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The Transversal Compression Behaviour of Mature Wood Particles Pressed at High Temperatures and Pressures

*NCUBE E.[1] MANSFIELD-WILLIAMS H.[2] and IRLE M.[3]
[1]The Copperbelt University, School of Natural Resources, Zambia
E-mail:*elisha.ncube@cbu.ac.zm or enncube@yahoo.com
[2]TRADA Technology, United Kingdom
[3]Ecole Supérieure du Bois, France

Abstract

The properties of a particle in a particleboard are dependent on the conditions surrounding it and these, in turn, change throughout the hot-pressing cycle and are therefore dependent on the location of the particle within the mattress. The behaviour of a mattress and its subsequent behaviour as a final product is an average of the particles that make up the product. Models to predict the distribution of particles in a mattress and its compression behaviour have been developed. What is needed is a method to observe the rheological behaviour of individual wood particles during the compression phase of hot-pressing cycle in order to improve understanding of the hot-pressing stage. Such a method is presented in this paper. This work will contribute to the development of a mattress consolidation model which combines deformation of a mattress and particles during hot-pressing.

Keywords: Cell wall collapse, Compression behaviour, Stress relaxation, Dimensional stability, Wood particle

Introduction

The overall behaviour of a particleboard mattress during hot-pressing and the performance of the resultant product in service can be readily evaluated, but the study of the behaviour of individual particles that make up particleboard is more difficult. The need to study the behaviour of single particles comes from the fact that the conditions within a mattress of particles change with time as it is hot-pressed and are dependent on the position within the mattress. In simple terms, the surface layers are heated rapidly and tend to dry out, whereas the core heats much more slowly and initially increases in moisture content (MC) before subsequently drying out (Bolton et al. 1989). The moisture content and temperature of a particle affect its rheological behaviour and so the rheological properties of a mattress are the sum of the behaviours of individual particles.

Statistics-based models have been developed for predicting the distribution of particles in a mattress (Lang et al. 1996a; Dai et al. 1994; Suchsland 1967). Attempts have also been made to develop empirical models of a mattress being pressed (Lenth and Kamke 1996; Lang and Wolcot 1996b; Dai and Steiner 1993). The basis of these models is that during mattress formation particles are stacked into columns. The number of columns across the mattress surfaces and of particles in each column can be described by exponential and Poisson's probability distributions.

The compression data of columns, which is basically a summation of the behaviour of individual particles, is normally used to validate theoretical models. The major limitation is that the localised variable strain resulting from the effects of differential mattress temperature and moisture content distribution and differences in wood properties of particles is not included. The problem is that localised stress-strain development in specific particles is difficult to quantify. Attempts have been made to determine the behaviour of particles at various mattress locations during hot-pressing (Dai and Steiner 1993; Zhou and Dai 2004; Adcock 1998) The purpose of the research described in this paper is to present a method for quantifying the behaviour of particles in various mattress layers and to show the effect of the pressing environment and wood properties on strain variation. Since mattress consolidation occurs simultaneously with individual particle compression, combining the two models may be an effective way to model mattress consolidation (Lenth and Kamke 1996; Zhou and Smith 2008).

This research requires very careful particle preparation and selection in order to minimise the variation present in a natural material like wood. Additionally, to observe the actual behaviour of wood any errors in the calculation of wood properties should be eliminated. This paper presents a method to observe and predict the behaviour of wood during the compression phase of hot-pressing that includes a wide range of error correction steps.

Methods

Particle Preparation

Wood strips 4 mm thick and 30 mm wide were sawn from the outer sapwood of Scots pine *(Pinus sylvestris)* logs so that they had either radial or tangential faces. The strips were planed on all faces and cut into blocks 25 mm long and stored in distilled water to maintain their saturated state. Radial and tangetial particles were sliced from the narrow edges of the saturated blocks using a sledge microtome. In this paper, a radial particle is one which was pressed in the radial direction and a tangential particle is one which was pressed in the tangential direction.

To ensure particle quality, the thickness of wet particles was measured with a micrometer (±0.001 mm) at three points, and particles with a variation of greater than 25 µm were rejected. Accepted particles were dried at 103 ±2 °C for 15 minutes and then screened again for thickness consistency in a similar manner.

Design of Experiment

Each particle had an Initial Moisture Content (IMC) of 0, 12 or 18 % and was either of low density (LD), i.e. 300-340 kg/m³, or high density (HD), i.e. 460-500 kg/m³. They were pressed either in the radial or tangential direction depending on how they had been cut from the log. The press temperature used was 20, 105, 130, 150 or 180 °C. Not all combinations of these variables were investigated.

