants in the three planes. The higher this parameter is the more homogeneous is the board.

CONCLUSIONS

There are two main advantages of the proposed ultrasonic techniques (velocity method and acoustic emission), namely the real time nature of the testing methods and the possibility of continuous monitoring of large size specimens. The development of an acoustic stimulation technique as a synthesis of ultrasonic and acoustic emission methods could be imagined for the benefit of the predicting power of nondestructive, in line testing for quality assessment of flakeboard production.

As was stated for thick composites (Sachse 1991), the development of ultrasonic techniques for the control of wood-based boards needs to improve the signal processing and to develop new sensors, to provide procedures for "in situ" characterization, for monitoring the evolution of material anisotropy induced by its macrostructure and microstructure, and for damage and defect detections.

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