FUNDAMENTALS OF VERTICAL DENSITY PROFILE FORMATION IN WOOD COMPOSITES. PART II. METHODOLOGY OF VERTICAL DENSITY FORMATION UNDER DYNAMIC CONDITIONS

Sigun Wang

Post-Doctoral Research Associate

and

Paul M. Winistorfer[†]

Professor and Director The Tennessee Forest Products Center The University of Tennessee P.O. Box 1071 Knoxville, TN 37901-1071

(Received May 1999)

ABSTRACT

The vertical density profile or density distribution through the panel thickness has been identified as one of the important panel characteristics that correlates well with strength and physical properties of wood-based composite panels. We have studied the fundamentals of oriented strandboard (OSB) vertical density profile formation during hot-pressing. Experimental results are from the in-situ density measuring system installed on our laboratory hot-press. Results indicate that the vertical density profile of OSB is formed from a combination of actions that occur both during consolidation and also after the press has reached final position (i.e., thickness). We propose a methodology to describe the formation of the density profile into two periods and five stages. The consolidation period is the time of consolidation until the press reaches final position and contains two stages. The adjusting period is the time after the press has reached final position and continues until the culmination of the cycle. The adjusting period contains three stages. The resulting density profile is influenced by both periods and all five stages. The vertical density profile results from the combined effects of many process variables, but basically occurs from the effects of furnish moisture conditions, mat structure and the pressing environment. During pressing the mat is always in an unsteady state, and internal mat temperature, moisture content distribution, vapor pressure, layer density, and compaction stress are all related to the pressing operation. The unsteady state of the mat during the early stages of pressing may result in poor bonding strength development throughout the mat.

Keywords: Density profile, *in-situ* measurement, oriented strandboard, pressing, radiation, consolidation, moisture, bonding, resin, unsteady state, compression.

INTRODUCTION

The vertical density profile or density distribution through the panel thickness has long been identified as one of the important panel characteristics that correlates well with strength and physical properties of woodbased composite panels (Harless et al. 1987; Kelly 1977; Wang 1986, 1987; Winistorfer et al. 1996; Winistorfer and Wang 1999b). The resulting shape of the density profile after pressing is influenced by three major factors: furnish moisture condition, mat structure, and the pressing environment. There are many underlying material and processing factors that can impact the formation of, and changes in, the density profile.

To achieve a more fundamental understanding of material behavior during the pressing process, several researchers have investigated and described the effects of mat structure on the composite performance

[†] Member of SWST.

Wood and Fiber Science, 32(2), 2000, pp. 220–238 © 2000 by the Society of Wood Science and Technology

A prediction of the density profile formation through the use of computer simulation modeling is needed. Once the density profile is predicted, it can be used as an important parameter in predicting board properties. Harless et al. (1987) developed an early model to predict the density profile of particleboard. The model simulates the physical and mechanical processes that occur in the press and mat system. Heat conduction, gas transport, layer compaction, and water phase changes were included in the model. Modeling of the compaction process currently terminates when the press platen reaches the final thickness. Changes in the density profile that might occur after closure due to differential relaxation were ignored. Suo and Bowyer (1994) simulated modeling of the particleboard density profile. Particleboard was modeled as a system consisting of a number of thin and uniform layers whose densities were determined by taking into account the effects of temperature and moisture content during hot-pressing and calculating the strains of the layers. Both of these models were based on the general condition that the density profile is formed as a result of the interactions of dynamic conditions in the wood mat during the consolidation process before the press platen reaches the final thickness, i.e., once the platen reaches position, the density profile is essentially formed.

Our previous paper in this series discussed *in-situ* density measurement during pressing as affected by moisture movement (Winistorfer et al. 1999a). Experimental results are from the *in-situ* density measuring system installed on our laboratory hot-press. Clearly established in all of our laboratory pressing studies is the indication that the vertical density profile of wood composite panels is formed from a combination of actions that occur both dur-

ing consolidation and also after the press has reached final position; measurements recorded in our press show that mat densification continues after the press has reached final position. In this report, the fundamentals of OSB vertical density profile formation during hotpressing are discussed. A methodology to explain the fundamental formation of the density profile into two periods and five stages is developed.

MATERIALS AND METHODS

Mat preparation

Five 5-layer OSB mats, identified as mats A-E, and two single-layer OSB mats, identified as mats F and G, were incorporated in the study (Table 1). The furnish was from a pine OSB mill. Furnish was conditioned to 3.9, 6.0, and 7.0% moisture content. The target panel density was either 0.608 g/cm³ or 0.673 g/cm³, and target panel thickness was 20.6 mm for mats A-F and 12.7 mm for mat G. Mats measured 330 \times 457 mm. A commercial liquid phenol formaldehyde resin was applied to the furnish at a rate 3% or 3.5% per dry wood weight in a rotating blender. Wax was not used for mats A through F, but a 0.65% wax application was used for mat G. The prepress moisture content of the furnish ranged from 7.89-10.1%.

To measure temperatures in discrete layers of the mats, copper-constantan thermocouples were placed in the mat during the forming procedure (Fig. 1). Unavoidably, some thermocouples were located in the path of the horizontal *in-situ* radiation beams when the mat was placed in the press.