Nine particles were pressed at each combination of variables selected. The IMC of the particles were achieved by storing over phosphorus pentoxide, ammonium nitrate or potassium chloride respectively. Adcock (1998) established that particles reach equilibrium moisture content after 72 hours conditioning. The sets of particles at 20 °C allow the effect of variation in the IMC to be studied. Similarly the sets of particles conditioned to 0 % IMC allow the effect of variation in the press temperature to be studied. In this paper these conditions provide comparisons to those conditions where both the temperature and the moisture content of the particle change during pressing.

Particles with an IMC of 12 or 18 % and pressed at 105 °C are thought to simulate mattress conditions in the core of a mattress (Bolton et al. 1989). Whereas, particles with an IMC of 0 % and pressed at 180 °C are thought to simulate the surface layer conditions. Temperatures of 130 and 150 °C will simulate intermediate layers.

Hot-pressing

A sealable mini-press was developed for this study. Great care was taken to ensure that the two platens were parallel to one another. After various verification experiments and modification of the platens, error due to misalignment of the platens was reduced to 4 µm over a typical particle length.

The top platen was secured to a load cell mounted on the cross-head of a Universal Testing Machine (UTM). According to the specifications of the UTM, the cross-head could be moved vertically with a position accuracy of □0.01 mm and position repeatability of □0.05 mm. When the assembly is loaded, the load cell generates an analogue signal proportional to the force applied.

Pressing particles within saturated steam mimicked mattress conditions during hot-pressing. Pressures exceeding one atmosphere were needed to maintain saturated conditions at 105 and 130 °C corresponding to 1.5 and 2.6 bars respectively. This was achieved by generating steam in a unit fitted with different pressure control valves to vent the system at specific pressures above one atmosphere. The steam generation unit was attached to the UTM to enable steam injection into a press chamber sealed by the bellows.

The pressing cycle consisted of a 30 s closure time followed by a 4 minute holding time at a constant strain. The compression behaviour of a particle was determined during press closure time and stress-relaxation behaviour during the holding phase.The pressing data of each particle was recorded by a real time data acquisition system at a rate of 10 Hz. To minimise electrical noise, each data point recorded was a mean of 5 sampled values.

The bellows system that created the sealed environment about the particles generated an additional load due to resistance of the flexible seal. The bellows were designed to flex within their elastic range and so the additional load was easily eliminated by subtraction.

Any error in the calculation of the strain applied to a particle was minimised by ensuring that the platens were adequately preheated and their initial position zeroed in a consistent manner and by taking into account particle shrinkage during hot-pressing.

Particles with initial moisture content (IMC) of greater than zero and which were pressed above ambient temperature will shrink as a result of loss in moisture. To account for this, matched particles were placed in the mini-press set at the same temperature, but without pressing, and measured at various short intervals in order to estimate the thickness change due to shrinkage. The results of these experiments indicated that the shrinkage was between 0.8 and 1.8 % depending on IMC and press conditions. These values were used to correct the particle thickness used in calculating strain applied and modulus of elasticity (MOE).

Particle modulus of elasticity and cell wall collapse

The error corrections described above were applied to the data to produce stress-strain curves like that shown in **Figure 1**. The MOE was calculated by means of an algorithm developed in MathCad™ to compute a regression line on the linear region of the stress-strain curve. The algorithm used a range of 10 to 20 % of the peak stress and then extended this range up and down where necessary, to find the best fit.

