PREDICTING THICKNESS SWELLING OF HOT-PRESSED WOOD STRANDS

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Strand board can be manufactured from sawmill residues, branches, and crown wood left in the forest. The thickness swelling of these residues is quite different from that of mature wood and can have a negative effect on the physical and strength properties of strand board. A mixture of these materials and pressing conditions can be optimized by assessing thickness swelling of wood strands after pressing. Individual wood strands conditioned to 12% moisture content were hot-pressed at 105 °C to 50% of their original thickness and conditioned at 20 °C and 33%, 100%, and 0% relative humidity for 72 hours to determine their thickness swelling. A mechanical model consisting of springs and dashpots was superimposed on a stress relaxation curve to determine strain components with a view to predict thickness swelling. The data were interpreted by analysis of variance in conjunction with Fisher's protected least significant difference method. The results showed a good agreement between measured and predicted thickness swelling of both juvenile and mature wood.

Keywords: Thickness swelling; Strands board; Stress relaxation; Juvenile/mature wood; Wood residues

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INTRODUCTION

In harvesting for sawlogs, only merchantable volume, 60%, of down to 13 cm tree top diameter is extracted, while in sawmilling, about 50% of sawlogs volume is converted into wood residues such as slabs, sawdust, and off-cuts (Izekor and Kalu 2008). The logging waste, slabs, and off-cuts can be used to manufacture strand board. Strand board is an engineered structural panel manufactured by blending dried wood strands with waterproof resin and forming into a thick, loosely consolidated mattress, which is then hot-pressed between 177 to 204°C at about 5 MPa to cure the resin in 3 to 5 min (Winandy and Kamke 2004; Geimer *et al.* 1998). The properties of a board made from wood wastes comprising juvenile wood are inferior to that made from mature wood.

While information on the physical and mechanical properties of solid wood is easily available (Deresse *et al.* 2003), this is not so for wood composites made from mixed stock of juvenile-, mature-, branch-, and crown-wood (Kretschmann 2008; Pugel *et al.* 2004; Li *et al.* 1991). The conventional methods for assessing dimensional stability of wood composites, such as exposure of samples to a single cycle 30 to 90% relative humidity and ovendry-vacuum-pressure-soak (Geimer *et al.* 1997; Pugel *et al.* 1990) are lengthy and more expensive. This problem can be overcome by simulating mattress heat and moisture transfer, as well as rheological and adhesion processes during pressing (Thoemen 2000).

Simulation models based on the premise that strands are stacked into columns across a surface during mattress formation have been developed (Lang and Wolcott 1996a; Dai and Steiner 1994). Attempts have been made to evaluate the overall rheological behavior of a strand board mattress during hot-pressing (Thoemen 2000; Lenth and Kamke 1996; Lang and Wolcott 1996b; Dai and Steiner 1993; Ren 1991). The compression data of columns, which is basically a summation of the behavior of individual strands, does not take into account the effects of pressing conditions on rheological properties. The rheological behavior of wood depends on compression direction, moisture content, and temperature (Ncube *et al.* 2012). Other researchers have set out to determine the behavior of strands at various mattress conditions during hot-pressing (Zhou and Dai 2004; Adcock 1998; Dai and Steiner 1993), but none have a focus on juvenile wood. A rheology model for estimating thickness recovery is presented here with the objective to develop a new understanding of dimensional stability of strand board made from a variety of wood raw materials.

The rheological behaviour of wood comprise instantaneous (*i.e.* elastic), as well as viscous or delayed-elastic deformation visualised as stress relaxation of a material held under constant strain and thickness recovery upon release (Winandy and Kamke 2004; Ren 1991). Thickness recovery is the restoration of strain applied on a strand, (*i.e.* cell wall deformation) induced during the hot-pressing phase of strand board manufacture. The model requires that rheological constants for each strain component for a specific strand type be determined experimentally for the entire pressing conditions in advance. The model for thickness recovery is based on the premise that when wood is compressed, changes in its behaviour are caused by the response in cellulose, hemicelluloses, and lignin as a result of molecular bonds' elastic movement, breakage and relocation, chain rupture, and degradation (Adcock 1998; Van der Put 1989).

