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Investigation of effects of wood variability and rheological properties on lumber drying: application of mathematical models

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Abstract

Three types of mathematical models (a single board-drying model, a kiln-wide drying model and a drying stress model) have been developed for the simulation of kiln drying of softwood lumber and the simulation of drying stresses. The single board-drying model employs comprehensive heat and moisture mass transfer knowledge and considers the influence of wood physical characteristics and moisture state. The model is used to investigate the influence of lumber variability such as wood density, green moisture content, growth ring pattern, mixture of sapwood and heartwood and thickness variation. The kiln-wide drying model, which was developed for the simulation of the drying of a kiln wide stack, is based on the transfer processes between the wood material and the drying medium. This model is able to examine the influence of varying wood properties and drying schedules on drying rate and moisture content distribution between boards. The stress model has been proposed to predict stress development in drying, and stress relief in final steam conditioning and post-kiln treatment. The stress model considers wood shrinkage, stress–strain relationships, mechano-sorptive behavior, creep and temperature effect. It is found that the rheological properties of wood play an important role in drying stress relief. The stress model is used to optimize drying schedules and to effectively relieve the residual drying stresses. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Softwood; Lumber drying; Drying model; Stress model; Moisture content; Drying stress

1. Introduction

In order to maintain global sustainability, more and more wood is being cut from plantation forests. The fast growing plantation species such as radiata pine in New Zealand show significant variation in wood properties [1] and these affect the kiln drying process. Also for wood produced from young trees, drying defects are of major concern due to the spiral grain and microfibral angle, which induce warp during drying. It is critical to understand how the variable wood quality affects the drying behavior, and to develop improved drying schedules for different types of raw materials for different end uses.

Drying experiments in pilot-scale kilns have shown that for drying of variable quality green lumber, the final moisture content after normal high-temperature (HT) drying could range from 4 to 22% with an overall average value of 10%. After final steam conditioning, the moisture content variation was reduced, but was still large enough to adversely affect performance of remanufactured products. In addition, up to 10% of lengths may be rejected due to excessive warp (twist, crook and bow).

In terms of drying rate and final moisture content distribution, the three factors believed to be important are board properties, drying schedules and drying condition variation within a kiln stack. The board properties include green moisture content, wood basic density, sapwood/heartwood mixture in a single board, board thickness variation and ring orientation pattern. Each of these variables can have a different level of influence on the drying rate and moisture content distribution, and can be examined by employing mathematical drying models. For different target products, different schedules should be used to meet customers' quality requirements. For example, for drying of radiata pine lumber, HT drying is recommended for structural products and accelerated conventional temperature (ACT) or conventional temperature schedules for appearance products [2]. However, for drying of lumber from different resource of forest sites and with different sawing patterns and stacking, the drying schedules need to be adjusted and, air temperature and humidity, as well as air velocity, need to be optimized. In addition to the schedule choice, it is also important to have an accurate kiln control system capable of achieving the required distribution of air temperature and velocity

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Nomenclature

a	exposed drying surface area per unit volume (m^2/m^3)
C_P	specific heat (J/kg/K)
E_{MS}	constant related to mechano-sorptive strain (Pa)
f	relative drying rate (–)
G	air mass flow rate (kg/m^2/s)
h	external heat transfer coefficient (W/m^2/K)
ΔH_{wv}	latent heat of water vaporization (J/kg)
j	moisture flux within wood (kg/m^2/s)
m	constant related to mechano-sorptive strain (1/Pa)
T	Temperature (K)
X	moisture content (kg/kg)
y	space coordinate in board width (airflow) direction (m)
Y	air humidity (kg/kg)
z	space coordinate in board thickness direction (m)
Greek letters	
α_{R}, α_{LS}	factor for heat radiation and heat loss (–)
ϵ	void fraction in the lumber stack, strain (–)
λ	thermal conductivity of moist wood (W/m/K)
ρ	wood basic density (kg/m^3)
σ	Stress (N/m^2)
τ	Time (s)
φK_0	modified external mass-transfer coefficient (kg/m^2/s)
Subscripts	
C	creep (strain)
G, a	air
MC	mechano-sorptive (strain)
S	saturation
Surf	wood surface
T	temperature induced (strain)
v	vapor
wood	wood
X	moisture induced (strain)
y	respect to y direction
z	respect to z direction
σ	instantaneous (strain)

over the stack inlet face. Localized lower inlet temperature and velocity will result in wet spot in the stack after drying.

