

3. MATERIALS AND METHODS

3.1 Overview

Properties of wood vary within a single tree and between trees (Walker, 1993; Pordage and Langrish, 2000; Dinwoodie, 2000; Wimmer, 2000). In addition, anecdotal evidence suggests that the timber properties of *plantation* timber appear to be more variable compared with the properties of *old growth* or *regrowth* timber. Hence, evaluating wood properties is critical to providing information for drying schedules resulting in high quality, dried, and dressed timber. The drying and mechanical properties of timber boards from two age classes, *regrowth* and *plantation* blackbutt logs, have been measured and analysed. *Regrowth* timber is defined as timber taken from a forest stand established by natural regeneration after logging. Natural regeneration can be in the form of seed fall, copice, or lignotuber growth (NSW Department of Primary Industries, 2006). On the other hand, *plantation* timber is taken from a planted forest where tree growth is a result of artificial management practices such as sowing seeds on prepared seedbeds, or planting stock from raised from local, regional or imported sources. The purpose for drying *regrowth* and *plantation* blackbutt timber is to estimate how much variability in the timber properties exists with a single tree, and between a number of trees, for both categories, and to find where the greatest amount of variability is found, whether within trees, between trees at the same location, or between locations. It is also necessary to determine adequate sample sizes, i.e. the total number of boards giving adequate estimates of variabilities in properties *within a single tree* and *between trees*. The location of the sample boards within each tree is also significant for this study. Figures

3.1 and 3.2 show where the sample boards have been obtained along the tree in terms of height, radius, and circumferential locations.

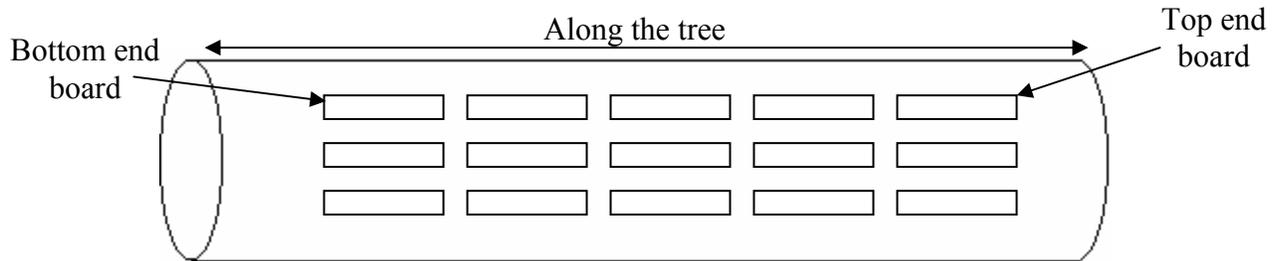


Figure 3.1. Location of sample boards used for height variations.

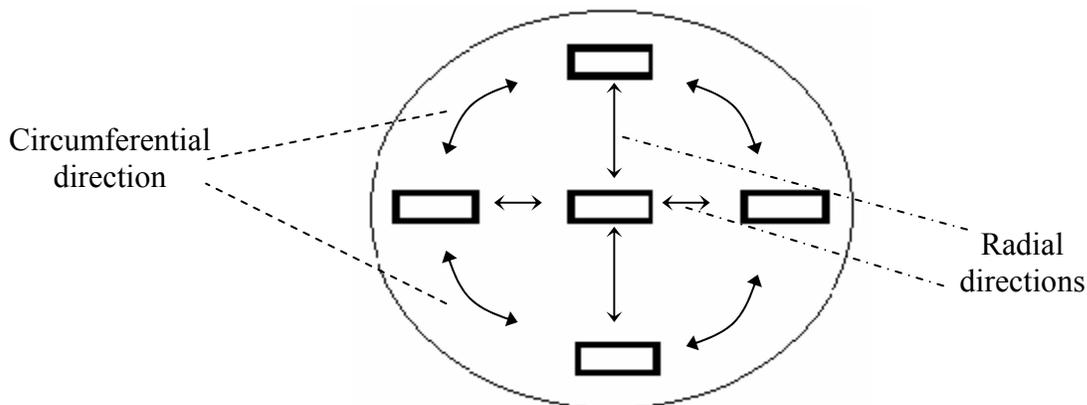


Figure 3.2. Circumferential and radial variations for a cross—section of the log.

The sample sizes chosen for this project were based on previous work that also studied different timber properties before and after drying. Tables 3.1a to 3.1c review the sample sizes that previous workers have chosen to analyse timber properties. Table 3.2 shows the equivalent botanical name of each of the species studied. The sample sizes ranged from one tree to fifty trees, depending on which properties were being studied. For this project, diffusion coefficients have been considered to be a very significant property. However,

other properties such as the initial moisture content, basic density, and mechanical parameters have also been evaluated, since they also affect the drying time and quality (Pordage and Langrish, 2000). Fotsing and Tchagang (2004), Langrish *et al.* (1997), and Innes and Redman (2003) studied boards from one tree each, while Alexiou (1993) used boards from three trees. Their studies focused closely on the behaviour of the diffusion coefficients. The number of boards that other workers took from each tree ranged from three to ten boards and the resulting data from these boards proved to be sufficient for analysis. Thus, to maximize the data taken for this project to estimate the variability of the properties *within* each tree, 18 boards from each of the two *regrowth* blackbutt trees, and 12 boards from each of the two *plantation* blackbutt trees, were studied. On the other hand, to assess the variability of the timber properties *between—trees*, two boards from each of the 12 *regrowth* logs and 10 *plantation* logs, were kiln—dried and evaluated. This figure is similar to the sample size that Bao *et al.* (2001) and Alexiou (1993) chose for their analysis.