EXPERIMENTAL

Materials

Preparation of strands

Wood strips measuring 4 mm thick by 30 mm wide were plain or quarter sawn from the pith region and outer sapwood of 1 m long freshly felled, defect-free 40-year-old softwood logs. Each strip was planed on all faces and cut into 25±0.25 mm long blocks and stored in water to maintain its saturated state. Radial or tangetial strands of 0.9 mm thickness were sliced from the narrow edges of the saturated blocks using a sledge microtome (Fig. 1).

To ensure strand quality, the thickness of saturated strands was measured with a micrometer (±0.001 mm) at three points, and strands with a variation of greater than 25 μm were rejected. Accepted strands were dried at 103±2 ^{o}C for 15 min, conditioned to constant weight at 20 ^{o}C and 65% relative humidity (RH), and screened for thickness consistency for the second time. The width was measured by a digital calliper (±0.02 mm), while the length was measured by a sliding microscope (±0.01 mm) and recorded.

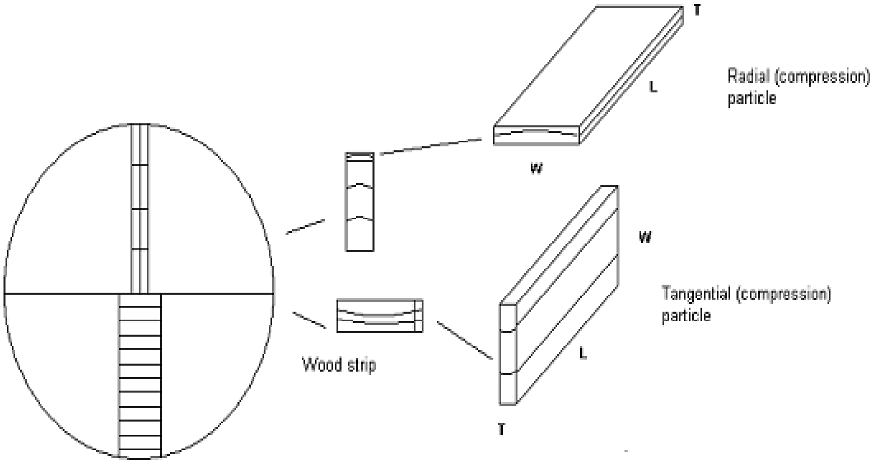

Fig. 1. Position and orientation of strands in a Scots pine (*Pinus sylvestris*) log

Hot-pressing

Eighteen strands from each of the four types of strands (*i.e.* radial juvenile and mature, tangential juvenile, and mature) were randomly selected and hot-pressed in a sealable miniature press attached to an Instron 4411 Universal Testing Machine (Fig. 2).

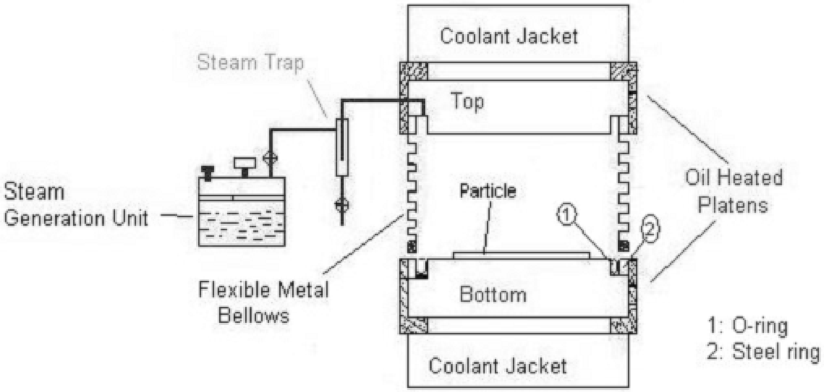

Fig. 2. Diagram of a miniature closed platens hot-press system (The diagram is not drawn to scale)

Prior to being hot-pressed at 105 °C platen temperature under saturated steam, the wood strands were conditioned to 12% moisture content (MC) for 72 h over a saturated solution of ammonium nitrate. Adcock (1998) established that strands reach equilibrium MC after 72 h conditioning. A saturated steam generation unit fitted with a pressure control valve to vent the system at 1.5 bar maintained saturated environment to prevent condensation inside the pressing chamber. The pressing condition mimicked mattress core environment during the hot-pressing phase of strand board manufacture (Bolton *et al.* 1989).