During drying, stresses develop due to moisture-content gradient and the non-uniform shrinkage properties of wood. Wood shrinks or swells with moisture content changes below the wood fiber saturation point. However, the shrinkage coefficient is different in three anisotropic directions (tangential, radial and longitudinal). The severity of the drying stresses is controlled by factors such as drying severity, wood permeability, wood shrinkage coefficients, wood stiffness, and wood rheological properties. If the wood is difficult to dry and mechanically stiff, then a slow drying schedule has to be used to minimize excessive drying stresses. However, wood shows mechano-sorptive behavior, which means that moisture content changes can be used to relieve drying stresses. The mechano-sorptive behavior is very useful for developing strategies for reducing stresses during and after drying.

The objectives of this work were to understand and quantitatively predict the drying differences for lumber boards with variable properties, and to investigate drying stress development during drying and relief during final steam conditioning and post-kiln treatment.

2. Description of the mathematical drying models

2.1. Single board-drying model [3,4]

In the drying of a single board, the drying generally occurs in three directions, meaning that the moisture moves and heat transfers in thickness, width and length directions. However, the drying in the three directions is quite different. For commercial drying (with board length over 3 m), most of the moisture is dried from the flat surfaces (drying in thickness direction) and less moisture is dried from board edges and the end drying is the least important. In order to simulate moisture movement and heat transfer within the board, a mathematical model has been developed, respectively, for one-dimensional drying and for two-dimensional drying. The one-dimensional model can capture the major drying processes and is fast to run. The two-dimensional model takes the actual variation in wood properties (the growth ring orientation and within-ring variation in wood basic density and green moisture content) and uses them to predict moisture content and temperature profiles over the board cross-section. Both of the one-dimensional and the two-dimensional models can predict drying rate curves under different conditions (drying, equalization and final steam conditioning). Detailed description of the constitution equations for the single board-drying is given in [3–5]. The constitute equations for two-dimensional drying model are as follows:

$$\frac{\partial}{\partial \tau}[C_P \rho T] = \frac{\partial}{\partial y}\left[\lambda \frac{\partial T}{\partial y}\right] + \frac{\partial}{\partial z}\left[\lambda \frac{\partial T}{\partial z}\right] - \Delta H_{\mathrm{wv}}\left(\frac{\partial j_{\mathrm{v},y}}{\partial y} + \frac{\partial j_{\mathrm{v},z}}{\partial z}\right) \qquad (1)$$

$$-\rho \frac{\partial X}{\partial \tau} = \frac{\partial j_y}{\partial y} + \frac{\partial j_z}{\partial z} \qquad (2)$$

Input data for model simulation include wood properties (such as wood basic density and green moisture content), lumber dimensions and drying conditions (air temperature, humidity and air velocity). Therefore, the single board-drying model is able to investigate the effects of mixture of heartwood and sapwood, the ring orientation and within-ring variations of wood properties (green moisture content, wood basic density, sapwood/heartwood). Depending on its green moisture content, the model can identify the wood at any point to be sapwood or heartwood.

2.2. *Kiln-wide drying model [6]*

During kiln drying of lumber, variation in wood moisture content across the stack is inevitable due to external drying condition changes (air humidity and air temperature). In order to describe such variation a kiln-wide drying model was proposed based on heat and moisture transfer process between the wood material and the drying medium. Also the model considered the changes in air temperature and humidity along the airflow direction. After modification of the original model [6], the current model is able to cover a wider range of conditions (high and low temperature drying, equalization and final steam conditioning) and able to consider variable properties of the lumber. The modified kiln-wide drying model is summarized as follows:

For moisture mass transfer

$$-\frac{\partial}{\partial \tau}[X\rho(1-\varepsilon)] = G\frac{\partial Y}{\partial z}\begin{cases}\varphi K_0 a(Y_{\mathrm{surf}}-Y_{\mathrm{G}}) & \text{(condensation)}\\ \varphi K_0 a f(Y_{\mathrm{s}}-Y_{\mathrm{G}}) & \text{(evaporation)}\end{cases} \tag{3}$$