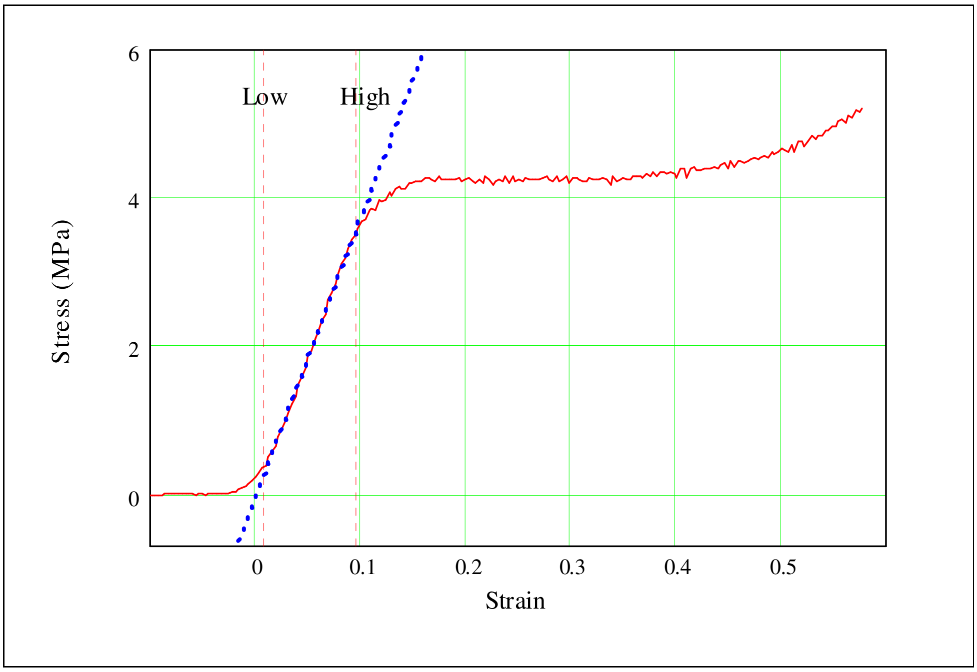


Figure 1 A typical stress-strain curve and regression line for a radial particle with a 12 % IMC and pressed at 105 °C with steam.

The point where the regression line diverges from the observed stress-strain curve, indicated as High in **Figure 1**, is known as the proportional limit. This limit is thought to coincide with the start of cell wall collapse (Irle 2000), by implication of the fact that strain increases significantly without much change in stress.

Results and Discussion

Modulus of elasticity

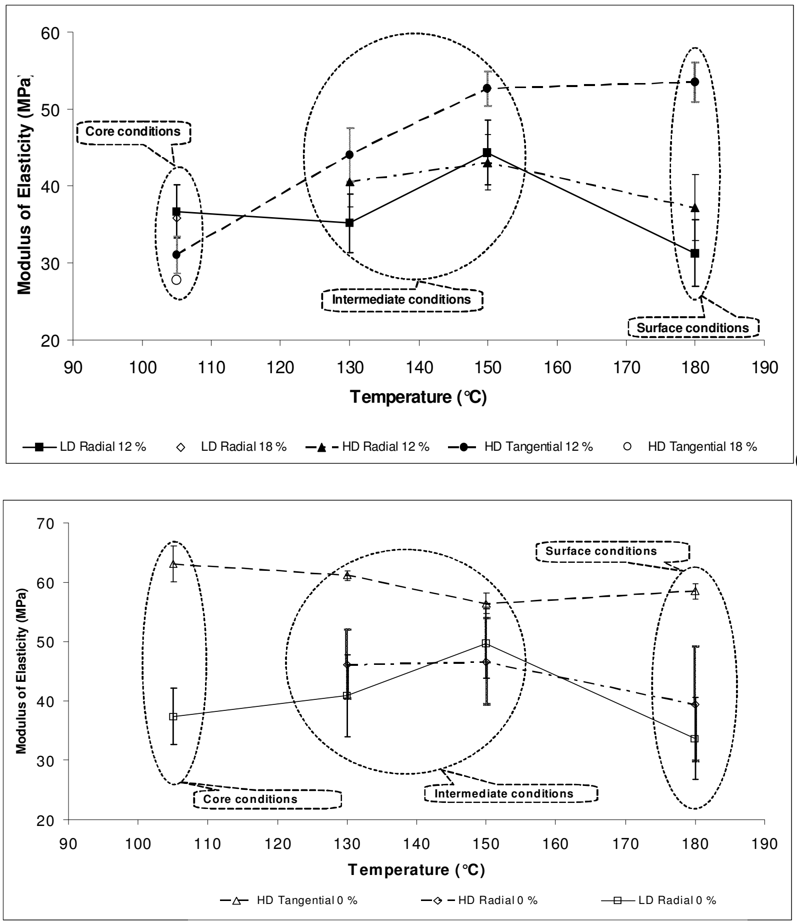
The observed modulus of elasticity (MOE) of a particle will be dependent on its MC when the platens make contact. At elevated temperatures, this contact MC will be lower than the IMC, see

Table *1*. An IMC of 18 % caused higher contact moisture contents, but, had no real effect on exit moisture content. This is not surprising given the small particle size. Press temperatures of 150 °C and above caused negative moisture contents because of the evaporation of volatile extractives. This helps explain why the HD Radial particles achieved low moisture contents than the LD Radial particles. Comparing the HD Radial and HD Tangential particles, it can be seen that the Radial particles tended to dry more rapidly. This is probably explained by the fact that most of the moisture will escape from the sides of the particle (because the faces are in contact with the platens) and so the water will escape by tangential flow in the Radial particles, which is faster than radial flow in *Pinus sylevestris*.