The hot-pressing cycle consisted of a 30 s closure time followed by a 4 min holding time at constant strain. The response of strands to compression and constant strain were determined during press closure time and stress relaxation during the holding phase, respectively (Fig. 3). The pressing data for each strand was recorded by a real time data acquisition system at a rate of 10 Hz. To minimize electrical noise, each data point recorded was a mean of 5 measured values.

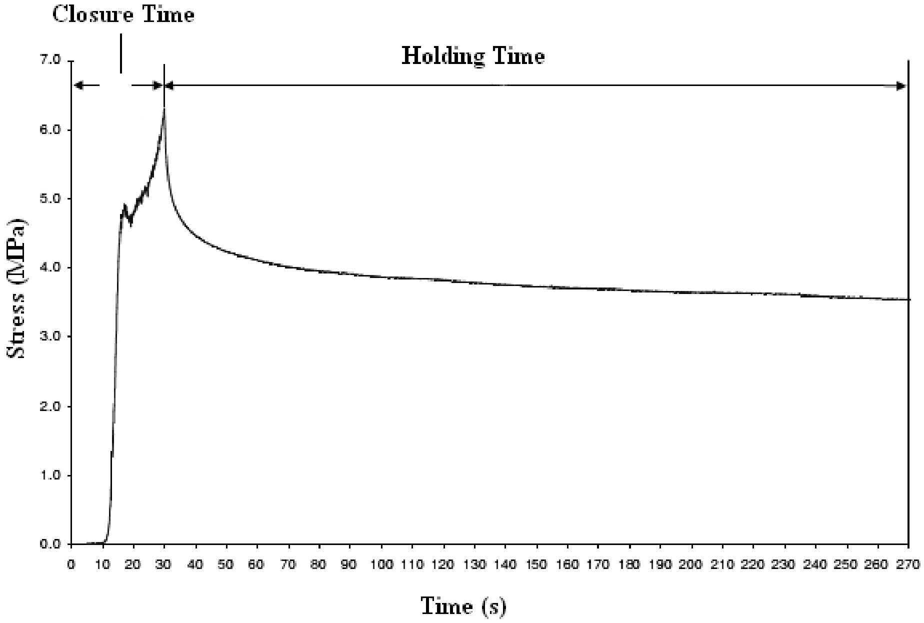

Fig. 3. A typical stress-time curve for a radial strand hot-pressed at 105 °C for 30 s and then held at a constant strain for 240 s under steam environment

