

INFLUENCE OF VERTICAL DENSITY DISTRIBUTION ON BENDING MODULUS OF ELASTICITY OF WOOD COMPOSITE PANELS: A THEORETICAL CONSIDERATION

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ABSTRACT

Vertical density distribution (VDD) has long been recognized as an important structural characteristic of wood composite panels. However, only a qualitative understanding of its influence on board properties has been achieved. This paper reports a theoretical consideration of the influence of VDD on bending modulus of elasticity (MOE) of composites. The consideration was based on the construction of VDD with a trigonometric function, linear layer MOE—layer density relationship, and laminate theory. Theoretical consideration shows that MOE benefits from the high density surface layer and increases linearly with the increase of peak density, but maximum MOE does not occur when peak density is right at the board surface.

Keywords: Density, laminate theory, modulus of elasticity, wood composite panels, vertical density distribution.

INTRODUCTION

The formation mechanism of VDD and its influence on board properties of composite panels have been extensively documented. However, most of the early studies relied on a qualitative, subjective approach, i.e., the general shape of VDD was used to interpret and attribute the influence of pressing parameters on VDD and the influence of VDD on board properties.

Recently, the author developed a fitting technique to quantitatively characterize VDD with a mathematical equation (Xu and Winistorfer 1996). The technique is based on the Fourier analysis, and the mathematical equation is in trigonometric form. The author also developed a model to predict the development of MOE of wood composite panels with a uniform VDD (Xu and Suchsland 1998). Wood species, compaction ratio (or density), and orientation level are the model inputs.

This paper combines the two techniques (Xu and Suchsland 1998; Xu and Winistorfer 1996) to consider theoretically and quantitatively

the influence of VDD on bending MOE of composite panels. Specifically, the distance of the peak density from board surface and magnitude of the peak density are used as the two principal parameters of VDD. Theoretical consideration is also compared with the general understanding about the influence of VDD on MOE drawn from the literature.

VERTICAL DENSITY DISTRIBUTION

Normal pressing operation results in a symmetric, high density face—low density core sinusoidal distribution of density in composites. Vertical density distribution can now be accurately, quickly, and nondestructively determined by X-ray technology. Xu and Winistorfer (1996) showed that by taking the Fourier transformation first of the measured discrete VDD data, and then taking the inverse Fourier analysis of the transformed data (A_k and θ_k), a trigonometric equation can be generated to fit VDD in the following form

$$\text{DEN} = A_0 + \sum_{k=1}^{k=N-1} A_k \cos[2k\pi x/T - \theta_k] \quad (1)$$

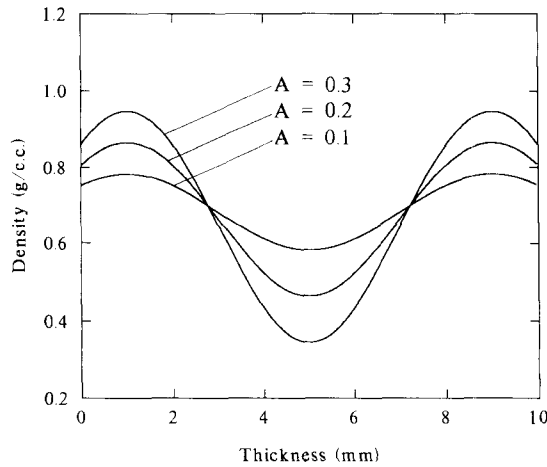


FIG. 1. Response of VDD to the change of parameter A (g/cm^3). θ : 0.785 (radian), average board density: 0.7 g/cm^3 , board thickness: 10 mm.

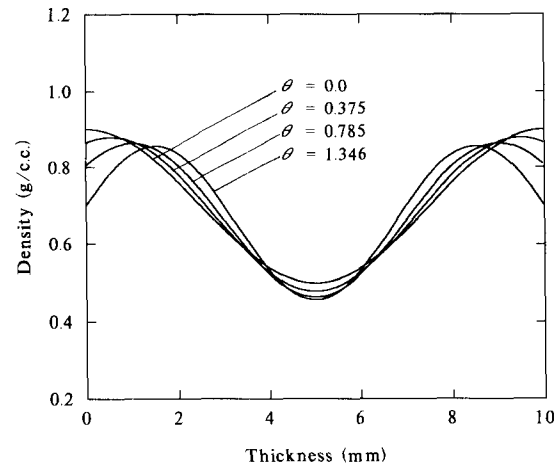


FIG. 2. Response of VDD to the change of parameter θ (radian). A : 0.2 (g/cm^3), average board density: 0.7 g/cm^3 , board thickness: 10 mm.

in which, DEN stands for point density variable (g/cm^3), T is the board thickness (mm), x is the thickness variable (mm), N is the number of density points used to describe VDD, A_k and θ_k are the k th magnitude and phase angle of the Fourier transformation of VDD.