For heat transfer

$$\frac{\partial T_{\mathrm{wood}}}{\partial \tau} = \frac{(1+\alpha_{\mathrm{R}}-\alpha_{\mathrm{LS}})ha(T_{\mathrm{G}}-T_{\mathrm{wood}})}{\rho(1-\varepsilon)C_{P,\mathrm{wood}}} \tag{4}$$

$$\frac{\partial T_{\mathrm{G}}}{\partial z} = \frac{(ha+GC_{P,\mathrm{v}}\partial Y_{\mathrm{G}}/\partial z)(T_{\mathrm{G}}-T_{\mathrm{wood}})}{G(C_{P,\mathrm{a}}+Y_G C_{P,\mathrm{v}})} \tag{5}$$

The symbols in the above equations are defined as in the nomenclature list. The key issue for solving the above model is to define the relative drying rate (*f*) which is a function of normalized moisture content [3,6].

The input parameters for the simulation of a kiln stack drying include both lumber variables and air conditions. The lumber variables are the actual board dimensions (thickness, width), fillet thickness, wood basic density and green moisture content of the individual boards. From the green moisture content, the model can identify whether a board is sapwood or heartwood. The air conditions are dry-bulb/wet-bulb (DB/WB) temperatures and air velocity. The model can take the actual DB/WB temperatures in a commercial kiln recorded by a data logger or by a control system.

The output parameters are overall stack average moisture content, moisture content of individual boards, air temperature and humidity changes across the stack, and wood surface temperatures.

2.3. *A stress model [7]*

During drying, stress within the wood is induced by differential shrinkage, which in turn is caused by a moisture-content gradient or differences in the moisture shrinkage coefficient. Through its influence on wood properties, the temperature profile also affects stress development. To relate the moisture content and temperature profiles to stress distribution, strain components need to be quantified. The total strain (ϵ) is comprised of moisture shrinkage (ϵ_{X}) when the moisture content is below the fiber saturation point, stress-induced strain (either elastic or plastic, ϵ_σ), mechano-sorptive strain (ϵ_{MS}), creep strain (ϵ_{C}) and temperature-induced strain (ϵ_{T}). The temperature-induced strain is due to wood thermal expansion and changes in the fiber saturation point. The definitions of each strain component have been given in [7], and a differential form of the strain constitution equation in a one-dimensional stress model can be written as follows:

$$\mathrm{d}\varepsilon = \left[\frac{\partial \varepsilon_{\mathrm{X}}}{\partial t} + \frac{\partial \varepsilon_\sigma}{\partial t} + \frac{\partial \varepsilon_{\mathrm{MS}}}{\partial t} + \frac{\partial \varepsilon_{\mathrm{C}}}{\partial t} + \frac{\partial \varepsilon_{\mathrm{T}}}{\partial t}\right]\mathrm{d}t \tag{6}$$

Because wood properties used in the stress model are related to wood moisture content and temperature, the one-dimensional single board-drying model has been incorporated into the stress model to determine moisture content and temperature. Of particular interest is the mechano-sorptive strain, which occurs as a consequence of moisture content change when the wood is stressed. This behavior was derived from the observation that wood would have prolonged shrinkage or swelling under constant load with changing moisture content (either gaining or losing moisture). Mathematically, the mechano-sorptive strain can be expressed by [8]:

$$\frac{\partial \varepsilon_{\mathrm{MS}}}{\partial \tau} = m\sigma\frac{\partial X}{\partial \tau} \tag{7}$$

A more comprehensive expression was proposed by Salin [9]:

$$\frac{\partial \varepsilon_{\mathrm{MS}}}{\partial \tau} = m(\sigma - E_{\mathrm{MS}}\varepsilon_{\mathrm{MS}})\frac{\partial X}{\partial \tau} \tag{8}$$

These two expressions are currently been evaluated to check which is more appropriate to *Pinus radiata* wood, and the results will be reported in a subsequent paper. Once each strain is defined and property constants determined, the above constitution equation can be solved by using appropriate boundary and initial conditions.