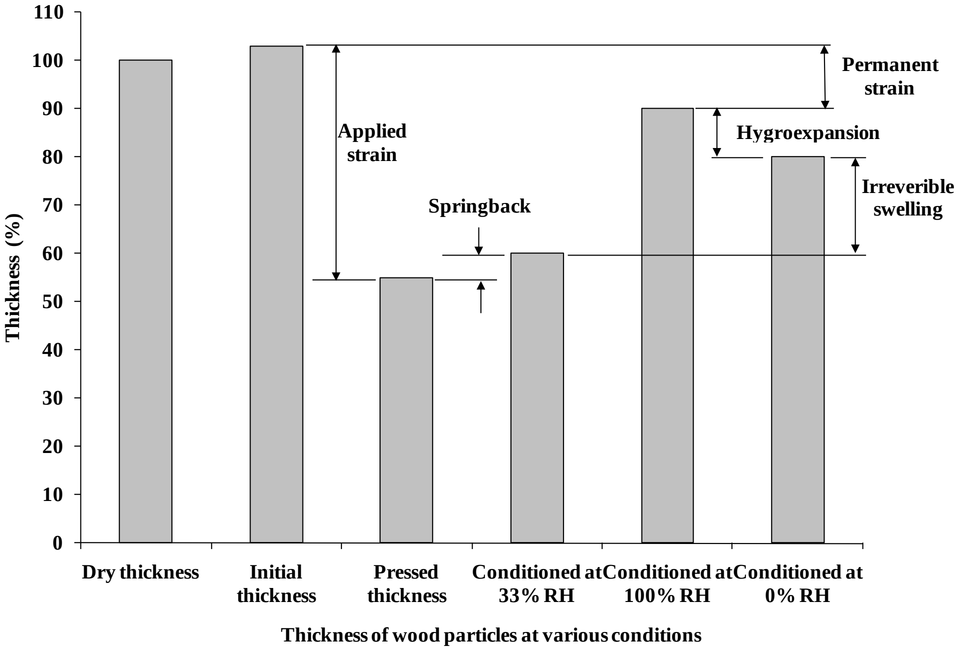

Fig. 4. Thickness recovery of wood strands pressed at 12% initial MC and 105 °C in steam and conditioned at various RH

Thickness swelling

When a pressed strand is released from the press, all or part of the cell wall deformation that is recovered can be partitioned into several strain components (Kunesh 1961) as shown in Fig. 4.

At the end of the hot-pressing cycle, strands were immediately removed from the press and measured for elastic springback of the compressed wood cell wall. Strands were conditioned for 72 h at 20 °C and 33% RH so that the equilibrium MC reached did not significantly deviate from the press-exit MC of strands, and so any additional changes in strand thickness after elastic springback were due to delayed-elastic springback. Springback (SB) is a summation of elastic- and delayed-elastic thickness recovery or a computation from measurements taken after delayed-elastic springback (Equation 1),

$$SB = \frac{T_{72} - T_p}{T_{init} - T_p} \tag{1}$$

where T_{init} is the initial thickness, T_p is the pressed thickness, and T_{72} is the thickness after 72 h at 0 °C and 33% RH.

After measurement of springback, strands were conditioned to the fiber saturation point and measured to determine their total recovery after first wetting. Strands were then re-dried over anhydrous phosphorus pentoxide to eliminate the effect of shrinkage and facilitate measurement of the irreversible swell (*IS*). Irreversible swelling is the thickness recovery that occurs during the first wetting of strands but is not reversed by re-drying (Equation 2),

$$IS = \frac{T_{od} - T_{72}}{T_{init} - T_p} \tag{2}$$

where T_{od} is the oven-dry thickness.

Hygroexpansion *(H)* is the dimensional change observed when a wood sample is wetted and re-dried (Equation 3). It includes both natural swelling and reversal of densification, so zero reversal of densification is expected on strands that have not been pressed. Pressed strands will incur cell wall damage (*i.e.* micro-fracture), which is indicated by an increase in their hygroexpansion (Equation 3),

$$H = \frac{T_{fsp} - T_{od}}{T_{init} - T_p} \tag{3}$$

where T_{fsp} is the thickness at the fibre saturation point.

Data analysis

The data collected were tabulated to help interpret the results and analyzed by analysis of variance (ANOVA) followed by Fisher's protected least significant test at the 5% level, where the null hypothesis is rejected.

Model for thickness recovery of pressed wood strands

The recovery of applied strain in a viscoelastic material such as wood is divided into elastic- and delayed-elastic springback, irreversible thickness swell, and hygroexpansion. Each strain component is represented in the mechanical model by individual or a combination of springs and dashpots of different constants (Fig. 5).

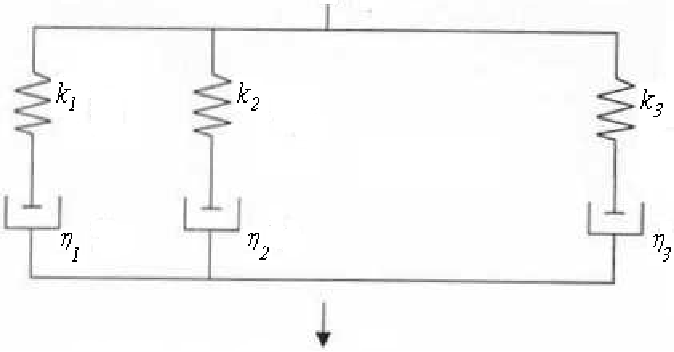

Fig. 5. Mechanical model comprising of a spring and Maxwell bodies in parallel (where: $k_{1...3}$ and $\eta_{1...3}$ represents spring and dashpot constants, respectively)