Usually, the first few terms in Eq. (1) depict the general trend of the VDD, and the rest describes the localized variation; only the first two or three terms are needed to obtain a good fit to a specific VDD (Xu and Winistorfer 1996). This paper takes the concept of Eq. (1) and uses the following two term equation to construct various shapes of VDD

$$\text{DEN} = A_0 + A \cos[2(\pi + \theta)x/T - \theta]. \quad (2)$$

Integration of Eq. (2) yields the average density (ρ)

$$\begin{aligned} \rho &= A_0 + \left\{ A \int_0^T \cos[2(\pi + \theta)x/T - \theta] \right\} / T \\ &= A_0 + A \sin(\theta)/(\pi + \theta). \end{aligned} \quad (3)$$

From Eq. (3), we have

$$A_0 = \rho - A \sin(\theta)/(\pi + \theta). \quad (4)$$

Inserting Eq. (4) into Eq. (2), the following is obtained

$$\begin{aligned} \text{DEN} &= \rho - A \sin(\theta)/(\pi + \theta) \\ &\quad + A \cos[2(\pi + \theta)x/T - \theta]. \end{aligned} \quad (5)$$

Various shapes of VDD can be constructed using Eq. (5) by changing parameters A (unit: g/cm^3) and θ (unit: radian); moreover, the same average density (ρ) will be observed regardless of the combinations of A and θ by using Eq. (5). Figure 1 shows a few VDDs by changing parameter A while θ was kept constant at 0.785 (radian), and Fig. 2 shows the VDDs by changing θ while A was kept constant at 0.2 (g/cm^3). In both cases, an average board density of 0.7 g/cm^3 and board thickness of 10 mm were used.

Location and magnitude of the peak density

The first two terms in Eq. (5) are constants for a given VDD. Point density in a VDD reaches its maximum when the third term in Eq. (5) is maximized. The distance (X_m) of this peak density from board surface is obtained from Eq. (5) by letting

$$\cos[2(\pi + \theta)x/T - \theta] = 1. \quad (6)$$

Solving Eq. (6), we have

$$X_m = \theta T/[2(\pi + \theta)] \quad (7)$$

or relative distance (RX_m) of peak density to board thickness

$$RX_m = \theta/[2(\pi + \theta)]. \quad (8)$$

The peak density (ρ_m) is given by replacing x with X_m in Eq. (5)

$$\rho_m = \rho + A[1 - \sin(\theta)/(\pi + \theta)] \quad (9)$$

or relative peak density ($R\rho_m$) to average density

$$R\rho_m = 1 + A[1 - \sin(\theta)/(\pi + \theta)]/\rho. \quad (10)$$

The distance (X_m) or RX_m and the peak density (ρ_m) or ($R\rho_m$) are the two principal parameters in this paper to examine the influence of VDD on MOE.

MODULUS OF ELASTICITY

A model was developed to predict MOE of composite panels with a uniform VDD (Xu and Suchsland 1998). For a given wood species and orientation level, MOE_{den} (MPa) is only a function of board density (DEN) and is given by

$$MOE_{den} = a + b \cdot DEN \quad (11)$$

where a and b are specific to wood species and orientation level.

For a composite panel with nonuniform VDD, bending MOE can be calculated using the laminate theory (Bodig and Jayne 1982) and is given by

$$MOE = \int_0^{T/2} \frac{6}{T^3} (T - 2x)^2 MOE_{den} dx. \quad (12)$$

Inserting Eqs. (5) and (11) into Eq. (12), we have

$$\begin{aligned} MOE &= \int_0^{T/2} \frac{6}{T^3} (T - 2x)^2 \\ &\quad \times \{a + b[\rho - A \sin(\theta)/(\pi + \theta)] \\ &\quad + bA \cos[2(\pi + \theta)x/T - \theta]\} dx \\ &= \int_0^{T/2} F_{MOE} dx \end{aligned} \quad (13)$$

in which

$$\begin{aligned} F_{MOE} &= 6 \cdot (T - 2x)^2 \\ &\quad \times \{a + b[\rho - A \sin(\theta)/(\pi + \theta)] \\ &\quad + bA \cos[2(\pi + \theta)x/T - \theta]\}/T^3 \end{aligned} \quad (14)$$

and is defined as the MOE function in this paper. Overall MOE is simply the area under the MOE function curve over half of the board thickness (VDD was assumed symmetric in this paper). Therefore, the MOE function shows how much contribution individual layers across the board thickness provide to the overall MOE.