3. Effects of wood variability on drying rates from the model simulation

3.1. *Mixture of sapwood and heartwood in a single board*

After sawing logs into lumber, boards often contain varying proportions of heartwood and sapwood. For modeling

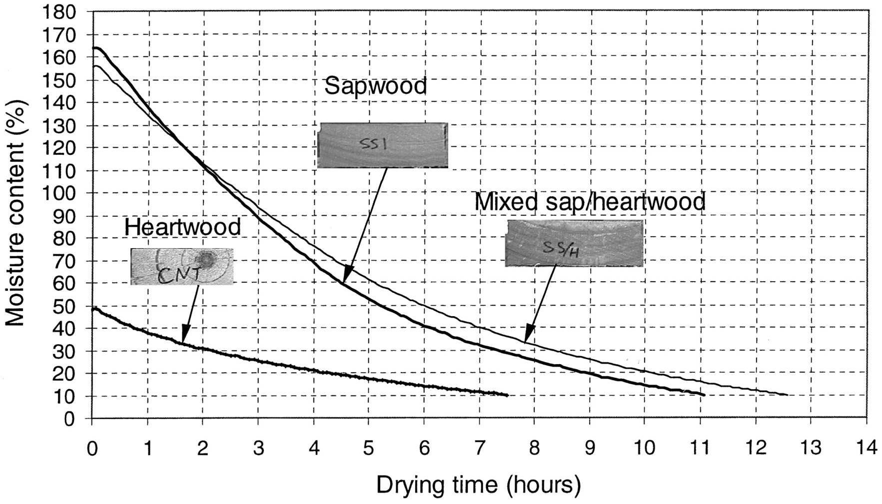

Fig. 1. Predicted drying-rate curves for sapwood, heartwood and mixed sapwood/heartwood boards.

purposes, the mixed sapwood/heartwood boards can be classified into three categories based on the cross-section composition: (1) a board with roughly half sapwood and half heartwood; (2) a board with more sapwood and less heartwood; (3) a board of mostly heartwood. For each type, the board can be flatsawn or quartersawn. In a flatsawn board, all of the growth rings are approximately parallel to board width direction and in a quartersawn board, the growth rings are approximately perpendicular to the board width direction. Regarding drying rate, sapwood and heartwood have different properties: the sapwood has higher density, higher green moisture content and is more permeable for moisture movement than the heartwood [1,3,10].

Thus sapwood normally dries faster but the higher volume of moisture present means that after the same period of drying, the sapwood is still wetter than heartwood.

Fig. 1 shows the simulation results for drying of a full sapwood board, a full heartwood board and a mixed sapwood/heartwood board. The simulation results show that the flatsawn boards with a thin heartwood layer on one face (e.g. $<20\%$ of the thickness) need longer drying. For other types of mixed sapwood/heartwood flatsawn boards, the drying time falls between the drying of a full sapwood board and the drying of a full heartwood board. For the mixed sapwood/heartwood quartersawn boards, the sapwood side tends to be wetter and the heartwood side to be drier. The drying time for all of the mixed sapwood/heartwood quartersawn boards is between the drying of a full sapwood board and the drying of a full heartwood board.

3.2. Sawing pattern: flatsawn versus quartersawn

Packs of lumber always show variation of sawing patterns of varying ring angles, but in New Zealand the majority of the radiata boards are flatsawn. The sawing pattern can have some impacts on drying rate due to wood permeability differences in tangential and radial directions. For HT drying the gas permeability in radial direction through ray cells is increased during drying thus enhancing the moisture vapor flow in radial direction [11]. However, the liquid flow in tangential direction is more favorable because the bordered pits are mainly located on the radial–longitudinal faces [12]. In a living tree, these pits on wood cell walls were for transportation of liquid nutrition (sap), and in wood drying they allow liquid water to flow between adjacent lumens.

Due to the permeability differences, the quartersawn boards dry faster in the early stages of drying when the liquid flow through pits is dominant but the flatsawn boards dry faster in the late stages of drying when the vapor flow controls. For HT drying of 100 × 40 mm boards, the model predicted a slightly longer drying time for quartersawn boards than the flatsawn boards. However, the difference may reverse for low temperature drying where the gas permeability in radial direction is lower than the HT drying.