It should be noted that Innes and Redman (2003) observed high collapse shrinkage to moisture content around the fibre saturation point for blackbutt. However, collapse was not significant in the blackbutt samples studied in this thesis (this will be discussed further in **Chapter 6**). One possible reason for the difference in the observed collapse shrinkage is the difference in location where the blackbutt boards were taken from. Location is found to be a significant source of variability for blackbutt (**Chapter 6**). It is possible that the blackbutt from the source used by Innes and Redman (2003) was more collapse—prone than the blackbutt samples studied in this thesis.

Table 3.1a. Sample sizes chosen by previous authors analysing timber properties.

Author	Sample Size	Species (Standard Trade Name)	Timber Property/ies Studied	Conclusions
Fotsing and Tchagang (2004)	One tree – nine samples.	Frake	Diffusion coefficients – radial, tangential, and longitudinal.	Longitudinal diffusion coefficient was largest, followed by radial then tangential.
Bao <i>et al.</i> (2001)	15 plantation hardwood trees. Five trees from each species. (Also studied softwoods).	Lemon eucalyptus, Lankao paulownia, and Sanbei poplar	Basic density, shrinkage, radial diffusion coefficients, mechanical properties.	Hardwoods appear to have less difference between juvenile wood and mature wood with regards to timber properties compared with softwoods.
Langrish <i>et al.</i> (1997)	One tree – four boards.	Grey ironbark	Diffusion parameters and mechanical properties.	Fitted diffusion model was used to optimize drying schedules to keep the strain below 0.02 m/m and the surface moisture contents above 7%. The new schedule reduced the number of cracks developed. Mechanical properties of the timber across the grain are a significant requirement for the optimization approach.

Table 3.1b. Sample sizes chosen by previous authors analysing timber properties

(continued).

Author	Sample Size	Species (Standard Trade Name)	Timber Property/ies Studied	Conclusions
Shupe <i>et al.</i> (1995a)	Two trees – 13 disks from each tree.	Yellow poplar	Moisture content and shrinkage.	Green moisture content, tangential shrinkage, and specific gravity of both middlewood and corewood differed significantly between the two trees. Definite property patterns from pith to bark.
Shupe <i>et al.</i> (1995b)	One tree – 13 disks.	Cottonwood	Moisture content and shrinkage.	Sapwood – greater specific gravity, radial and tangential shrinkage compared with heartwood. Heartwood, higher initial MC than sapwood during winter.
Alexiou (1993)	Three trees – two pairs from each tree. Six boards allocated for the control run, and the other six for the pre-steamed run.	Blackbutt	Effect of pre-steaming on drying rate.	Pre-steaming changed the drying rate by -6 to 16%. Pre-steaming possibly mobilized and partially removed heartwood extractives, hence allowing greater access for water molecules to diffuse through cell walls, increasing radial and tangential diffusion.

Table 3.1c. Sample sizes chosen by previous authors analysing timber properties

(continued).

Author	Sample Size	Species (Standard Trade Name)	Timber Property/ies Studied	Conclusions
Evans <i>et al.</i> (2000)	Six trees.	Red alder	Modulus of elasticity (MOE), and specific gravity (SG).	Juvenile wood did not influence the SG of red alder. MOE increased during the early years of growth. MOE in red alder was found to have a mean join point (end of juvenility) of approx. 16 years for the bottom part of the tree, and 10 years for the top section of the tree.
Raymond and Muneri (2001)	Fifty trees of each species.	Blue gum and Shining gum	Basic density.	Six whole-tree samples (disc samples) or eight core samples are required to estimate the average density of a stand at a certain location to give a 95% confidence interval of $\pm 20 \text{ kg.m}^{-3}$.
Innes and Redman (2003)	Ten boards from each species.	Blackbutt, (others: Jarrah, Spotted Gum, Messmate, Mountain Ash, and Alpine Ash)	Green moisture content, density, unconfined shrinkage and diffusion coefficient.	Blackbutt: low diffusion coefficient, $2.64 \times 10^{-11} \text{ m}^2 \text{ s}^{-1}$, and high collapse shrinkage to moisture content around the fibre saturation point.

Table 3.2. Standard trade names and the equivalent botanical names of each of the species studied by previous authors.

Standard Trade Name	Botanical Name
Frake	<i>Terminalia superba</i>
Lemon eucalyptus	<i>Eucalyptus citriodora</i>
Lankao paulownia	<i>Paulownia elongata</i>
Sanbei poplar	<i>Populus nigra</i> × <i>P. simonii</i> cv. “Zhonglin Sanbei – 1”
Grey ironbark	<i>Eucalyptus paniculata</i>
Yellow poplar	<i>Liriodendron tulipifera</i> L.
Cottonwood	<i>Populus deltoids</i> Bartr. ex Marsh.
Blackbutt	<i>Eucalyptus Pilularis</i> Sm.
Red alder	<i>Alnus rubra</i>
Blue gum	<i>Eucalyptus globulus</i>
Shining gum	<i>Eucalyptus nitens</i>
Jarrah	<i>Eucalyptus marginata</i>
Spotted gum	<i>Corymbia maculata</i>
Messmate	<i>Eucalyptus obliqua</i>
Mountain ash	<i>Eucalyptus regnans</i>
Alpine ash	<i>Eucalyptus delegatensis</i>