Integration of Eq. (13) yields

$$\begin{aligned} MOE &= a + b\rho + 2bA \sin(\theta)/(\pi + \theta) \\ &\quad + 6bA[\cos(\theta) - \sin(\theta)/(\pi + \theta)] \\ &\quad \div (\pi + \theta)^2. \end{aligned} \quad (15)$$

Eq. (15) shows that for a given wood species, orientation, and board density, bending MOE is influenced by VDD through parameters A and θ , which are related to X_m (or RX_m) and ρ_m (or $R\rho_m$) by Eqs. (7)–(10).

RESULTS AND DISCUSSION

Trembling aspen (*Populus tremuloides*) and northern red oak (*Quercus rubra*) were selected as the two species to consider the influence of VDD on MOE. For uniform density and random in-plane orientation of particles, layer MOEs at 7% moisture content for these two species are given by Eqs. (16) and (17), respectively,

for aspen board,

$$MOE_{den} = -20.5 + 6,055 \cdot DEN \quad (16)$$

for oak board,

$$MOE_{den} = -6.6 + 5,570 \cdot DEN. \quad (17)$$

Equation (16) is the regression result of simulated data of aspen board from a previous investigation (Xu and Suchsland 1998); Eq. (17) was obtained in similar fashion for oak board for this study. The constants in Eqs. (16)

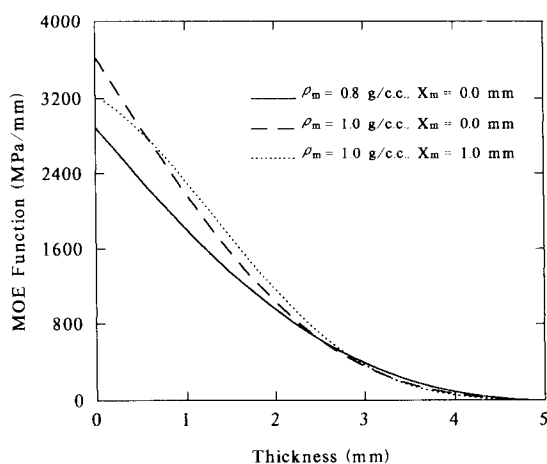


FIG. 3. MOE function as influenced by VDD. Species: aspen; board density: 0.7 g/cm³, board thickness: 10 mm.

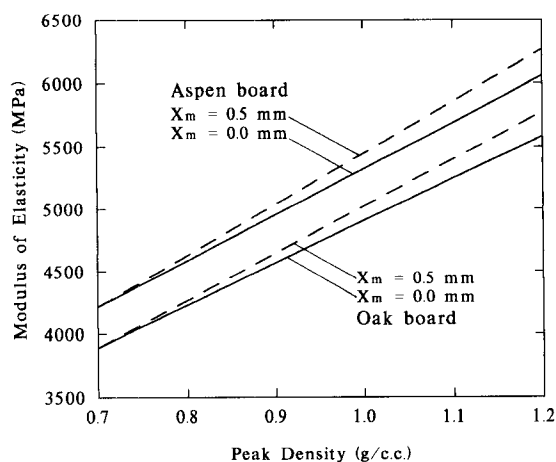


FIG. 4. Influence of peak density (ρ_m) on MOE at two locations of peak density. Average board density: 0.7 g/cm³, board thickness: 10 mm.

and (17) are the necessary inputs of parameters a and b in Eqs. (14) and (15).

Figure 3 shows the MOE function at three VDD scenarios; overall MOE is the area under the MOE function for each scenario, i.e., the integration of the MOE function over half of the board thickness (Eq. (13)). This relationship was based on aspen board with an average board density of 0.7 g/cm³ and thickness of 10 mm. As indicated earlier, MOE function shows the contribution of individual layers (zones) on overall MOE, two conclusions can then be drawn from Fig. 3:

1). The inner portion of a board (approximately $2 < x < 8$ mm in 10 mm board, in this paper) contributes very little to overall MOE, and MOE function in this region or zone is insensitive to VDD;

2). The outer portion (the outer 2-mm layer in 10-mm board in this paper) controls MOE of a board, and MOE function in this region is sensitive to VDD. It is the difference of MOE function in this outer portion of the board that explains the influence of VDD on MOE.