3.3. Thickness variation

Commercially sawn lumber always has thickness variation, which affects drying rate because the thicker boards need longer time to dry than the thinner boards. In the range of ±3 mm thickness variation, the drying time is in linear with the thickness. For drying of 100 mm × 40 mm sapwood boards using a 120/70 °C schedule, the boards of 43 mm thick need about 1 h more than the 40 mm thick boards to dry to 10% moisture content. A board of 37 mm thick needs about 1 h less to dry to the same final moisture content. However, it should be noted that these differences cannot be directly extrapolated to the drying of a stack comprised of boards of variable thickness [13]. When a thicker board is placed in a layer adjacent to normal thickness boards, the thicker one will support more stack weight and the fillet space over the thicker board will be less than that over the normal thickness boards. Thus, the air velocity over the thicker board is higher than over a normal thickness board which consequently enhances the drying of the thicker boards. If a thinner board is placed adjacent to the normal thickness boards, the larger void space above the thinner board reduces the air velocity over this board. Airflow velocity is related to the external transfer coefficient to a power of about 0.78 which in turn affects the drying rate [14].

3.4. *Wood density and green moisture content*

Wood density and green moisture content are two important factors, among others, which affect the drying rate and the drying time. Wood density varies between trees and within a tree. The overall board density for radiata pine sawn lumber can vary from 300 kg/m^3 for the pith-in pieces to 500 kg/m^3 for the mature outerwood. Whereas the heartwood can have a green moisture content ranging from 30 to 50%, the green moisture content of the sapwood varies from 100 to 200%. For sapwood, the saturation is normally constant close to a value of 90%, thus the green moisture content can be related to the wood basic density. Denser sapwood usually has a lower green moisture content than less dense sapwood.

The denser wood is less permeable but more favorable for heat conduction, whereas the lighter wood is more permeable but has less material for the heat conduction in late stage of drying when the liquid water has been removed. Therefore, the drying time is balanced between the differences in density and green moisture content. If a reference sapwood board has a density of 420 kg/m^3 and a green moisture content of 165%, then a denser board of 500 kg/m^3 with a green moisture content of 145% needs slightly longer time (approximately 5%) to dry to 10% moisture content. For a board of 350 kg/m^3 with a green moisture content of 200%, the drying time is slightly shorter (approximately 5%). If a board has a higher density and a higher green moisture content, the drying time is much longer, and for a board with a lower density and a lower green moisture content the drying time is much shorter to dry to the same final moisture content of about 10%.

3.5. *Board position and mixed sapwood/heartwood boards within one stack*

Within a kiln stack, the drying conditions vary with position across the stack. When the air flows through the stack (along the stack width direction), the air provides its sensible heat to the wood for evaporation of the water and, at the same time, carries away the evaporated moisture vapor. Therefore, along the flow direction, the air temperature decreases and humidity increases. These changes reduce the air's potential for drying; thus decreasing the drying rate. Based on this observation, kiln operators use airflow reversals to reduce the drying differences between the two sides of the stack. However, due to the less favorable drying conditions, the central zone of the stack is still likely to be the wetter spot.

When sapwood boards and heartwood boards are mixed in a stack, the sapwood boards tend to be wetter than the heartwood boards after drying. In particular, sapwood boards near the central zone are likely to be the wettest and the heartwood boards close to the stack side the driest, as shown in Fig. 2. In this example, the stack of the mixed sapwood/heartwood boards was dried using a drying schedule of 90/60 °C (DB/WB temperatures) and 5 m/s air velocity. The board size was 100 mm × 40 mm. After 22 h, the average moisture content was 22%, but the moisture content of the heartwood boards was 10% and that of the sapwood boards was 30%. After 30 h, the difference between the sapwood and the heartwood boards was reduced, but still significant, with heartwood moisture content being 7% and sapwood 14%. The overall stack moisture content after 30 h was 11%.