3.2 Sampling Procedure

14 *regrowth* blackbutt logs and 12 *plantation* blackbutt logs, which were all of commercial size, were felled for this study. The logs were estimated to be 40 years old (except logs 685 and 686, for which the ages of both these logs were unknown) and the diameters at breast height (1.3 m from the bottom of the log) ranged between 31 cms to 51 cms. 36 boards were taken from two *regrowth* logs: log 685 was taken from the Newry Creek region, and log 686 from the Lower Bucca area, while 24 boards were taken from two *plantation* logs, logs 7 and 8 taken from the Wedding Bells/Conglomerate area, to assess *within—tree* variability. Templates were glued to the ends of each of these logs so that, once the boards were sawn, the location of each board within each tree could be determined. Only two boards at breast height (1.5 m from the bottom of the log) were taken from the remaining 12 *regrowth* logs and 10 *plantation* logs, to assess the variation of the timber properties *between trees*. The 12 *regrowth* logs were harvested from the Lower Bucca area, while the 10 *plantation* logs were felled from the Wedding Bells/Conglomerate area. Logs used for the study of the variability of timber properties *within trees* were backsawn into board dimensions of 28 mm thick \times 108 mm wide \times 4.8 m long, and the other 12 *regrowth* logs and 10 *plantation* logs were backsawn into board dimensions of the same thickness and width, but 1.5 m in length. The predicted longitudinal modulus of elasticity for the 4.8 m long boards from logs 685 and 686 was calculated by measuring the acoustic speed using an acoustic tool called Director HM200 (manufactured by Carter Holt Harvey Limited, Auckland, New Zealand). The Director HM200 instrument measures the speed of sound (acoustic speed) from one end of the board to the other. One end of the board is hit with a small hammer, and the speed of

sound is derived from the resonance speed found from the reflections at the end of the timber board. The 4.8 m and 1.5 m long boards were further divided into 900 mm length boards. The 900 mm length boards were end-sealed with silicone and covered with aluminum foil to prevent longitudinal drying.

To measure the variability *within trees*, boards were taken from different locations within each log, as shown in Figures 3.3 and 3.4 for the *regrowth* blackbutt logs. The boards for the *plantation within—tree* analysis were also taken from similar locations within each of the two *plantation* logs (Figures 3.5 and 3.6). Each ‘A’ board (from the bottom end of the log) has its corresponding ‘E’ board that was taken from the top end of each log. In addition, one board was taken close to the pith, and a second board was taken from the outer heartwood at breast height from each of the 12 *regrowth* logs and 10 *plantation* logs (*between—trees*). A 20 mm thick sample was taken from each end of every green board to calculate its corresponding initial moisture content using the oven—dry method, and the basic density. Basic density is the oven—dried weight/green volume. The sample dimensions were measured to give the green volume. Each 20 mm sample was oven dried at a temperature of 105°C for seven days. Another 30—50 mm sample was cut and wrapped in polythene film to test mechanical properties, such as the modulus of elasticity. Figures 3.7 to 3.9 show the lengthwise layout of how the samples were cut from each of the 4.8 m, 900 mm, and 1.5 m long boards.

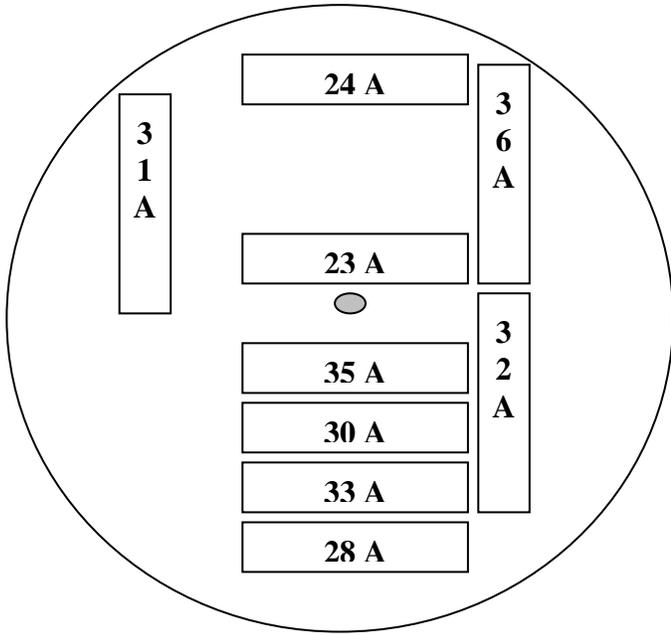


Figure 3.3. Cross-section of the bottom end of log 685, showing where each ‘A’ board was taken.

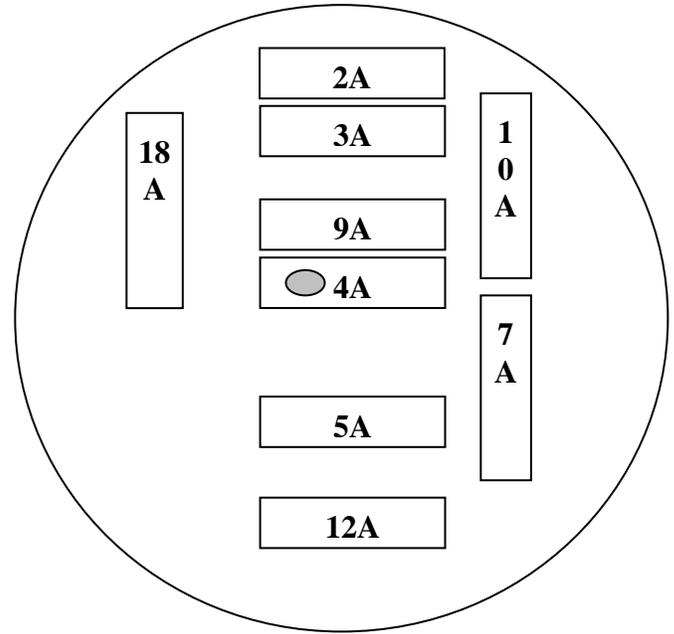


Figure 3.4. Cross-section of the bottom end of log 686, showing where each ‘A’ board was taken.