These two points, of course, have been known qualitatively to some extent in the composite community.

Since VDD in this paper is characterized by ρ_m and X_m , these two parameters are further

used to examine the influence of VDD on MOE. Figure 4 shows the influence of peak density ρ_m on bending MOE of the two species at two X_m values: 0 and 0.5 mm. This analysis was also based on an average board density of 0.7 g/cm³ and board thickness of 10 mm. MOE increases as peak density increases, a relationship which has been long recognized in the composite board industry (Kelly 1977). Specifically, the linear relationship between MOE and ρ_m agrees well with the finding by Suchsland and Woodson (1976), who reported a linear relationship between MOE and face density of fiberboard in an experimental study.

Figure 5 shows the influence of the distance of peak density (X_m) from board surface on MOE for both species at two peak density levels: 0.8 (g/cm³) and 1.0 (g/cm³). MOE increases slowly as the location of peak density shifts away from the board surface and then decreases after this shift exceeded approximately 1.4 mm. It has been generally assumed that MOE increases when peak density moves toward the board surface, and board manufacturing processes (fast closing speed of press and precision sanding) have been designed to achieve that effect. This study shows, however, that the peak density does not necessarily need to be right on the board surface to maximize MOE.

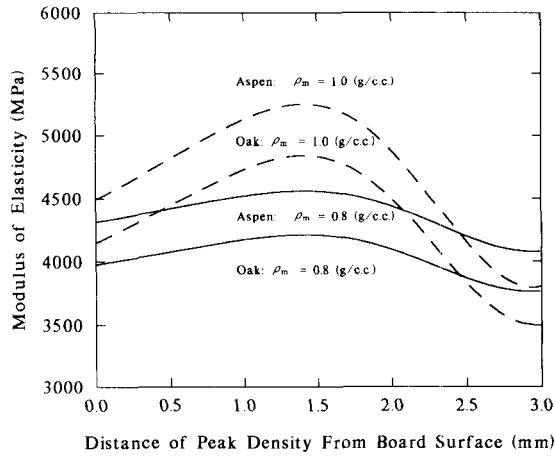


FIG. 5. Influence of distance of peak density (X_m) from board surface on MOE at two peak density values (ρ_m). Average board density: 0.7 g/cm^3 , board thickness: 10 mm.

The fact that maximum MOE occurs at $X_m \neq 0$ can be explained by Fig. 3 that it is the high density surface layer or zone (the top 2-mm thickness layer in a 10-mm board, in this study) controls MOE. When X_m is small, the overall MOE function of the surface layer (zone) increases (Fig. 3) as X_m increases. At larger X_m ($>1.4 \text{ mm}$ in this case), average MOE function of the surface region starts to decrease, which reduces MOE as X_m further increases.

Figure 6 shows in a three-dimensional fashion the influence of RX_m and $R\rho_m$ on MOE of the aspen board. This figure can be viewed as a composite of Figs. 4 and 5 showing that a linear relationship exists between MOE and $R\rho_m$ for all RX_m , and maximum MOE occurs at approximately $RX_m = 0.14$ (or $X_m = 1.4 \text{ mm}$ for 10-mm thickness board). This analysis