Table 1 Predicted moisture content (%) of particles when platens make contact and observed moisture content on press exit. (The standard deviation is shown in brackets)

Temperature (°C)	MC (%) at	LD Radial		HD Radial	HD Tangential	
		12 % IMC	18 % IMC	12 % IMC	12 % IMC	18 % IMC
105 °C	Contact	8.6 (0.8)	10.8 (0.5)	-	9.7 (1.1)	12.3 (0.3)
	Exit	3.5 (1.1)	4.1 (0.9)	-	6.5 (0.6)	6.8 (1.0)
130 °C	Contact	4.3 (0.6)	-	3.2 (0.3)	5.7 (0.4)	-
	Exit	2.2 (0.6)	-	2.7 (0.6)	3.0 (0.7)	-
150 °C	Contact	-1.3 (0.9)	-	-0.7 (0.7)	4.5 (0.7)	-
	Exit	0 (0)	-	-1.2 (1.2)	-0.4 (0.8)	-
180 °C	Contact	-2.8 (1.4)	-	-1.8 (0.7)	-0.5 (1.4)	-
	Exit	-1.0 (0.4)	-	-1.5 (0.6)	-1.8 (1.1)	-

It is expected that higher temperatures will tend to reduce the MOE of particles. On the other hand, higher temperatures cause lower moisture contents and lower moisture contents would be expected to increase MOE. **Figure 2** shows that these two factors have a tendency to cancel one another out. Particles pressed with an IMC of 0 % generally show the expected trend of decreasing MOE with increasing press temperature (**Figure 2 b**).



(a)

(b)

Figure 2 Observed modulus of elasticity of particles pressed at various temperatures and initial moisture contents (a) 12 or 18 %, and (b) 0 %

Cell wall collapse

Figure 3 shows the trends in strain at cell wall collapse for particles pressed at 0, 12 or 18 % IMC and various temperatures. The most notable trend is the reduction in the range of strains observed as pressing temperature increases. This indicates that moisture content has some influence on strain at cell wall collapse because particles pressed at 180 °C were all oven dry during the actual pressing stage, whereas particles pressed in cooler conditions had a greater range of moisture contents. The trends are that the strain at cell wall collapse tended to increase for LD particles as press temperature increased, whereas the opposite, and less obvious trend, occurred for the HD particles. The strain at cell wall collapse has been linked to yield stress reductions (Wolcott 1989) caused by increased wood cell wall flexibility at elevated temperatures. (Adcock 1998). The trends in changes of stress at cell wall collapse are similar to those for MOE (**Figure 2**; **Figure 3**), and there is a better correlation between the yield stress and MOE than with strain at cell wall collapse (**Figure 4**). This indicates that the strain at cell wall collapse is dependent on MOE and compression strength. In a mattress, both strength and stiffness of a particle will be reduced by increases in temperature and/or moisture, but not necessarily by the same amount. An increase in strain at cell wall collapse occurs when the rate of change in MOE is faster relative to that of stress at cell wall collapse; a combination of low stiffness but high strength will bring about high strains before cell wall collapse occurs and vice versa (**Table 2**). The findings by Irle (1999) that the strain at cell wall collapse is dependent on pressing conditions rather than particle density (and therefore strength) are not supported by the findings above except, perhaps, when the press conditions are at 180 °C (when there is relatively no moisture present in the particles).