A special mat-forming technique was used that incorporates a collapsible forming box, in which the mat is formed between two pieces of OSB panel material. The mat is then trimmed to final desired size while it is held prepressed between the OSB panel material. This technique allows for trimming the loose edge of the mat prior to pressing and was developed specifically for use with our in-press radiation monitoring system that requires a

			WOOD AND
U	3.92	3.5 0.65 single-layer None 8.58	0.673 12.7 60 204
F	6	3 No single-layer None 7.98	0.608 20.6 200 Bottom 204,

Surface 7.98,

7.98

7.98

Cefton

i-layei

J-layer

-layer Otton 10.1

5-layer eflon 10.1

efton

5-layer **Teflon** core 16.1

0.608

0.608

0.608

20.6

0.608 20.6

0.608

Mat initial moisture content (%)

Preventing material

Mat structure

20.6 40

[arget panel thickness (mm) Farget panel density (g/cm³)

Pressing temperature (°C)

Closure rate (second)

Pressing cycle (second)

50

20.6

8

20.6

20

222

well-formed mat edge for enhanced in-situ radiation measurement accuracy.

Pressing and measuring conditions

Mats A-F were produced with a bottom platen temperature of 204°C, a top platen temperature of 220°C, a pressing cycle of 370 or 500 s, and press closure rate of 40, 50, 60, or 200 s. Mat G was produced with a platen temperature of 204°C and a 60-s press closure rate. Closure rate was defined as the time required to reach final position from the initial contact of the mat with the upper platen for the up-acting press. The three in-situ radiation beams for density measurements during pressing were positioned at 10, 50, and 90% of the mat thickness for mats A-F. For mat G, the insitu radiation beams were positioned at 18.7, 50, and 81.3% of mat thickness. The position of the moving platen is determined by a programmable logic control position-control system. The press control system, radiation monitoring system, and temperature acquisition electronics allow radiation count data, press position, and temperature to be recorded in real-time. The press hydraulic pressure for mat G was also recorded.

In-situ density profiles without moisture movement during hot-pressing

To investigate the effect of moisture movement during pressing on the measurement of in-situ density profiles, 0.076-mm-thick polytetrafluoethylene (Teflon[®]) film was used to prevent the moisture movement from the surface to the core of the mat. Whole mats were divided into 5 layers based on weight fractions of the furnish (Fig. 1). The five-layer weight fractions were 17.7, 24.5, 15.9, 24.6, and 17.7% (by weight) through the panel thickness. These five layer percentages were dictated by the fixed locations of the three radiation beams, i.e., we desired three of the five discrete layers of the furnish material to be matched to the position of the radiation beam. After completion of the pressing cycle, each mat was immediately disassembled into the

informe
facturing
l manu
Panei
TABLE

ш

Ω 9

C 9

ш

∢

Flake MC (%)

Mat

PF resin (%)

Wax (%)

Ó

317

top 225 500

top 224 500

3 ottom 204

Bottom 204. top 223 500

30ttom 204.

3ottom 204 top 221 370

30ttom 204.

top 220 370

40

top 222 500



Top Surface

- O Thermocouple wire not positioned in radioactive beam.
- Thermocouples located in the radioactive beam.

E denotes position of thermocouple wire near mat edge. C denotes position of thermocouple wire near mat center.

FIG. 1. Five-layer structure and locations of polytetrafluoethylene (Teflon⁽⁹⁾), cotton sheets and thermocouples in OSB mat.

original five discrete layers for moisture content (MC) determination.

RESULTS AND DISCUSSION

Measurement of layer moisture content of panel after pressing

To get MC data for a control or normal mat, thin cotton fabric was used to separate the five furnish layers during forming. The cotton fabric was not considered to be a barrier to moisture movement during pressing. Immediately after completion of the pressing cycle, thermocouple wires were severed at the edge of the board and the panel was weighed. The panel was then separated into the five layers by disassembly at the cotton interfaces, and the layer MC was measured.

In-situ density profiles during hot-pressing under moisture movement

The *in-situ* density profiles and temperature data for mat B with a 40-s closure rate treatment are shown in Fig. 2. During the first 40 s of the closing period, the densities of three layers increased quickly with nearly the same consolidation rates before the press reached final position. Immediately upon reaching final closure position, there was a marked change in mat density at the three monitoring locations. Most notable is that mat density continued to change after the press had reached final position. Both face-monitoring detectors re-



FIG. 2. *In-situ* density profile and internal temperatures during pressing, 40-s closure rate, 330-mm mat width, 10.1% mat MC, 5 layers separated with cotton sheets (Mat B).

flected increasing density by 18.7-20.4%, up to about 100-120 s in the cycle and then face densities gradually declined 3.07-3.52% during the remainder of the cycle. Because the thickness of the mat during pressing was precisely controlled by the position-control system, the average mat density was stable after the press had reached final position, if moisture escalation from the mat edges is ignored.

the pressing cycle and is shown in Table 2. While initial moisture content of the top layer was 10.1%, its moisture content at the end of the press cycle was only 1.12%. Moisture migration into the mat and moisture escape via the mat edges result in a large decrease in top layer density. However, the amount of change recorded in the top layer density based on the *in-situ* density measurement system was 14.56% (Table 3), which is much higher than

was measured immediately after completion of

Mat B was a 5-layer structure separated by cotton fabric. Moisture content of each layer

TABLE 2. Layer moisture content after pressing and density change due to steam escaping.