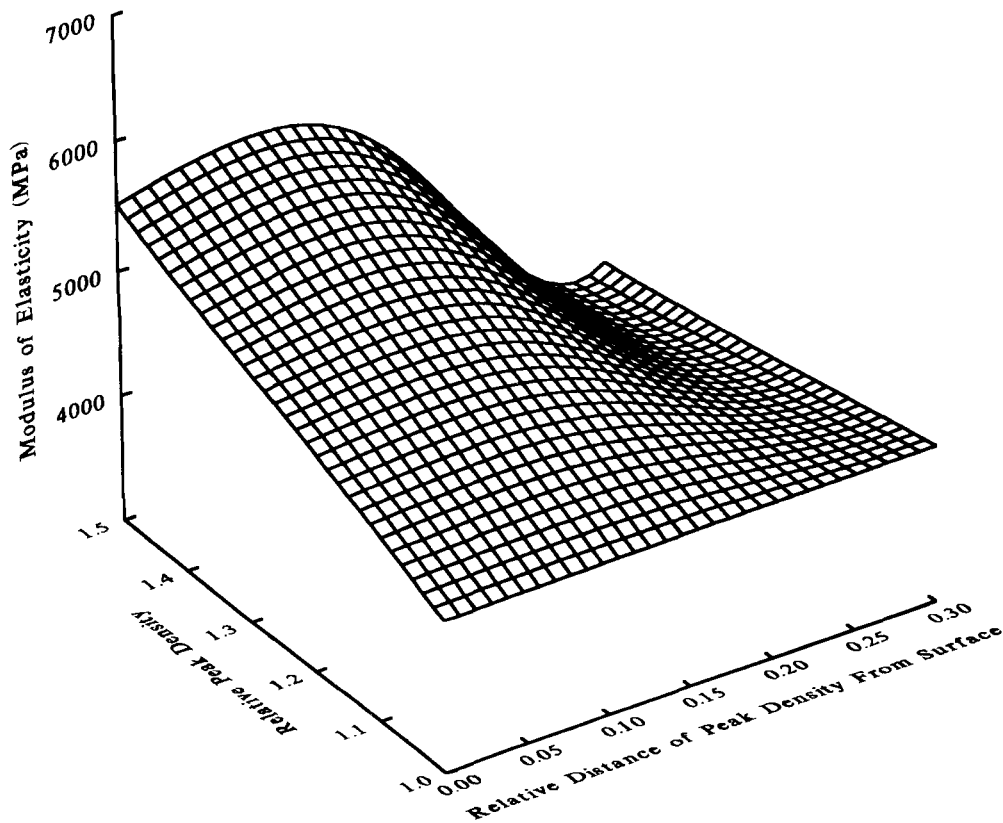


FIG. 6. Influence of RX_m and $R\rho_m$ on MOE of the aspen board. Average board density: 0.7 g/cm^3 .

was also based on average board density of 0.7 g/cm^3 but independent of board thickness. This figure also shows that the influence of RX_m on MOE is dependent on $R\rho_m$ and increases as relative peak density increases. This relationship suggests that if high peak density is sought for improving MOE, the location of the peak density becomes more important and should be controlled more accurately to capitalize the effect of high peak density.

This theoretical study assumed random in-plane orientation of particles and same furnish (particles) across the board thickness; out-of-plane orientation due to particle size was also ignored (the author believes that the effect of particle size on MOE is from the out-of-plane orientation phenomenon; Xu and Suchsland 1998). Oriented strandboard deviates from this simplified structure in that different orientation levels and orientation directions are used for the face and core flakes; three-layer particleboard also deviates from this structure in that different wood species and particle sizes can be used for the face and core layers. Our next paper will report the influence of orientation level, face/core ratio, and use of different wood species in a three-layer board on MOE.

CONCLUSIONS

It is well known that high density face—low density core benefits MOE. The theoretical analysis agrees in general with this qualitative understanding on this long researched subject. Although the approach is theoretical, the results and interpretation of this study are practical and applied. The analysis shows that a linear relationship exists between MOE and peak density, but maximum MOE occurs when the peak density is at some distance (ap-

proximately 14% of the board thickness in this paper) from board surface. The theoretical technique and results should be useful as a training tool to quality control personnel in board manufacturing processes to demonstrate the significance of VDD on MOE and the importance of proper selection and control of VDD.

This theoretical consideration adds a component of theoretical understanding to the influence of VDD on MOE.

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EFFECT OF PLANING ON PHYSICAL AND MECHANICAL PROPERTIES OF SUGAR MAPLE WOOD

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ABSTRACT

Matched specimens of sugar maple wood were prepared using two types of planing machines, a conventional planer, and a fixed-knife pressure-bar planer. The equilibrium moisture content (EMC), swelling in all principal directions, and the compliance coefficient in radial compression were measured after adsorption and desorption experiments. Two specimen sizes were used for these experiments. The results showed that conventional planing affected the superficial layer, and a significant negative effect on the EMC and swelling behavior of sugar maple after a cycle of moisture adsorption-desorption existed. No differences were found between planing methods for the radial compliance coefficient. These findings are in agreement with earlier results showing a negative effect of conventional planers on the superficial layer of wood. We confirmed that less affected properties could be obtained using the fixed-knife pressure-bar method. Finally, the EMC and the radial compliance coefficient, but not the swelling, were slightly affected by the specimen size.

Keywords: Wood planing, moisture sorption, adsorption, desorption, mechanical properties, compliance coefficient, swelling, sugar maple.