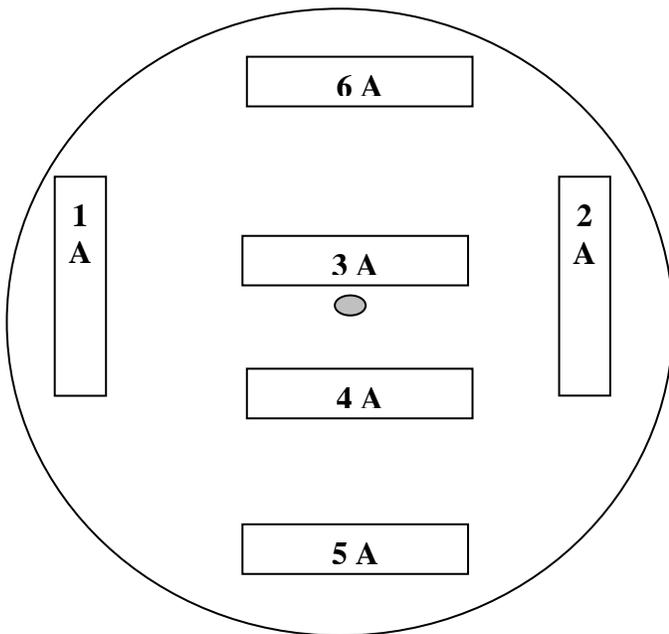


Figure 3.5. Cross-section of the bottom end of log 8, showing where each ‘A’ board was taken.

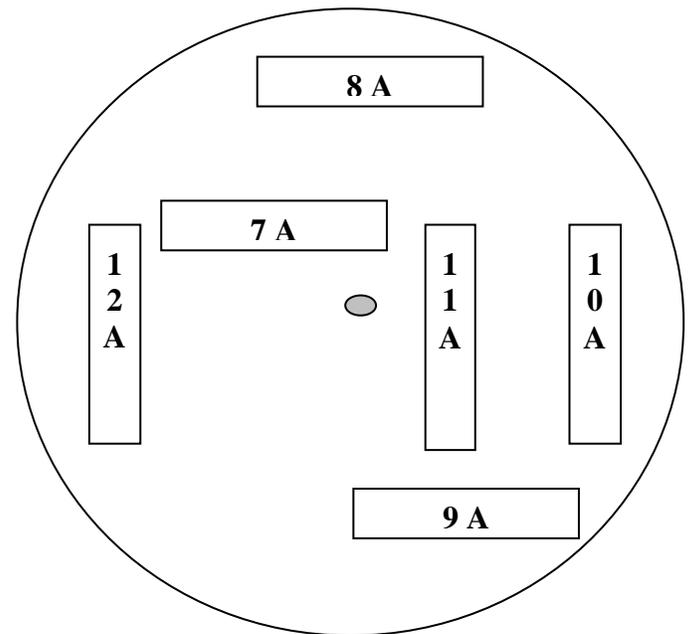


Figure 3.6. Cross-section of the bottom end of log 7, showing where each ‘A’ board was taken.

Table 3.3. Drying schedule used for all experiments (Mills, 1991).

Day to Carry Out Change Point	0	5	8	10	12	15
Estimated Moisture Content at Change Points (%)	Green	40	30	25	20	15 to final (usually 12)
Dry Bulb Temperature (°C)	55	60	65	65	70	70
Wet Bulb Depression (°C)	3	4	5	8	10	15

Furthermore, 25 mm × 25 mm × 100 mm samples were also cut from a position after the ‘A’ board (‘BH’ – breast height board) and before the ‘E’ board (‘D’), both lengthwise (Figure 3.7), for the *within—tree* variability assessment of both *regrowth* and *plantation* blackbutt. A sample with the same dimensions was taken from both the 1.5 m *regrowth* and *plantation* boards to analyse the variation *between—trees* (Figure 3.9). Tangential and radial shrinkages were measured from these samples, from green moisture content to 12% moisture content, using the HEIDENHAIN apparatus (manufactured by Dr. Johannes Heidenhain GmbH, Germany) located in the Forests NSW Research and Development laboratory at West Pennant Hills. The shrinkage measuring apparatus consists of two Heidenhain-Metro MT10 digital gauges with +/-1 micron accuracy, and a Heidenhain-Metro Difference Counter VRZ104 unit mounted on a steel jig. The remaining board length was kiln dried in a drying tunnel, using the conventional drying schedule published in the Australian Timber Seasoning manual (Mills, 1991) suited for mixed sawn blackbutt boards, 25 mm in thickness, shown in Table 3.3. The boards were left to dry in the drying tunnel, stacked on top of each other, separated by stickers, with the changes in the schedule based on the number of days. Each experiment took 21 days to run.

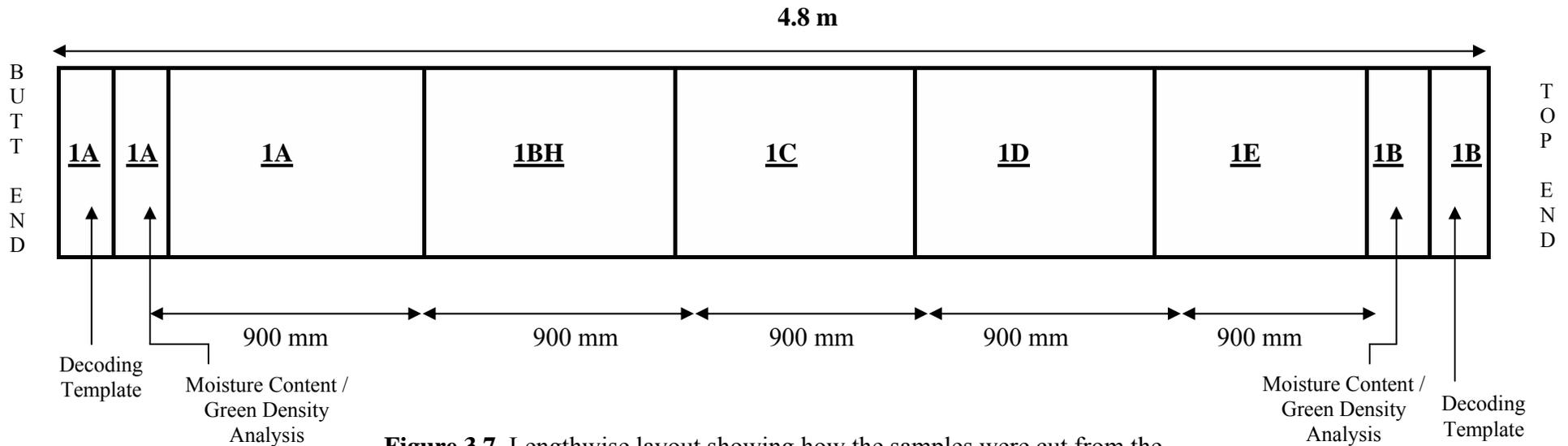


Figure 3.7. Lengthwise layout showing how the samples were cut from the 4.8 m long board.