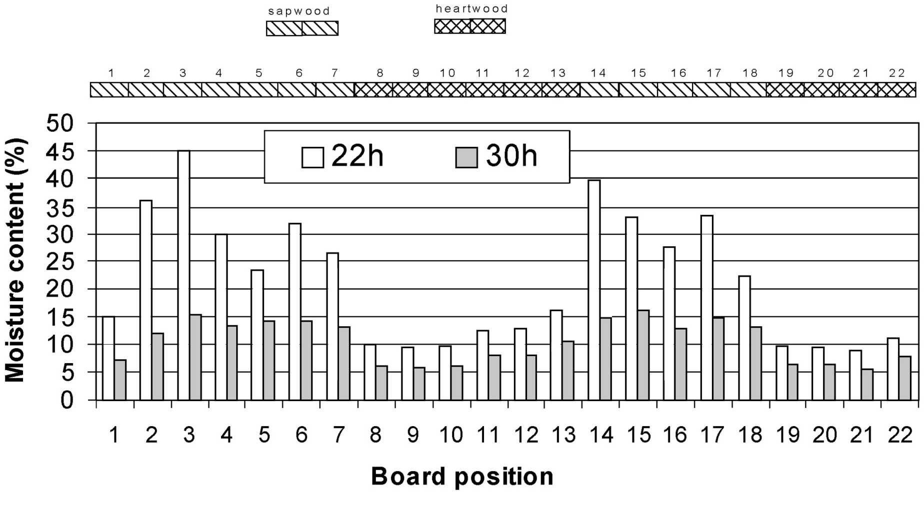

Fig. 2. The moisture content variation for a stack of mixed sapwood/heartwood boards after 22 and 30 h of drying.

4. Effects of wood rheological properties on drying stress development and relief

In simulation of the drying stresses, the moisture-content gradient and temperature profile are needed to define the wood mechanical and rheological properties. The moisture-content gradient and temperature profile were predicted from the single board-drying model. Fig. 3 shows the predicted stress pattern for HT drying of a 100 mm × 40 mm sapwood board. The drying schedule included drying phase at 140/90 °C (DB/WB temperatures) for 8.5 h (plus 0.5 h for heatup) followed by 1 h cooling and 2 h steam conditioning. From the simulation results, it can be seen that after 2 h of drying the surface is in tension but the interior of the board is in compression to balance the tensile force. After 5 h, the surface stress is reversed to compression and the stresses in the interior are progressively reversed to tension. At the end of drying, the residual stresses are very high both for compressive outer layers and tensile interior zone. The wood is then cooled down before steam conditioning without significant changes in the stress pattern. However, during steam conditioning, the wood surface initially picks up moisture, which increases the compression stress of the wood surface. The compression stress builds to a level where there is an instantaneous yield of the stress in the lumber surface layer, this helps to release the stress when the moisture-content gradient is reduced and the wood is cooled down. The mechano-sorptive properties of wood also play an important role to relax the residual stresses within the wood material. Thus the speed with which high humidity conditions are attained could influence the effectiveness of stress relief. A slow increase in humidity could be expected to give a less marked moisture pickup and therefore lower stress yield.

From the above simulation and the experimental results, a certain level of residual stress still exists after steam conditioning. This is not a concern for most of the products; however, these residual stresses can cause problems in remanufacturing of the dried lumber. Under such circumstances, the wood mechano-sorptive behavior can be used to develop effective strategies for improved relief of the residual stresses. Experimental results at Forest Research have demonstrated that simple humidity cycling could not reduce the residual drying stresses and in some cases the stresses were even slightly increased. This could be explained as follows. When the humidity was cycled to the high value the wood surface picked up moisture and the compression stress at the surface increased (but increased to a lesser extent because the mechano-sorptive strain helped to relax the constraint between the surface layer and the interior zone). However, when the humidity was cycled to a low level, the surface lost moisture and the surface stress then became tensile as it attempted to shrink. In this way, the previous mechano-sorptive compressive strain increased the surface tension in the subsequent lower humidity environment. Therefore, simply repeating high/low humidity cycle was not an effective means for relief of drying stresses. An improved strategy can be proposed by employing the stress model. The basic concept is that the humidity is alternated between high and low levels, but the high/low difference is gradually reduced towards the condition corresponding to target equilibrium moisture content.

In this way, the surface stress does not cycle between compression and tension, and with the moisture content changing the constraint between wood surface layer and the board core is relaxed. The simulated results of the surface and the center transverse stresses are given in Fig. 4 for both strategies. Strategy 1 simply repeats the high (90%)–low (30%)