Mat		A	В	С	D	E
Layer moisture co	ntent (%):					
Top layer	1	0.88	1.12	0.56	0	3.21
	2	4.26	3.81	2.01	1.73	3.14
Core layer	3	6.1	8.71	2.76	2.87	8.47
	4	3.77	3.72	1.93	1.94	2.39
Bottom layer	5	0.84	1.35	0.29	0.26	0.89
Density decrease of	lue to steam a	escaping (%):				
Тор		-8.37	-8.16	-6.87	-7.39	-4.42
Core		-3.63	-1.26	-4.83	-4.73	-6.57
Bottom		-8.41	-7.95	-7.12	-7.15	-6.57

TABLE 3.	In-situ <i>density</i>	analysis at	layers a	luring	pressing.
----------	------------------------	-------------	----------	--------	-----------

	Top layer	Core layer	Bottom layer
Density at press closing point	0.703	0.710	0.710
Maximum density	0.849	0.724	0.889
Density before press opens	0.813	0.704	0.856
Density increase from closing to maximum point	20.77%	2.03%	25.23%
Density decrease from Max. point to opening	-4.25%	-2.83%	3.73%
Change from closing point to opening	15.63%	-0.86%	20.56%
Mat B			
Density at press closing point	0.658	0.712	0.692
Maximum density	0.782	0.747	0.834
Density before press opens	0.754	0.744	0.808
Density increase from closing to maximum point	18.74%	4.87%	20.43%
Density decrease from Max. point to opening	-3.52%	-0.40%	-3.07%
Change from closing point to opening	14.56%	4.45%	16.72%
Mat C			
Density at press closing point	0.823	0.772	0.954
Maximum density	0.900	0.751	0.967
Density before press opens	0.837	0.731	0.905
Density increase from closing to maximum point	9.40%	-2.74%	1.31%
Density decrease from Max, point to opening	-7.02%	-2.58%	-6.36%
Change from closing point to opening	1.72%	-5.25%	-5.13%
Mat D			
Density at press closing point	0.872	0.694	0.886
Maximum density	0.904	0.716	0.881
Density before press opens	0.878	0.710	0.833
Density increase from closing to maximum point	3.71%	3.15%	-0.64%
Density decrease from Max. point to opening	-2.94%	-0.91%	-5.42%
Change from closing point to opening	0.66%	2.21%	-6.03%
Mat E			
Density at press closing point	0.755	0.862	0.802
Maximum density	0.854	0.853	0.803
Density before press opens	0.824	0.831	0.777
Density increase from closing to maximum point	13.23%	-1.06%	0.11%
Density decrease from Max. point to opening	-3.56%	-2.54%	-3.21%
Change from closing point to opening	9.19%	-3.58%	-3.11%

moisture content change measured for layer #1 at the end of pressing. This confirms the transient mass throughout the mat after the press has reached target position. Compared to OSB pressing, results from MDF pressing showed more significant transient mass throughout the mat after the press has reached target position and maintained position (Wang et al. 1999b).

In Fig. 2 the core density showed an initial slight decrease during the period from 60 s to about 200 s, and then steadily rose until the culmination of the press cycle. Our previous work showed that at only about 30 s into the

press cycle, moisture in a 12-mm-thick medium density fiberboard (MDF) panel (i.e., not a consolidating mat, but a panel sample) was migrating into the core from the panel surface layers, as evidenced by the increasing density measurement in the panel core (Winistorfer et al. 1999a). We recognize that closing the press on a panel and monitoring moisture migration is different than monitoring moisture migration of a compacting mat, where the mat may more easily breath during the consolidation process; moisture migration will be greater in a compacting mat of loose particles than in an already-pressed panel. Moisture migration during the period from 60 s to about 200 s (Fig. 2) did not result in increasing density measurement in the core. The experimental results showed the opposite trend. Core layer density slightly decreased from 0.712 g/cm³ at press closing point to 0.709 g/cm³ at 140 s to 160 s. The only explanation of this phenomenon is that the surface layers more easily consolidate due to reduced temperature-induced compression stress, causing the core material to actually spring back due to higher compression stress exhibited in the core material. The temperature gradient in the mat also reflects greater densification of surface layer furnish. The largest temperature gradient of 75°C occurred between the bottom and core layers at 105 s, then steadily declined during the remainder of the cycle. Core density began to rise when coreline temperature reached 87.7°C, and the temperature difference between the bottom surface and core layers decreased to 38°C.