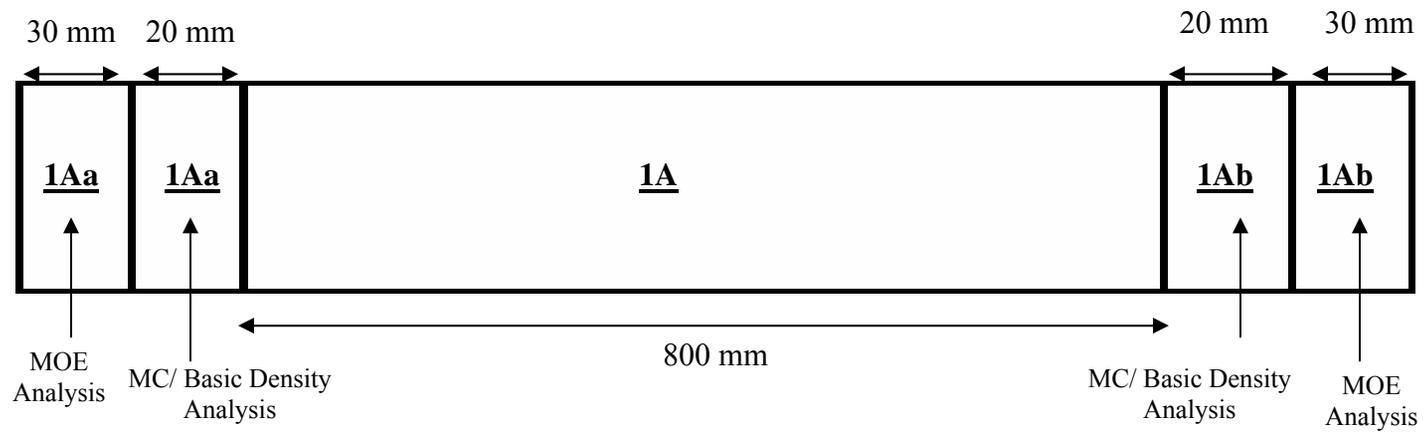


Figure 3.8. Lengthwise layout showing how the samples were cut from the 900 mm long board.

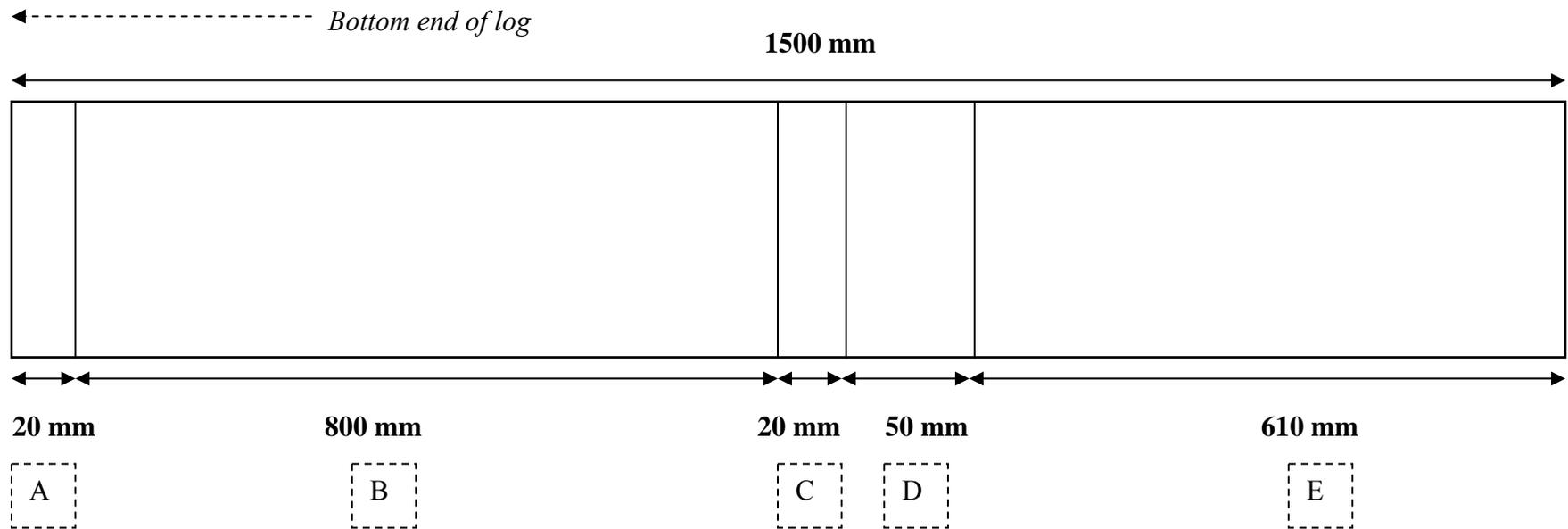


Figure 3.9. Lengthwise layout showing how the samples were cut from the 1.5 m long boards. Samples A and C were used to calculate the initial moisture content of the board; sample B was the board for kiln-drying; sample D was used to determine the board's modulus of elasticity, and the shrinkage sample was taken from sample E.