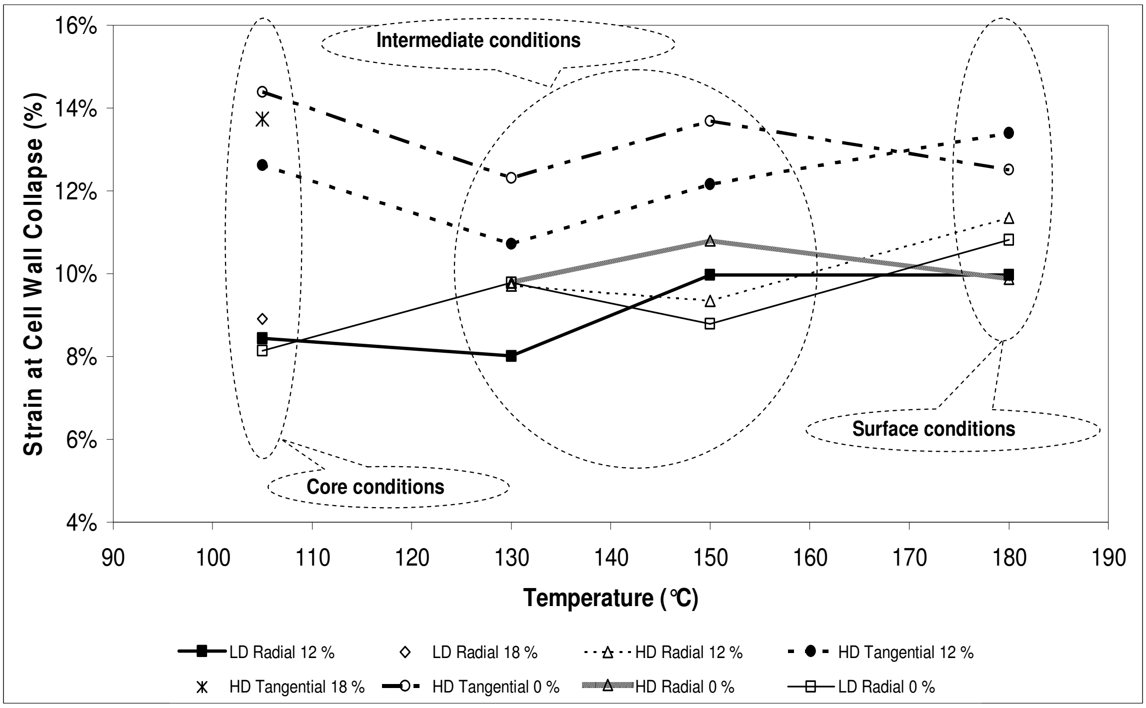


Figure 3 Trends in strain at cell wall collapse for particles pressed at 0, 12 or 18 % IMC and various temperatures

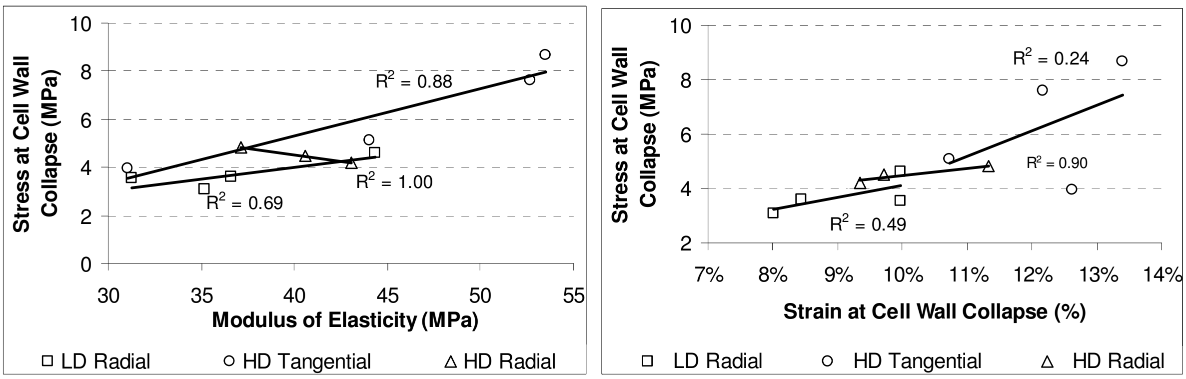


Figure 4 Correlation of the stress at cell wall collapse to the MOE and the strain at cell wall collapse (MPa)

The strain at cell wall collapse in Radial particles is lower than that in Tangential particles because of a difference in their load bearing cell walls (**Figure 3**). The change in MOE relative to stress at cell wall collapse is small because the strength of latewood decreased slower which allowed larger strain to be sustained before cell wall collapsed.

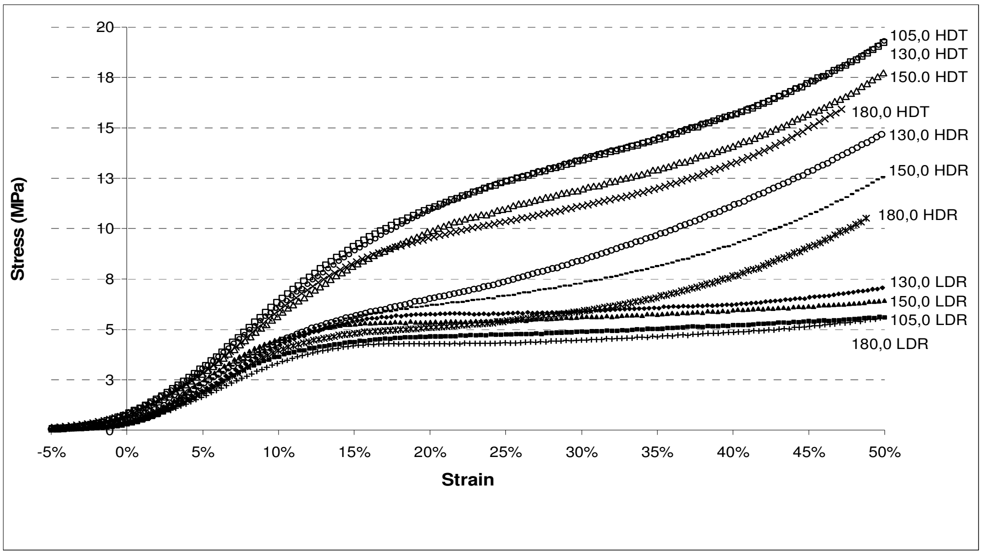
Strain variation in relation to the density profile