The density and temperature conditions of an unrealistically slow closure rate for mat F (single layer) are shown in Fig. 3. Note that the final press position was not reached until 200 s for this mat. During consolidation, the density of the mat was mostly uniform as each detector reflects a constant, increasing densification. However, due to the extreme slow closure rate, moisture was lost from the mat during consolidation. Moisture is known to aid temperature rise in the mat interior and also impacts compression characteristics of individual furnish elements. At final closure position at 200 s, maximum face density was achieved and then constantly diminished during the remainder of the cycle. As the face density diminished, the core density slightly increased almost an equal amount. Note that the press cycle length was doubled to account for the length of time consumed by the slow closure rate to ensure adequate resin cure. Notable in the slow closure rate condition is the difference between face and core densities of about 22% at the time of final closure condition. By contrast, the fast closure mat (mats A and B) showed a difference of only about 5% between face and core densities at the time of final closure position. The magnitude of change recorded by the *in-situ* system during the remainder of the cycle may provide important insight into the dynamic conditions within the composite mat during pressing. It should not be ignored that the density of the core layer did not increase until the layer temperature reached at least 100°C for either the 40- or 150-s closure rate treatments.

Preheating of the bottom face of the mat during mat loading into the press resulted in density and compaction rate differences between top and bottom surfaces, which generally results in an unbalanced density distribution through the mat (i.e., bottom layer density is greater than top layer density). Figure 3 shows that preheating results in a higher bottom laver temperature than top laver temperature during the beginning period of the press cycle and then the top layer temperature exceeded bottom layer temperature by 20°C during the remainder of the cycle. Although the bottom layer had a slightly greater density before the press reached final position, the highest layer density was found in the top layer at the end of the cycle, due to the unsymmetrical temperature gradient that developed in the mat.

Figure 4 shows in-situ density profiles, press position, and calculated stress for mat G. Pressing conditions for mat G were 60-s closure rate, 317-s pressing cycle, 4% furnish moisture content, 3.5% liquid phenolic resin, and 0.65% emulsion wax based on dry wood weight. As the press closed, the stress in the mat quickly increased to a maximum when the press reached final position. While the press was held at final position and heat continued to penetrate into the mat, the stress in the mat relaxed due to temperature-moisture induced effects on the wood furnish. Figure 4 shows that core layer density increased when the stress in the mat had decreased to 2.96 Mpa, approximately 60% of the peak stress value.

These results indicate that the vertical density profile of OSB is formed from a combi-



FIG. 3. In-situ density profile and internal temperatures during pressing, 200-s closure rate, 330-mm mat width, 7.98% mat MC, single layer (Mat F).



FIG. 4. *In-situ* density profiles and pressing pressure in the mat G, 60-s closure rate, 317-s pressing cycle, 4% furnish moisture content, 204°C top and bottom platen temperature.

nation of actions that occur both during consolidation of the mat and also after the mat is at final thickness.

In-situ density profiles during hot-pressing without moisture movement

We reported in our previous paper that moisture movement in the mat during hotpressing would significantly affect the precision of our in-situ density measurement (Winistorfer et al. 1999a). When the specimens of commercial MDF were repeatedly measured during cold and hot-pressing, there were significant in-situ density differences between the two conditions (hot and cold). The reason for the measurement discrepancy is not wood consolidation, but rather moisture migration from the surface to the core of the MDF during hotpressing. Theoretically, steam migration during hot-pressing has two paths: migration from the mat surface to the mat core and migration from the interior mat confines to the mat edges. As steam dissipates from the mat edges, the moisture content in the core at the end of the pressing cycle is higher than that in the core at the beginning of pressing. However, the moisture content in the surface layers at the end of the pressing cycle is always much lower than that at the initiation of pressing.

Table 2 lists the moisture content of the five mat layers immediately after pressing. Both mats A and B were 5-layer mats of uniform structure and material. Layers of mat A were separated by Teflon[®] film, and mat B layers were separated by cotton fabric. Moisture migration from the surface layers to the core was prohibited for mat A and permitted for mat B. After pressing, the moisture content of the core layer in mat B was higher than the core layer in mat A, as expected, due to moisture migration. However, the moisture content of the core layer in panel B was 1.3% less than the initial mat moisture content (10.1%) due to steam escaping from the mat edges. When the 500-s pressing cycle was used, the moisture content in the mat surface layers was nearly oven-dried, and the core layer moisture content was only 2.76–2.87% (panels C and D). In the case of mat E, core layer moisture content was 8.47%, which is about half the original moisture content of the blended flakes. The width of the mats used in this experiment was 330 mm, and it is reasonable that the steam more easily migrated the shorter distance to the mat edge, rather that the longer distance to the mat ends.

Figures 5 and 6 show the *in-situ* density profiles and internal temperatures of OSB mats that included Teflon[®] film to prevent the moisture migration from the surface to the core layers of the mat. The density of the core layer in mat D increased slightly when coreline temperature reached 100°C (Fig. 5). Table 2 shows that core layer moisture content was only 2.87% at the end of the pressing cycle, much lower than the original average mat moisture content of 7.98%. Although the moisture content decrease in the core layer resulted in decreased core layer density by 4.73%, in-situ density analysis shows the opposite result (Table 3). The core layer density increased a maximum of 3.15% from the initial closing point and then decreased 0.91% from the maximum density to the end of pressing cycle. The in-situ density system indicated a 2.21% density increase in the core layer while the press maintained final position. Considering a 4.73% density decrease due to steam release, increasing densification in the core layer was 6.94%. It can be concluded that the density increase of the core layer is due to actual wood consolidation. Both top and bottom layer density continued to decrease after 250 s as moisture escaped from those mat areas. Springback could contribute to the measured density decrease in surface layers.