The final moisture contents were calculated by cutting another 20 mm sample from each board at the end of the drying process, and repeating an oven—dry test. The actual moisture contents of each board were calculated from daily weighing of the individual boards. The order of the boards was rotated within the stack on a daily basis to minimise stacking effects on drying. Further samples, 30 mm in width, were cut from the kiln—dried boards to test for the mechanical properties after drying. A milling machine was used to cut the samples (both green and kiln—dried) into ‘dog bone’ profiles. The ‘dog bone’ samples properties were necked down to a width of 5 mm over a 30 mm gauge length, as shown in Figure 3.10. An INSTRON 5567 testing machine (manufactured by INSTRON, Pennsylvania, USA) that was equipped with a 1 kN load cell, and located in the School of Aerospace, Mechanical and Mechatronic Engineering, University of Sydney, was used to measure the sample’s stress (MPa) and strain (mm/mm) values (Haque, 2002). Thereafter, the modulus of elasticity was calculated from the stress—strain curves.

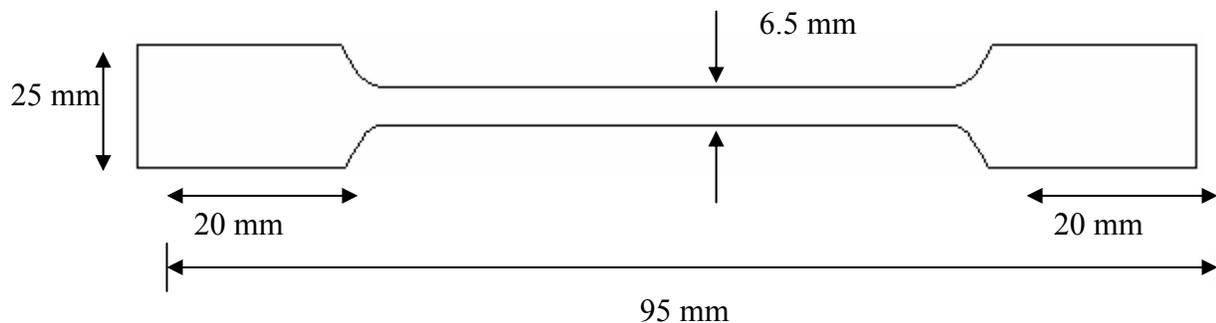


Figure 3.10. ‘Dog bone’ shape for stress-strain analysis.

3.3 Calculating the Diffusion Coefficients

3.3.1 Relevant Theory: Drying Model

Following the literature discussed in Chapter 2.2.4, a more detailed explanation of the drying model is presented next. The diffusion coefficient was fitted using a drying model that has been validated in previous work. As mentioned in Chapter 2.2.4, the diffusion of moisture across the grain was a significant timber property for this drying study. The predicted overall drying curve is dependent on the diffusion coefficients and operating temperatures for each experiment (Langrish *et al.*, 1997). The model is based on solving Fick's Second Law of diffusion for mass transfer, Equation (2.4), and Fourier's Law for heat transfer, Equation (3.1).

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left(\frac{\lambda}{\rho C_p} \frac{\partial T}{\partial z} \right) \quad (3.1)$$

Pordage and Langrish (1999) show that the practical consequence of solving this equation under many typical drying conditions for hardwoods is that the timber has a virtually uniform temperature at most drying times during this process.

Moisture is assumed to diffuse through the timber and evaporate near the surface. It is often difficult to measure the diffusion coefficient directly, but it can be fitted to experimental data, as here. Schaffner (1981) and Wu (1989) both successfully fitted diffusion coefficients to observed data for eucalypt timbers. Therefore, in this work, least-squares parameter fitting was used to adjust the values of the reference diffusion coefficient, D_r , and the activation energy, D_E , in a temperature dependent Arrhenius—

type equation (Langrish *et al.*, 1997), Equation (2.5). D_E , in units of Kelvin, represents the E/R part of the exponent term (where E is the activation energy in J/mol, and R is the gas constant, 8.314 J/mol.K) since it represents the temperature dependence of moisture diffusion (Keey *et al.*, 2000). Equations (2.4) and (3.1) are solved simultaneously, since the diffusion coefficient, D , is dependent on temperature, and the heat capacity, C_P , the thermal conductivity, λ , and the density, ρ , are functions of moisture content and temperature (Langrish *et al.*, 1997).

There are boundary conditions to Equations (2.4) and (3.1). The mass flux of water from the timber surface, J , is proportional to the difference between the humidity in the bulk air, Y_G , and the gas humidity just above the surface of the timber, Y_S . This relationship is represented by Equation (3.2).

$$J = \rho_{air} k_m (Y_S - Y_G) \quad (3.2)$$

The humidity of the bulk air, Y_G , can be calculated from the dry and wet—bulb temperatures (T_G , T_W) in the kiln. In addition, the surface humidity, Y_S , is a function of the moisture content at the surface of the timber, X_S (Wu, 1989). Hence, Equation (3.2) forms a boundary condition for Equation (2.4).

Both convective heat transport and the transfer of heat associated with moisture evaporation at the surface of the board must be considered:

$$Q = h_F(T_G - T_S) - (\lambda_W + \lambda_S)J \quad (3.3)$$

Equation (3.3) forms a boundary condition for Equation (3.1). The specification of the heat flux to the board involves the implicit assumption that the moisture evaporates close to surface of the board. Equation (3.1) would be modified to account for internal evaporation if this internal evaporation occurred.