In particleboard manufacture a mattress is compressed to the target density by applying specific platen pressure or by traversing the platens to stops at a desired thickness. Although a uniform load is applied, particles at different mattress layers and locations incur different strain. The effect of strain variation is density profile (Suchsland 1967; Wolcott et al. 1990; Strickler 1959).To mimic platen pressure, 5 MPa constant stress is applied on individual particles (Geimer et al.1998). Where the applied stress did not cause cell wall collapse (**Table 3**), particles reached 10-20 % strain and particles which collapsed at lower stresses incurred higher strains of up to 50 %.

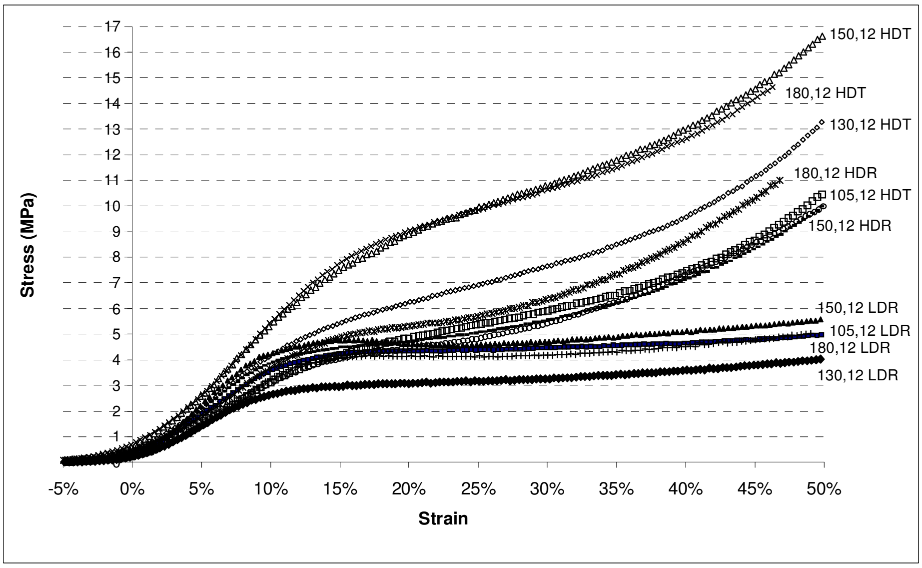
The development of stress after cell wall collapse slows into a plateau zone which diminishes with increased proportion of latewood layers in radial particles and when particles are pressed tangentially (**Figure 5**). The strain incurred by individual particles progressively increases with stress. **Figure 6** shows the normalised deformations incurred by the pressed particles. Where the plateau persisted much higher strains were attained at lower stresses. The results show that LD particles pressed at core and surface conditions contribute most to the formation of the M-shaped density profile while HD particles tend to promote a flat density profile (**Figure 6**).

Table 2 Stress at cell wall collapse for particles pressed at 0 or 12 % initial moisture content and various temperatures (Shading indicates stress significantly above 5 MPa and the standard deviation is shown in brackets)

Temperature (°C)	Initial moisture content (%)					
	0	12	0	12	0	12
	LD Radial		HD Radial		HD Tangential	
105	3.6 (1.1)	3.6 (0.8)	-	-	11.2 (1.2)	4.0 (0.5)
130	4.5 (1.0)	3.1 (0.5)	5.2 (0.9)	4.5 (1.2)	10.2 (1.0)	5.1 (1.5)
150	4.8 (0.7)	4.6 (0.7)	5.4 (1.4)	4.2 (0.8)	9.5 (1.3)	7.6 (1.2)
180	4.1 (1.2)	3.5 (1.0)	4.3 (0.8)	4.8 (1.3)	8.9 (1.3)	8.7 (0.6)