In the case of the 40-s closure rate (Fig. 6), core layer density was stable after 100 s pressing time. Core layer moisture content decreased from 10.1% to 6.1% (Table 1). The moisture content decrease in the core layer offset wood consolidation in that layer, so that there was no measured density change of the core layer. This again confirms that wood con-



FIG. 5. In-situ density profile and internal temperatures during pressing, 200-s closure rate, 330-mm mat width, 7.98% mat MC, 5 layers separated with Tcflon[®] film (Mat D).



FIG. 6. *In-situ* density profile and internal temperatures during pressing, 40-s closure rate, 330-mm mat width, 10.1% mat MC, 5 layers separated with Teflon⁽⁵⁾ film (Mat A).



FIG. 7. In-situ density profile and internal temperatures during pressing, 50-s closure rate, 330-mm mat width, 7.98% surface layer MC, 16.1% core layer MC, 5 layers separated with Teflon⁵⁹ film (Mat E).

solidation was taking place after the press had reached final position.

The presence of a temperature gradient in the mat and greater densification of the surface layers mainly influenced the formation of the density gradient. High core moisture will increase wood plasticity or densification of the core layer. Mats C and E were pressed at the same conditions except the core furnish moisture content. Both mats were of 5-layer structure that included Teflon[®] film to prevent moisture migration from the surface layers to the core of the mat. The moisture content of all five layers in mat C was 7.98%. In mat E, the core layer moisture content was 16.1%; the remaining four layers were at 7.98% (2 surface layers and 2 intermediate layers). Figure 7 shows high core layer moisture influence on in-situ density profiles of mat E. The high core moisture content resulted in higher in-situ core density. Contrary to this, there was lower measured core density in mat C (Fig. 8). At the culmination of pressing, moisture contents of the core layer in mats C and E were 2.76% and 8.47%, respectively (Table 2). The measured densities of the layer at the end of pressing were 0.837 g/cm^3 for mat E and 0.733 g/cm³ for mat C, respectively. The oven-dry densities of both core layers were 0.766g/cm^3 for mat E and 0.713 g/cm^3 for mat C, respectively. This indicates that the oven-dry density of the core layer of mat E was 7.36% higher than mat C at the end of pressing. Moisture content distribution throughout the mat is a useful tool to manipulate the vertical density profile.

Compression behavior and in-situ density

All cellular materials exhibit similarities in mechanical behavior (Gibson and Ashby 1988), and their compressive stress and strain curves have the same characteristic shape. There are three different mechanisms of cell deformation. The linear elastic regime corresponds to cell-wall bending; the stress plateau to cellular collapse; and the final sharp increase in stress is due to densification of the cell wall after the majority of cell walls have collapsed. Cellular collapse occurs by either



FIG. 8. *In-situ* density profile and internal temperatures during pressing, 50-s closure rate, 330-mm mat width, 7.98% mat layer MC, 5 layers separated with Teflon[®] film (Mat C).

elastic buckling, plastic yielding, or brittle crushing, depending on test conditions and the nature of the cell-wall material (Lenth and Kamke 1996a, b).

A characteristic mechanical response for OSB mat G in compression and resulting insitu densities are shown in Fig. 9. Figure 9 does show a typical complete deformation through several stages, including nonlinear collapse and final densification. Dai and Steiner (1993) noted that wood mats do not exhibit so-called early stage linear stress-strain relationships. During the initial nonlinear collapse of the mat, there is no vertical density formation. The mat was uniformly compressed through the mat thickness as the mat compression stress was very low and there was no significant internal temperature gradient and moisture content gradient in the mat at the beginning period of hot-pressing. A yield point is exhibited at the onset of cellular collapse and the material continued to deform at nearly a constant stress level. Due to the temperature and moisture content profiles developed in the

mat during pressing, the mat layer exhibiting high temperature and moisture content deformed or was compressed more than the layer with low temperature and moisture content. Harless et al. (1987) determined the stressstrain relationship for southern pine particle mats at various temperatures. The results showed that increasing the temperature from ambient to 112°C resulted in a lower stress-tostrain ratio. Under the same stress, the strain at a higher pressing temperature was larger than strain at a lower temperature. Figure 11 shows that during nonlinear cellular collapse, there was a slight density difference among three layers, in which the bottom layer had the highest density and the core layer had the lowest density. During final cell-wall densification, stress rapidly increased as the collapsed cell walls consolidated. The density increase in a layer was mainly affected by temperature and moisture content distribution in the layer. The higher the temperature and/or moisture content of the layer, the larger the strain or deformation that accumulates in that laver. At



FIG. 9. Stress-strain and *in-situ* densities-strain relationships for mat G.

final closure position at 40 s, maximum density and minimum density were achieved in the bottom layer and the core layer, respectively. The maximum density was achieved in the bottom layer rather than the top layer because there was a difference of the stress-tostrain ratio between the bottom and top layer.



FIG. 10. *In-situ* densities-strain relationships for mat D under 200-s closure time.

When the press reaches target thickness, the compression stress on the mat has been or had been at a maximum, depending on the panel target density and press properties. The density profile is mainly formed at the final cellwall densification stage of the press closure period.