The moisture and temperature profiles may be symmetric about the centre of the timber board if the assumption that the rates of heat and mass transfer are the same at the upper and lower surfaces of the board is true, and the properties of the board are also symmetric about the center. Therefore, another two boundary conditions, Equations (3.4) and (3.5), are defined.

$$\left. \frac{dX}{dz} \right|_{centre} = 0 \quad (3.4)$$

$$\left. \frac{dT}{dz} \right|_{centre} = 0 \quad (3.5)$$

The temperature and moisture gradients may be approximated using finite differences (Wan and Langrish, 1995). Then the drying model, applicable at the surface, within the timber board, and at the center of the board, reduces to a “stiff” system of ordinary differential equations (Langrish *et al.*, 1997).

Surface of the timber board

$$\frac{dX_s}{dt} = \frac{1}{\Delta z_s} \left[\frac{D(X_1 - X_s)}{\Delta z_s} - J \right] \quad (3.6)$$

$$\frac{dT_s}{dt} = \frac{1}{\Delta z_s \rho c_p} \left[\frac{k(T_1 - T_s)}{\Delta z_s} + Q \right] \quad (3.7)$$

Within the timber board

$$\frac{dX_i}{dt} = \frac{D}{\Delta z} \left[\frac{X_{i+1} - X_i}{\Delta z} - \frac{X_i - X_{i-1}}{\Delta z} \right] \quad (3.8)$$

$$\frac{dT_i}{dt} = \frac{k}{\Delta z \rho c_p} \left[\frac{T_{i+1} - T_i}{\Delta z} - \frac{T_i - T_{i-1}}{\Delta z} \right] \quad (3.9)$$

Centre of timber board

$$\frac{dX_c}{dt} = \frac{-D}{\Delta z_c} \left[\frac{X_c - X_{c-1}}{\Delta z_c} \right] \quad (3.10)$$

$$\frac{dT_c}{dt} = \frac{-k}{\Delta z_c \rho c_p} \left[\frac{T_c - T_{c-1}}{\Delta z_c} \right] \quad (3.11)$$

A system of 34 differential equations, (i.e. two describing conditions for the surface and another two for the centre, and 30 within the board), result from the division of the board into 17 elements. 17 elements have been found to be adequate in previous work (Haque, 2002). This can be easily solved using an integrator appropriate for “stiff” systems, such as Gear’s method. This model has been used here to fit the diffusion coefficients to actual

experimental data for the changes in moisture content as functions of time for drying different boards of blackbutt timber.

3.3.2 Fitting Procedure for the Diffusion Coefficients

The parameter fitting procedure minimizes the sum of squares for the differences between the predicted and actual average moisture contents for each board. Bramhall (1979) defined the activation energy as the sum of the heat of sorption and the latent heat of vaporization. However, Keey *et al.* (2000) reports that most values for the activation energy range between 23 to 43 kJ/mol (2800—5200 K), which is lower than the heat of vaporization for water (45 kJ/mol). Keey *et al.* (2000) suggests that it is possible that some kind of surface diffusion occurs for the bound water molecules as they move through the timber, rather than the vaporization of moisture. Therefore, the value of D_E used in this simulation was 3800 K, because it was used by Wu (1989) and Schaffner (1981) in their simulations of Tasmanian eucalypts. In addition, Haque (2002) used the value of 3800 K for D_E for his drying simulation of blackbutt, which is the same species studied in this report. A typical initial value for D_r was $0.6 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ in the fitting procedure. The final fitted value of D_r did not depend significantly on the initial value. Changing the initial value of D_r from $0.6 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ to $1.15 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ altered the final fitted value by less than 2%. This suggests that the final fitted values were unique to each board, despite what initial value of D_r was used. The recorded moisture contents that were measured throughout the drying process, and the dry and wet bulb temperatures, depended on each board and each experiment. The fitted initial moisture content was set equal to the actual initial moisture content. Fick's Second Law of diffusion for mass

transfer, Equation (2.4), and the conduction equation for heat transfer, Equation (3.1), were then solved simultaneously, with convective boundary conditions at the board surfaces and symmetry at the centerline of each board. Overall, the final adjusted value of D_r characterized the drying behaviour of the corresponding timber board.

The heat—transfer coefficient, h_F , is a function of the air velocity, the physical properties of air (Hewitt *et al.*, 1994), and the system geometry, which in this case is a timber sample. Firstly, the heat—transfer coefficient was calculated using equations and correlations for Reynolds and Nusselt numbers (Keey, 1992). A sample calculation is shown here.

Streamed length (width of sample), $L = 0.108$ m;

Kinematic viscosity of air, $\nu = 1.6 \times 10^{-5} \text{ m}^2\text{s}^{-1}$ at 300 K (Hewitt *et al.*, 1994);

Thermal conductivity of air, $\lambda = 0.026 \text{ Wm}^{-1}\text{K}^{-1}$ at 300 K (Hewitt *et al.*, 1994);

Air velocity through and around the boards (from the fan), $u = 1.3$ m/s.

Reynolds number, Re_L , based on streamed length, Equation (3.12):

$$\begin{aligned} \text{Re}_L &= \frac{Lu}{\nu} & (3.12) \\ &= \frac{(0.108\text{m})(1.3\text{ m/s})}{1.6 \times 10^{-5} \text{ m}^2\text{s}^{-1}} \\ &= 8775 \end{aligned}$$

For $100 < \text{Re}_L (=8775) < 10^5$, Keey (1992) gives Equation (3.13) for the Nusselt number,

Nu_L .

$$\begin{aligned}
 Nu_L &= 0.6 \text{Re}_L^{0.5} = \frac{h_F L}{\lambda} & (3.13) \\
 \therefore h_F &= \frac{0.6 \times \text{Re}_L^{0.5} \times \lambda}{L} \\
 &= \frac{0.6 \times (8775)^{0.5} \times 0.026 \text{Wm}^{-1} \text{K}^{-1}}{0.108 \text{m}} \\
 &= 13.5 \text{Wm}^{-2} \text{K}^{-1} \\
 &\approx 14 \text{Wm}^{-2} \text{K}^{-1}
 \end{aligned}$$