The spring and dashpot constants were obtained from a mathematical model (Equation 4) by applying a MathCad™ curve fitting algorithm 'genfit' on the stress relaxation curve (see, 'holding phase' in Fig. 3). The different constants result from the elastic nature of atomic and molecular bonds of wood (Van der Put 1989; Bodig and Jayne 1982). Although the approach is limited, in that assumptions about the behaviour at molecular level are based on the mechanical behavior at macroscopic level, it provides a basis for predicting thickness recovery of wood strands that have been compressed during the hot-pressing stage of strand board manufacturing process.

$$\sigma(t) = \varepsilon\left[k_1 + k_2 \cdot \exp\left(-\frac{t}{\left(\frac{\eta_2}{k_2}\right)}\right) + k_3 \cdot \exp\left(-\frac{t}{\left(\frac{\eta_3}{k_3}\right)}\right)\right] \tag{4}$$

In Eq. 4, $\sigma(t)$ is stress as a function of time t, ε is the strain, $k_{1...3}$ are the spring constants, and $\eta_{2,3}$ are the dashpot viscosity constants.

RESULTS AND DISCUSSION

Thickness recovery and hygroexpansion of strands being hot-pressed are summarized in Table 1. ANOVA shows that mature- and juvenile wood thickness recovery only differed when elastic- and delayed-elastic springback are considered separately. Hygroexpansion clearly shows that juvenile wood strands pressed in the radial direction incurred the least cell wall microfracture, while tangential juvenile wood strands experienced the highest cell wall damage.

Table 1. Mean Differences in Thickness Recovery of Wood Strands by Fisher's Protected Least Significant Method at 5% Level (Standard deviation shown in brackets)

-wood →	Radial mature-	Radial juvenile-	Tangential mature-	Tangential juvenile-
Elastic springback (%)	5.5 (1.6)^{b}	2.5 (2.0)^{a}	8.3 (2.3)^{c}	6.8 (1.3)^{b}
Delayed-elastic springback (%)	2.9 (1.6)^{a}	5.6 (2.8)^{b}	2.4 (1.6)^{a}	4.3 (1.5)^{b}
Springback (%)	8.3 (1.6)^{a}	8.0 (2.6)^{a}	10.7 (2.2)^{b}	11.1 (1.8)^{b}
Irreversible Swell (%)	50.1 (2.6)^{a}	55.7 (3.2)^{b}	50.9 (7.2)^{a}	56.1 (2.5)^{b}
Hygroexpansion (%)	7.4 (1.1)^{b}	5.8 (1.0)^{a}	9.4 (0.9)^{c}	12.4 (0.7)^{d}
N.B.: Means in the same row and bearing the same superscript are not significantly different				

Rate of stress relaxation

Table 2 shows constants obtained after the mechanical model (Fig. 5) expressed in Equation 1 had been fitted on the stress relaxation curve recorded during the 'holding phase' of the hot-pressing cycle (Fig. 3).

Table 2. Elastic and Viscosity Constants Calculated from Stress Relaxation Curves ($\tau_r = \eta/k$ is a relaxation time constant)

- wood ↓	k_1	k_2	k_3	$k_1/(k_2+k_3)$	η_2	η_3	$(k_2+k_3)/(\eta_2+\eta_3)$	τ_2	τ_3
	Radial strands								
Juvenile-	0.46	0.25	0.19	0.96	39.79	1.00	0.0108	159.08	5.26
Mature-	0.51	0.23	0.18	0.80	36.04	1.05	0.0111	159.87	5.99
	Tangential strands								
Juvenile-	0.53	0.23	0.16	0.74	31.67	0.87	0.0120	138.20	5.29
Mature-	0.57	0.20	0.15	0.61	32.80	0.95	0.0104	161.82	6.24
$k_{1\ldots2}$ are elastic constants, η_2 and η_3 are viscosity constants, and τ_2 and τ_3 are time constants									

The smaller the relaxation time values τ_2 and τ_3, the faster stress is relaxed (Table 2), which indicates that the relaxation time is a measure of how quickly the stress relaxes (Bodig and Jayne 1982). The model predicts that juvenile wood relaxes stress much faster than mature wood, as shown by the reduced stress relaxation time. This means that initial setting of resin during hot-pressing will occur under lower stress in a strand board made from juvenile wood than in that made from mature wood. This partly explains the improvement of internal bond strength observed by Stefaniak (1985) on particleboards made from juvenile wood.