Figures 10 and 11 show the effect of press closure time on the in-situ density-strain relationships without moisture movement, which are nonlinear. During the 200-s closure period, the rate of density increase among the three layers was not constant, as the strain increased nonuniformly among the layers (Fig. 10). For the 50-s closure rate, the rate of densification continued to increase as strain increased, and then decreased at the end of the press closing period. At this point of about 93% total strain, a distinct elbow was noted in each of the *in-situ* density profiles (Fig. 11); the core layer stopped increasing in density. The top layer slightly increased and the largest density increase occurred in the bottom layer.



FIG. 11. *In-situ* densities-strain relationships for mat C under 50-s closure time.

Figure 8 shows that the temperature of the bottom layer was the highest among the three layers and consequently the stress-to-strain ratio of the bottom layer was the lowest.

Methodology to explain fundamental formation of density profile

The vertical density profile begins to be formed after the press pressure increases nearly to maximum pressure. Under the same compressed stress, the densification in a layer is dependent on the material plasticity, which is mainly affected by the temperature and moisture content of that layer. Densification of surface layers increases more rapidly than all other layers. To consider clearly the density change during pressing, the formation of the whole vertical density profile can be divided into 2 periods and 5 stages. The principal drawing of the vertical density profile formation is shown in Fig. 12. The fundamental density forming phenomena are described as follows:

Consolidation period.—The time of consolidation until the press reaches final position. The consolidation period contains 2 stages:

Stage I—A uniform consolidation period among all layers before the press reaches final position. During Stage I after the press begins to close and before the press reaches final position, the mat is continually compressed uniformly as the press is quickly closing. The consolidation mainly results from betweenflake void volume decrease. There is no presence of a vertical density gradient throughout the mat.

Stage II-A nonuniform consolidation period among all layers before the press reaches final position. As the press closes near to target thickness (T3), the beginning of nonuniform compression (consolidation) among layers in the mat is due to initial temperature and moisture changes in the mat surface lavers. There is no change evident in the core layers, but densification of surface layers is increasing more rapidly than all other layers. The dotted line directions in Fig. 12 reflect low to high compression rate. The outside surface layers do not have the highest compression rate due to quick moisture loss from both outside layers. At the end of stage II, the density gradient reflects the highest density is in the bottom layer and the lowest density is in the core layer.

Adjusting period—The time of the cycle after the press has reached final position and continues until the culmination of the cycle. The adjusting period is broken into three stages.

Stage III—A period of surface layer consolidation. During stage III, as there is a temperature gradient in the mat, flakes in the surface layers continue to incur microstructural deformation under maximum press pressure and higher temperature than core layer flakes. The press pressure diminishes as surface layer consolidation and stress relaxation occur. On the contrary, the core layer acts like a spring due to a higher stress-strain ratio in the cold core layer as the press pressure decreases from the maximum. As the temperature of the mat geometric center and the core is the lowest, there is a greater spring-like response there. Generally, the vertical density profile mainly develops from actions that occur in stages II and III (shown in Figs. 2 and 6). Under a very slow closure rate, the vertical density profile mainly develops from actions that occur in Stage II (shown in Figs. 3 and 5). There is a high spring rate in the material at the mat cen-



FIG. 12. Principal drawing of vertical density profile formation during pressing (dotted line directions from low to high compression or spring rate). T1 & T2—*In-situ* thickness of mat being pressed. T3—Designed thickness of panel. T4—Actual thickness during press opens to let steam escape from mat. T1>T2>T3, T4>T3. Stage I: Uniform compression. Stage II: Nonuniform compression. Stage III: Surface layer consolidation. Stage IV: Core layer consolidation. Stage V: Spring-back.

ter and a high compression rate in the material near the mat face. Stage III is completed when the temperature difference between the surface and core layers is at a maximum.

Stage IV—A period of core layer consolidation. As the core temperature rises and moisture content in the core becomes higher than the surface layer, due to steam migration into the core, the stress-to-strain ratio of the core layer increases such that the density of the core layer increases even at low compression stress. The density of the surface layers will decrease during this stage because the greater surface layer densification formed under high temperature and compression stress during stages II and III cannot be maintained under the same temperature and much lower compression stress during stage IV.

Stage V—A period of springback of the whole mat when the press opens to let steam escape from the mat. This phenomenon can be characterized as springback, since the thickness (T4) of OSB immediately out of the press generally is greater than the thickness (T3) at the end of pressing (Fig. 12). The springback is not uniform through the mat thickness be-

cause of nonuniform mat structure, temperature, moisture, density gradients, and internal bonding differences in the mat. High springback is expected to occur in the mat core area. The authors have suggested an in-process measurement and control theory during the pressing cycle through monitoring immediate springback during stage V (Wang and Winistorfer 1999a).

The influence of the adjusting period on the density profile formation is mainly affected by the press closure rate and compression stress when the adjusting period begins. The shorter the press closure rate or the higher the compression stress when the adjusting period begins, the larger influence it exerts. The occurrence of the adjusting period is due to the high compression stress and the difference of the stress-to-strain ratio between face and core layer material when the press reaches final thickness. Although press closure in a cold press results in the disappearance of the consolidation period, the adjusting period can result in vertical density profile formation; Wu's (1998) experimental results proved this analysis. Subsequent heating after press closure on a cold mat caused a slight density profile in the panels, except of the board of 0.55 g/cm³ target density.