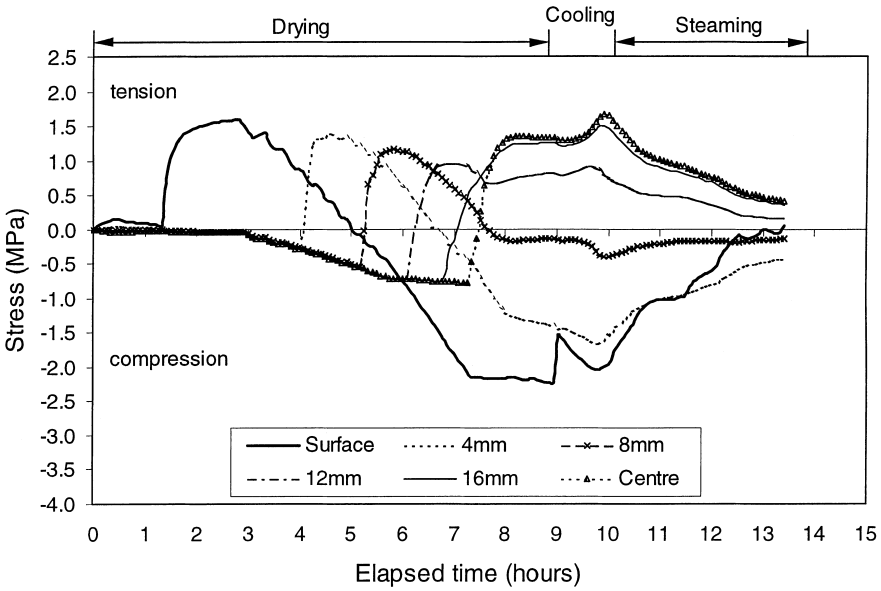

Fig. 3. Predicted transverse stress profile in a 40 mm thick sapwood board during HT drying followed by cooling and steam conditioning.

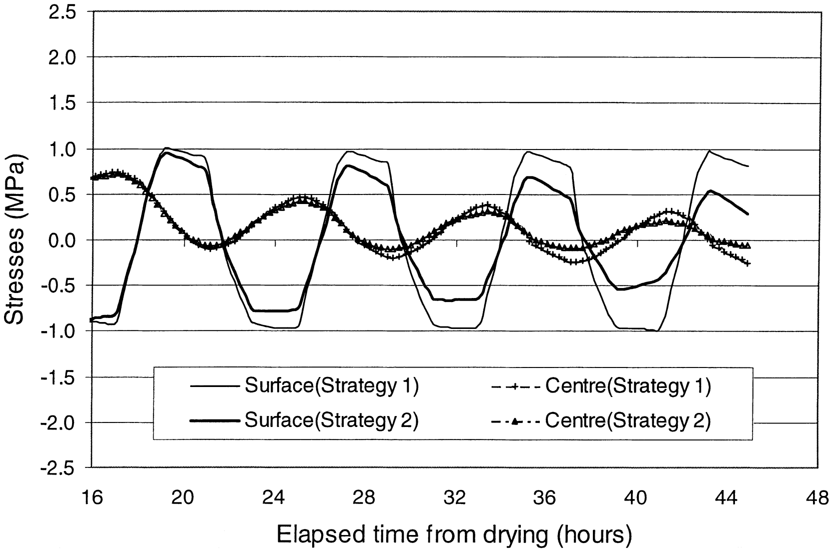

Fig. 4. Comparison of transverse stress relief between two strategies for post-kiln treatment. Strategy 1 uses high/low humidity cycling and strategy 2 employs a new schedule with humidity being gradually changed from high/low towards a condition corresponding to target equilibrium moisture content.

humidity cycle, whereas strategy 2 employs an improved schedule with the relative humidity being gradually changed from high (90%) to low (30%) towards 50% for both phases. From the simulation results, it is observed that with simple high–low humidity repetition the stresses at board surface and board center are repeated but their levels cannot be reduced. However, when using the improved strategy, the surface and center stresses are gradually reduced to a low level. In this way, the residual stresses are more effectively relieved.

5. Conclusion

From studies covered in this work, the followings have been predicted from the drying models:

Final moisture content variation after drying is a combined result of wood property (such as wood basic density and green moisture content) variability, processing variability (such as sawing pattern and stacking) and drying condition variation (air temperature, humidity and velocity). However, the drying time for the mixed sapwood/heartwood boards varies with sawing pattern and proportions of the sapwood and heartwood. A flatsawn board with a thin heartwood layer at one face needs longer drying time than the full sapwood board. The drying time for other types of mixed sapwood/heartwood boards falls between drying of a full sapwood board and drying of a full heartwood board. Compared to flatsawn boards, the quartersawn boards dry faster in early stages of drying but slower towards the end of drying. Thicker boards dry slower than thinner boards; however, the drying difference is reduced in a mixed thickness kiln stack. Wood basic density and green moisture content are two important factors affecting the drying time.