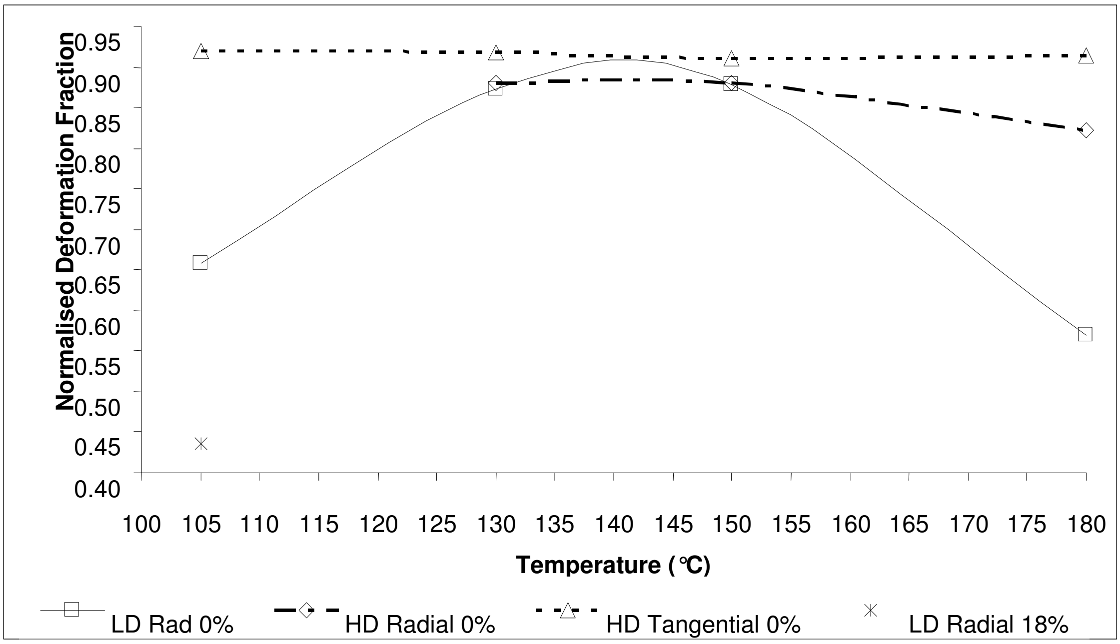


(a)



(b)

Figure 5 Stress-strain curves for particles pressed at initial moisture content of 0 or 12 % and various temperatures (Abbreviations: L-low, H-high, D-density, R-radial, and T-tangential)



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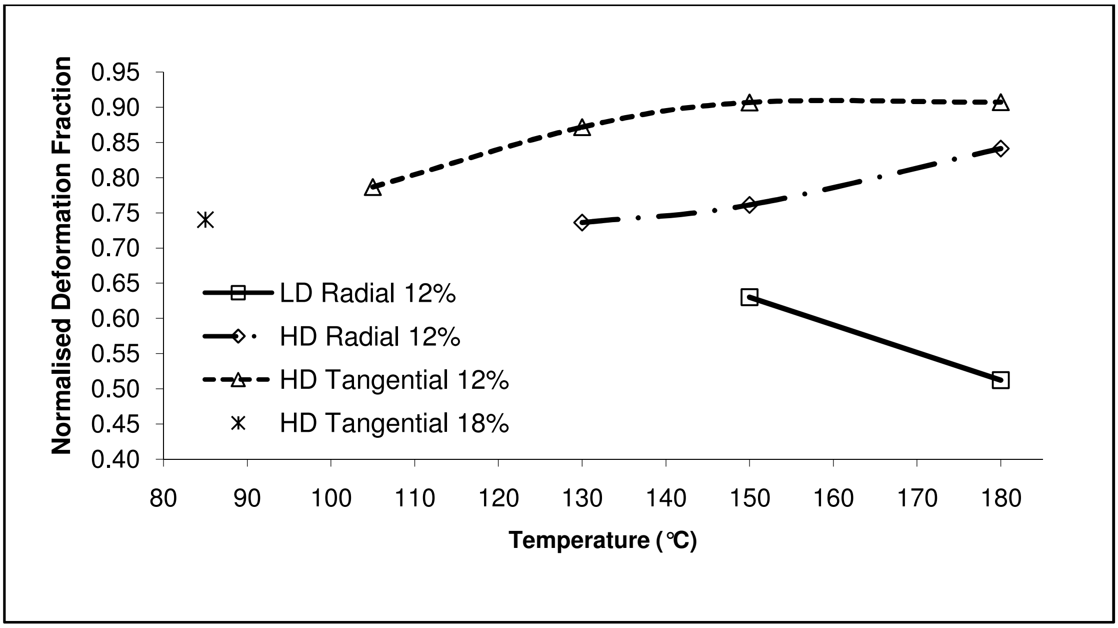