Influence of unsteady contacting phase on resin cure and bond formation

A condition of contacting among flake surfaces is not a steady state due to significant density changes throughout the mat, even after the press closes to target thickness. This implies that there is not a steady phase in the mat for resin cure and bond formation among flakes, neither during press closing nor while the press maintains final position. The resin will mostly cure in an unsteady contacting phase because the resin continues to cure after the press closes to target thickness in an industrial pressing condition. At final position the mat continues in an unsteady state because of temperature and moisture movement that results in nonuniform compression. One of the major objectives during hot-pressing is to

achieve resin cure and bond formation between flakes. During panel manufacture, internal mat temperature, moisture content, vapor pressure, layer density, and compaction stress are related to pressing. Wang et al. (1995, 1996) showed the effects of process variables such as temperature, moisture content, and relative humidity on the resin curing and bond formation. Follensbee (1990) has distinguished between two different modes of resin cure: mechanical cure measured with a DMA, and chemical cure measured with a DSC. The mechanical cure, dependent on resin stiffness, generally developed at a faster rate than the chemical cure. Resin cure and bond strength may develop at different rates. The results from Wang et al. (1996) showed that bond strength development is much later than the chemical degree of cure. The effect of the contacting state on the resin cure and bond formation between flakes is so important that the contacting face between flakes and bonding links can be adversely affected.

The unsteady contacting phase can be divided into a continual compression state and a springback state. The springback state occurs in the core area during stage III, both surface areas during stage IV and in the whole mat during stage V (Fig. 12). The arrow directions of the dotted lines in Fig. 12 indicate compression or springback strength, from weak to strong. For example, the compression rate in the surface area is higher than the core area during stage II. The springback may cause the failure of weaker bonds between the wood components if the springback stress is greater than the bond strength. Springback decreases effective bonding area between flakes of endproduct panels.

The continual compression state occurs in the whole mat during the consolidation period, in surface areas during stage III, and in the core area during stage IV. Despite the fact that the continual compression state increases the contact area among flakes, and consequently improves new bond formation, continual compression at the same stage may destroy the bond network that has already formed. The continual compression phase during the adjusting period may have some negative influence on the bond performance of end-product panels. No prior published work shows this correlation.

The unsteady contacting state between flakes intensifies the bonding differences and results in poorer bonding strength between flakes throughout the mat. Due to the unequal distribution of heat and moisture as a result of the pressing operation, resin cure and bond strength development in the core are much later than in the surface layers. The unsteady contacting state during stage III will mainly affect bond strength development in the surface layers, and the unsteady contacting state during stage IV will mainly affect bonding strength development in the core layer.

The theory of the unsteady contacting state can be used clearly to explain some phenomena relating to manufacturing processes of wood composites and end-product panel properties. In practice, the strength properties of thin panels generally are better than thick panels with the same average density. For instance, property requirements for mediumdensity fiberboard (ANSI/A208.2-1994) are based on the nominal thickness. The bending strength, internal bond strength, and screwholding ability for 20.6-mm-thick panels and thinner are greater than that required for 22.2mm-thick panels and thicker. The probable difference in the vertical density profile between these two kinds of products does not explain the performance differences, because a steeper density profile in the thick panel will result in poor internal bond strength, while improving bending strength. A better explanation is that the severer the unsteady phase in the thick mat, as a consequence of large temperature and moisture gradients during hot-pressing, the poorer quality of the bond formation. We noted that although two panels pressed via different pressing schedules exhibited the same core density, the panel made under a severer unsteady phase exhibited significantly lower internal bonding strength (Wang et al. 1999c).

Steam injection pressing is a new technology that utilizes perforated platens to inject steam directly into the board and permits the transfer of heat into the core of a board much faster than conventional pressing. The main objective of this technology was to reduce press time. Another advantage of steam injection pressing is the potential for improved product quality. Several papers (Geimer et al. 1992) reported more dimensionally stable panels when pressed via steam injection. The improvement was due to partial hydrolysis of hemicellulose or substantial plastic flow of lignin and hemicellulose under steam pressure. Effectively eliminating the unsteady contacting state between the flakes with steam pressing is perhaps another potential reason for improved performance. Stage IV in steam injection pressing may occur much earlier than in conventional pressing. Resin cure and bond strength development throughout the mat will be in the weaker, unsteady contacting state. The high-frequency heating used in MDF production is another tool to eliminate the unsteady contacting state between the fibers. It is clear that the extent of stress relaxation should be lower, and the residual stress levels higher, at the board edges. Hence thickness swelling can be expected to be greater at the edges of a board than at its center, which has been observed experimentally (Bolton et al. 1989).

CONCLUSIONS

The pressing operation is one of the most important and complicated operations in the manufacture of wood composites. The vertical density gradient results from the combined effects of many manufacturing parameters. Hotpressing is an unsteady state. Internal mat temperature, moisture content distribution, vapor pressure, layer density, and compaction stress are all related to pressing.

Results of laboratory studies indicate that the vertical density profile of OSB is formed from a combination of actions that occurs both during consolidation and also after the press has reached final position. A methodology was developed to describe the formation of the density profile into two periods and five stages.