In the drying of a stack of mixed full sapwood boards and full heartwood boards, full sapwood boards need much longer time to dry than the heartwood boards. For drying endpoint determination, kiln operators should pay more attention to the pieces with high density and high green moisture content and to those pieces with low density and low green moisture content. The former needs much longer drying time and latter needs much shorter drying time. Boards in the central zone across the stack tend to be wetter while the boards close to the stack side tend to be drier after drying. Severe drying schedules cause greater moisture variation across the stack, but faster airflow slightly reduces the variation. Airflow reversals reduce the difference between two stack sides, but cannot eliminate difference between the stack side and the stack center. The models confirmed that too frequent airflow reversal is unnecessary. Uniform airflow and temperature distribution over the stack inlet face is important to achieve uniform drying.

After drying, residual stresses exist within the wood, which can cause problems in remanufacturing of the dried lumber and in service of the wood products. Due to the rheological property of wood, the residual stresses can be relieved to a low level with final steam conditioning. However, for high quality products, the stresses are often too high and further post-kiln treatment is necessary. This treatment again uses the wood rheological property and improved strategy for humidity changes is critical in order to reduce the residual stresses to an accepted level.

It is anticipated that the drying models will be incorporated into a kiln control system in order to assist in determining drying endpoint and to develop optimized drying schedules. Kiln operators can use the models to predict effects of new schedules and to examine consequences when drying lumber from a new resource.

References

[1] D.J. Cown, D.L. McConchie, Radiata Pine Wood Properties Survey (1977–1982), FRI Bulletin No. 50, New Zealand Forest Service, 1983.

[2] A.N. Haslett, Drying Radiata Pine in New Zealand, FRI Bulletin No. 206, New Zealand Forest Research Institute Limited, 1998.

[3] S. Pang, High-temperature drying of *Pinus radiata* board in a batch kiln, Ph.D. Thesis, University of Canterbury, New Zealand, 1994.

[4] S. Pang, Relative importance of vapor diffusion and convective flow in modelling of softwood drying, Drying Tech.-An Int. J. 16 (1–2) (1998) 271–281.

[5] S. Pang, Moisture content gradient in a softwood board during drying: simulation from a 2D model and measurement, Wood Sci. Technol. 30 (1996) 165–178.

[6] S. Pang, Development and validation of a kiln-wide model for drying of softwood lumber, in: Proceedings of the Fifth International IUFRO Wood Drying Conference, Quebec, Canada, 1996, pp. 103–110.

[7] S. Pang, Modelling of stress development during drying and relief during steaming in *Pinus radiata* lumber, Drying Tech.-An Int. J. 18 (8) (2000) 1677–1696.

[8] A. Ranta-Maunus, Rheological behavior of wood in directions perpendicular to the grain, Mater. Struct. 26 (1993) 362–369.

[9] J.-G. Salin, Numerical prediction of checking during timber drying and a new mechano-sorptive creep model, Holz als Roh- und Werkstoff 50 (1992) 195–200.

[10] S. Pang, R.B. Keey, J.F.C. Walker, Modelling of the high-temperature drying of mixed sap and heartwood boards, in: Proceedings of the Fourth International IUFRO Wood Drying Conference, Rotorua, New Zealand, 1994, pp. 430–439.

[11] R.E. Booker, J.M. Evans, The effect of drying schedule on the radial permeability of *Pinus radiata*, Holz als Roh- und Werkstoff 52 (1994) 150–156.

[12] R.E. Booker, Changes in transverse wood permeability during the drying of *Dacrydium cupressinum* and *Pinus radiata*, New Zeal. J. For. Sci. 20 (2) (1990) 231–244.

[13] S. Pang, Drying of sapwood, heartwood and mixed sapwood and heartwood boards of *Pinus radiata*, Holz als Roh- und Werkstoff 58 (2000) 363–367.

[14] S. Pang, External heat and mass transfer coefficient for kiln drying of timber, Drying Tech.-An Int. J. 14 (3–4) (1996) 859–871.