(b)

Figure 6 Proportions of deformation on particles conditioned to 0 % or 12 % initial moisture content and pressed to a fixed stress of 5 MPa at various temperatures

Wang and Winistorfer (2000) reported that commercial southern pine narrow flakes are generally radial face flakes (i.e. Tangential particles) because flakes break more easily in the tangential thickness direction. As a result tangential face flakes (i.e. Radial particles) were found to be wider than radial face flakes. The density profile for particles compressed in the same direction is not M-shaped as expected (**Figure 6**). However, average deformations for LD Radial and HD Tangential particles pressed at the same conditions give the expected M-shaped density profile (**Figure 7**). This illustrates that it is possible to include data for individual particles into hot-pressing models. This approach has the advantage that both pressing conditions and wood material variables, such as particle density, wood maturity and grain orientation are considered.

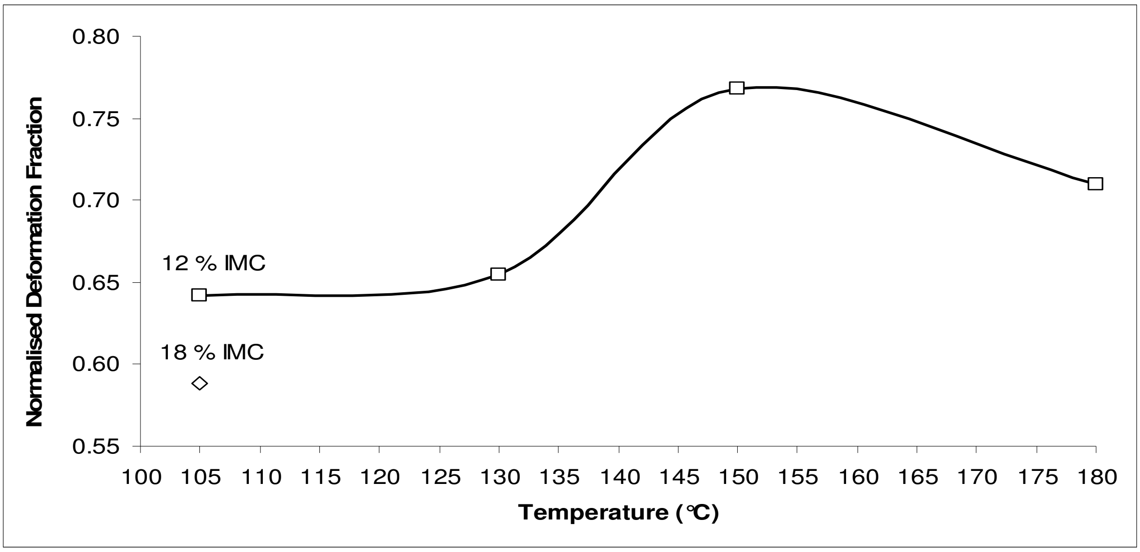

Figure 7 Proportions of deformation on particles conditioned to 12 % or 18 % initial moisture content and pressed to a fixed stress of 5 MPa at various temperatures (Values for LD Radial particles are based of a fixed stress of 4.5 and 4.9 MPa respectively)

Conclusions

The MOE and strain at cell wall collapse show a dependency on grain orientation, moisture content and temperature. The MOE of particles pressed with IMC of 0 % tends to decrease with increasing temperature as expected. Further decreases in MOE were expected for particles pressed at higher IMC, but at higher press temperatures the effects of temperature and moisture content cancel out.

The deformation of radial particles contributes most to the formation of an M-shaped density profile while Tangential particles promote a flat profile. The data collected has the advantage that it accounts for the effect of various pressing conditions and any differences in wood material properties. The data also show how the compression behaviour of individual particles is related to the density profile. This demonstrates that compression data of individual particles can be used to develop a mattress consolidation model which combines deformation of a mattress and particles during hot-pressing.

Table 3 Stress relaxation rates for particles pressed at 0 0r 18 % initial moisture content and various temperatures

Temperature (°C)	Initial moisture content (%)					
	0	12	0	12	0	12
	LD radial		HD radial		HD tangential	
105	0.061	0.061			0.040	0.050
130	0.056	0.067	0.045	0.051	0.037	0.043
150	0.058	0.063	0.045	0.048	0.040	0.041
180	0.062	0.065	0.054	0.053	0.049	0.051

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