INTRODUCTION AND BACKGROUND

During wood machining, surfaces are usually prepared with a conventional knife planer, which works with a peripheral cutting action. This machine and circular saws currently used appear to produce a good quality surface, without noticeable defects.

Although the conventional planing technique appears to give good quality surfaces, some previous studies indicate that this assumption is not always true. Stewart (1989) observed crushed and damaged cells at the surface and subsurface of the wood machined by this technique. The severity of damage depends on specific machining conditions. River and Miniutti (1975) noted that previous machining could cause a decrease in the shear

strength of glued joints in wood. These researchers tested wood surfaces machined by a circular saw, a conventional planer, and a jointer. Although there were differences between species, the glue joint performance generally decreased from jointed surfaces to planed surfaces and with the poorest performance for sawn surfaces.

Other workers have shown that abrasive-planed surfaces perform more poorly than knife-planed surfaces when glue joint shear strength is tested (Jokerst and Stewart 1976; Caster et al. 1985). These researchers pointed out that the perpendicular-to-surface component of cutting forces is greater during abrasive planing than during conventional planing. This vertical force exceeds the stress at the

proportional limit, which causes permanent crushing of cells at or near the surface of the wood. The abrasive particles generally have negative rake angles, causing normal forces to become greater (Stewart 1971).

Microscopic surface analysis has shown that crushed or damaged cells occur more frequently in abrasive-planed material than in knife-planed material (Jokerst and Stewart 1976; Stewart and Crist 1982). However, an accelerated aging exposure test was required, in order to detect differences in gluing strength and delamination between abrasive-planed and knife-planed surfaces (Jokerst and Stewart 1976; Caster et al. 1985). Detailed microscopic analysis has also shown damaged cells on the surface of knife-planed wood. Murmanis et al. (1983) indicated that after one cycle of soak-dry exposure, knife-planed Douglas-fir specimens had some microruptures between the S_1 and S_2 cell-wall layers as well as within the S_2 layer. These microruptures could explain the decrease in glue-line shear strength after the aging exposure treatment previously mentioned.

Stewart (1986, 1989) proposed the fixed-knife pressure-bar system, as an alternative planing method, to reduce or eliminate sub-surface damage induced in wood. The method works in a manner similar to a veneer cutter, using a high rake angle, but applied to planed surfaces. In addition, the wood feed is nearly along the grain rather than perpendicular to the grain. Micrographs from these studies show that the fixed-knife pressure-bar planed wood surfaces remained virtually intact. Recently, we have demonstrated that this new method produces wood surfaces with improved gluing behavior compared to conventional planing (Hernández 1994).

Apart from the effect of machining on gluing behavior of wood, little information is available on the effect of this process on other wood properties. Some earlier data from the literature might be reconsidered in light of the above findings. For example, many basic studies use small dimension (about 1-mm-thick) wood specimens to reduce experimental time or to facilitate matching techniques. Such experiments have

been conducted with material already possibly affected by wood machining itself.

The purpose of this investigation was to compare the effect of two surfacing methods on wood properties of sugar maple. The conventional knife planing method and the fixed-knife pressure-bar planing method were applied to two sizes of specimens. The properties evaluated and reported here are: swelling in all principal directions, compliance coefficient in radial compression, and equilibrium moisture content obtained during the first adsorption-second desorption cycle at 21°C. Normal cutting forces produced during peripheral planing act in the transverse direction of wood. Knowing that the tangential direction is the least resistant in wood, we expected that the effect of planing on the superficial layers formed in the radial-longitudinal plane of wood would be detected by the changes in radial compliance coefficient. A better knowledge of these effects may lead to better wood machining techniques, which have fewer negative effects on the quality of this material.

MATERIALS AND METHODS

Experiments were carried out with sugar maple (*Acer saccharum* Marsh) sapwood. Six logs with minimum visual defects were selected in the green state. Groups of boards matched tangentially were prepared from these logs; each group included four adjacent radial sawn boards with two different cross sections. The final cross section of the two middle boards used for preparing the small specimens was 15 (t) by 45 (r) mm. The final cross section of the two outside boards used for preparing the large specimens was 25 (t) by 75 (r) mm. These green boards were slowly dried to 14% MC, by dehumidification at room temperature. Final surfacing took place at this MC with two different methods.

Surfacing treatment

The final surfacing on the radial and tangential faces of the boards was done either by the rotating knife-planing method (peripheral