Knowledge of the unsteady contacting state during pressing enables an adequate explanation of some phenomena in relation to manufacturing processes of wood composites and end-product panel properties.

ACKNOWLEDGMENTS

This work has been supported by the USDA National Research Initiative Competitive Grants Program Grants No. 95-37103-2104 and the Tennessee Agricultural Experiment Station, Project MS #70. The authors wish to acknowledge William Moschler and Chris Helton of the Tennessee Forest Products Center for their participation in this work. The authors would like to thank Georgia-Pacific and Huber Engineered Woods for providing experimental materials.

REFERENCES

- BOLTON, A. J., P. E. HUMPHREY, AND P. K. KAVVOURAS. 1989. The hot pressing of dry-formed wood-based composites. Part 6. The importance of stresses in the pressed mattress and their relevance to the minimization of pressing time, and the variability of board properties. Holzforchung 43(6):406–410.
- DAI, C., AND P. R. STEINER. 1993. Compression behavior of randomly formed wood flake mats. Wood Fiber Sci. 25(4):349–358.
- FOLLENSBEE, R. A. 1990. Using dynamic mechanical analysis to characterize the cure of phenolic resins. Ph. D. thesis, University of Wisconsin-Madison, WI.
- HARLESS, T. E. G., F. G. WAGNER, P. H. SHORT, R. D. SEALE, P. H. MITCHELL, AND D. S. LADD. 1987. A model to predict the density profile of particleboard. Wood Fiber Sci. 19(1):81–92.
- GEIMER, R., S. E. JOHNSON, AND F. A. KAMKE. 1992. Response of flakeboard properties or changes in steam injection pressing environments. Res. Pap. FPL-RP507. USDA, Forest Serv., Forest Prod. Lab., Madison, WI.
- GIBSON, P. R., AND F. G. ASHBY. 1988. Cellular solids: Structure and properties. Pergamon Press, New York. NY. 357 pp.
- KELLY, M. W. 1977. Critical literature review of relationship between processing parameters and physical properties between processing parameters and physical properties of particleboard. Gen. Tech. Rep. FPL-10. USDA Forest Serv., Forest Prod. Lab., Madison. WI.

LANG, E. M., AND M. P. WOLCOTT. 1996. A model for

viscoelastic consolidation of wood-strand mats. Part I. Structural characterization of the mat via Monte Carlo simulation. Wood Fiber Sci. 28(1):100–109.

- LENTH, C. A., AND F. A. KAMKE. 1996a. Investigations of flakeboard mat consolidation. Part 1. Characterizing the cellular structure. Wood Fiber Sci. 28(2):153–167.
- , AND _____, 1996b. Investigations of flakeboard mat consolidation. Part 2. Modeling mat consolidation using theories of cellular materials. Wood Fiber Sci. 28(3):309–319.
- STEINER, P. R., AND C. DAI. 1994. Spatial structure of wood composites in relation to processing and performance characteristics. Part 1. Rationale for model development. Wood Sci. Technol. 28:45–51.
- SUO, S., AND J. L. BOWYER. 1994. Simulation modeling of particleboard density profile. Wood Fiber Sci. 26(3): 397–411.
- WANG, S. 1986. A study and application of density gradient of wood-based panel. Science Report of Postgraduate 1(1):3-6 (in Chinese).
- . 1987. A study of single-step hot pressing technology of oriented strand composite plywood. J Nanjing Forestry Univ. (2):74–84 (in Chinese, English abstract).
- , AND P. M. WINISTORFER. 1999a. In-process measurement and control of hot pressing. Submitted to Forest Prod. J.
- , _____, T. M. YOUNG, AND C. M. HELTON. 1999b. Step-closing pressing of mediate density fiberboard. Part 1: Influence on the vertical density profile. Holz Roh Werkst. (in-press).
- pressing of medium density fiberboard. Part 2. Influences on the panel performance. Submitted to Holz Roh Werkst.
- WANG, X.-M., B. RIEDL, A. W. CHRISTIANSEN, AND R. L. GEIMER. 1995. The effects of temperature and humidity on phenol-formaldehyde resin bonding. Wood Sci. Technol. 29:253–266.
- ———, ——, R. L. GEIMER, AND A. W. CHRISTIANSEN. 1996. Phenol-formaldehyde resin curing and bonding under dynamic conditions. Wood Sci. Technol. 30:423– 442.
- WINISTORFER, P. M., T. M. YOUNG, AND E. WALKER. 1996. Modeling and comparing vertical density profiles. Wood Fiber Sci. 28(1):133–141.
- —, W. W. MOSCHLER, S. WANG, AND E. DEPAULA. 1999a. Fundamentals of vertical density profile formation in wood composites. Part 1. *In-situ* density measurement of the consolidation process. Wood Fiber Sci. (in press).

- WOLCOTT, M. P. 1989. Modeling viscoelastic cellular materials for pressing of wood composites. Ph.D. dissertation, Virginia Polytechnic Inst. State Univ., Blacksburg, VA.
- WU, Q. 1998. In-plane stability of oriented strandboard: Layer properties in relation to processing variables. Pages 15–24 *in* Proc. No. 7272: Engineered Systems Using Structural Panels, Forest Products Society.