Springback

Springback is comprised of elastic and delayed-elastic strain components that were determined by conditioning strands to an environment that did not alter their press-exit MC. The amount of strain recovered instantaneously depends on the level of potential energy in spring *1* and the amount by which k_1 exceeds the sum of k_2 and k_3 at the end of a pressing cycle (Table 2). This is determined by the residual stress in k_1 relative to k_2 and k_3. If k_1 is k_2 plus k_3, then the residual stress is not relaxed.

A comparison between mature- and juvenile wood shows that $k_1/(k_2$ and $k_3)$ is smaller in mature wood strands. The model correctly predicts that mature wood pressed in both the radial and tangential direction will show more elastic springback (Table 1). The unison behavior of mature wood in both compression directions illustrates the reducing effect of increased juvenile wood microfibril angle on transverse swelling.

The mechanical model shows that dashpots *2* and *3* yield overtime to allow springs *2* and *3* to release stress, which in turn allows delayed-elastic springback of spring *1* after recovery of elastic springback. The level of stress in spring *1* provides the driving force behind delayed-elastic springback. The amount of stress released during delayed-elastic springback is determined by the viscosity of dashpots *2* and *3*. To induce delayed-elastic springback, springs *2* and *3* reverse the remaining strain against the resistance offered by dashpots *2* and *3*.

A small dashpot value indicates a thin fluid, while increased relative ratio of (k_2+k_3) to $(\eta_2+\eta_3)$ shows an increased capacity of springs to reverse the strain. The model predicts increased delayed-elastic springback in radial mature- and tangential juvenile wood strands. This prediction is only correct for radial strands. The inability of the model to correctly predict delayed-elastic springback of tangential strands was attributed to excessive cell wall damage, which was not incorporated in the model. A very high value of hygroexpansion shows that tangential juvenile wood strands indeed incurred excessive cell wall damage (Table 1).

Irreversible swell

The potential energy in a wood strand after springback is not sufficient to reverse the induced deformation, but an external force in the form of moisture adsorption can break the secondary hydrogen bonds. This allows the release of energy measured as irreversible swell (Fig. 4). The amount of irreversible swell remaining in the model after springback depends on the viscosity of dashpots. If the dashpots are to mimic irreversible swelling of cell wall polymers, it was assumed that the cooling of strands at press exit increased the viscosity of dashpots (Adcock 1998).

The adsorption of moisture into the cell wall polymers effectively reduces the viscosity of dashpots η_2 and η_3, causing them to yield, which allows further recovery of springs 1, 2, and 3. The higher moisture-induced recovery in juvenile wood could be associated with an increased level of hydrophilic polymers. Juvenile wood has a higher content of hemicelluloses and lignin content than mature wood (Rowell *et al.* 2005). The higher hemicelluloses content of juvenile wood accentuated moisture adsorption. Since moisture adsorption lowers the viscosity of dashpots, the model correctly predicts higher irreversible swell in juvenile wood.

If the assertion that reduced stress relaxation time of juvenile wood promotes formation of stronger resin-wood bonds is true, the strength of such bonds in a resinated strand board will be superior to that of mature wood and agrees with observations by Stefaniak (1985) and Pugel (1990) on particleboard. This can be validated by including adhesion processes in simulating rheological behavior of strands during hot-pressing.

CONCLUSIONS

1. The study shows that it is possible to predict the differences between the recovery of juvenile- and mature wood hot-pressed in two grain directions for varying moisture content in composites.
2. The assertion that strand board made from juvenile wood has improved internal bond strength requires verification by incorporating adhesion processes in simulating the rheological behavior of strands.

ACKNOWLEDGMENTS

I acknowledge and express my gratitude to the Forest Products Research Centre, Buckinghamshire Chilterns University, UK, for facilitating the experimental work reported and undertaken using their facilities and the Forestry Commission, UK, for providing the wood specimens.

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Article submitted: February 27, 2012; Peer review completed: March 26, 2012; Revised version received and accepted: April 22, 2012; Published: May 2, 2012.