The heat—transfer coefficient, h_F , is therefore predicted to be $14 \text{Wm}^{-2}\text{K}^{-1}$ for these conditions. Some trial simulations, where the heat—transfer coefficient was fitted to the experimental data, were also conducted. The value of $h_F = 16 \text{Wm}^{-2}\text{K}^{-1}$ produced a slightly better fit, compared with the fitting procedure that used $14 \text{Wm}^{-2}\text{K}^{-1}$. Using the properties of a random board, board 1E (*plantation timber*), the fitting that used a value of $16 \text{Wm}^{-2}\text{K}^{-1}$ for h_F gave a standard error of 0.006 kg/kg, while the fitting that used $14 \text{Wm}^{-2}\text{K}^{-1}$ gave a standard error of 0.009 kg/kg. In addition, the difference in the resulting D_r 's was less than 2%. Hence, using $16 \text{Wm}^{-2}\text{K}^{-1}$ for the heat—transfer coefficient fits the experimental data slightly better than a value of $14 \text{Wm}^{-2}\text{K}^{-1}$, and the sensitivity of the fitted diffusion parameters to the heat—transfer coefficient is small. The value of $16 \text{Wm}^{-2}\text{K}^{-1}$ for h_F was then subsequently used for the parameter fitting of all the timber boards, since all the velocities and board geometries were the same.

The heat—transfer coefficient can be related to the mass—transfer coefficient, k_m (m/s), using the Chilton—Colburn analogy between heat and mass transfer, i.e. the heat—transfer coefficient is proportional to the mass—transfer coefficient and vice versa (Hewitt *et al.*, 1994). Equation (3.14) shows the relationship between the Nusselt,

Prandtl, Sherwood and Schmidt numbers, as shown in Equations (3.14) to (3.17) (Hewitt *et al.*, 1994).

$$NuPr^{-1/3} = ShSc^{-1/3} \quad (3.14)$$

where

$$Pr = \frac{\nu}{\kappa}, \quad (3.15)$$

$$Sh = \frac{k_m L}{D_{12}}, \quad (3.16)$$

$$Sc = \frac{\nu}{D_{12}} \quad (3.17)$$

ν is the kinematic viscosity (m^2/s), κ is the thermal diffusivity (m^2/s), k_m is the mass transfer coefficient (m/s), and D_{12} is the diffusivity (m^2/s). While the parameters D_r and D_E are fitted to the data, for comparison between different experiments, an average temperature, T , of 333.15 K was used for calculating the average diffusion coefficient, in Equation (2.5), because it reflects the average temperature of each board during the drying process. This value for T was based on the average of all the dry—bulb temperatures, shown in Table 3.3, during the drying experiments.

The standard error is a measure of the difference between the predicted and the experimental moisture contents. The standard error for each timber board was calculated using Equation (3.18):

$$\text{Standard Error} = \sqrt{\frac{\sum_{i=1}^n \text{Weight}_i [(X_{Exp_i} - X_{Pred_i})^2]}{n-1}} \quad (3.18)$$

An average of 15 experimental data points was present from each experiment. Excluding the first experimental data point, the weights were allocated values of unity. The moisture contents were calculated for exactly the same samples used in the drying tests, the whole sample board. The first experimental data point, i.e. the actual initial moisture content, was assigned half the weighting of the other actual moisture contents (0.5). Here, the initial moisture content was estimated from a biscuit sample, a small piece of timber cut from the end of the board. The lower weighting for this initial moisture content reflects the additional uncertainty in the extent to which the biscuit sample represented the moisture content of the rest of the board. A sensitivity test was carried out by allocating the weighting of the initial moisture content a value of unity. The result is that the final adjusted parameters, D_r and D_E , did not change significantly (< 1%), but it is considered that giving the first data point a lower weighting is a physically meaningful and reasonable procedure.

3.3.3 Relevant Theory: Stress/Strain Model

During drying, a moisture content gradient develops between the drier outer part of the timber board and the wetter core (or inner part) of the board. This then leads to uneven shrinkage of the timber from the centre to the surface of the board. Under these circumstances, a variation in shrinkage results in differential stresses right through the board. Shrinkage at the surface of the timber leads to tensile stress, which can then result

in surface checking or cracking, distortion, and end splits. A simple stress/strain model may be used to represent this movement within timber during drying and to understand the critical mechanical properties for drying studies. There can also be considerable moisture evaporation from the exposed end grain of unsealed timber. However, for this work, the timber boards were end-sealed so that most of the moisture movement would occur across the grain rather than along the grain.

Free unrestrained shrinkage for each layer, i , in the board, can be estimated by a linear relationship below the fibre saturation point between the moisture content in the layer and the moisture content at fibre saturation (Johnson, 1989), shown in Equation (3.19). It should be noted that M_i is a difference in moisture content in kg/kg, i.e. $M_i = X_{fsp} - \min(X_i, X_{fsp})$. X_i is the moisture content of layer i .

$$\zeta_i = \beta M_i \quad (3.19)$$

The stress to keep the layer at its original length, σ , is then calculated using Hooke's law, along with a moisture and temperature dependent Young's modulus, E_i :

$$\sigma_i = E_i \beta M_i \quad (3.20)$$

Since timber boards tend to keep their original shapes, but not sizes, as shrinkage occurs, none of the layers can move independently. Hence, the internal forces must be calculated in relation to the average shrinkage, ζ_{ave} , of the whole board (Langrish *et al.*, 1997). The sum of the internal forces must be zero, represented by Equation (3.21):

$$\int_{thick} E_i (\zeta_{ave} - \beta M_i) \Delta x_i = 0 \quad (3.21)$$

From Equation (3.21), the average shrinkage, ζ_{ave} , is calculated as:

$$\zeta_{ave} = \frac{\int_{thick} E_i \beta M_i \Delta x_i}{\int_{thick} E_i \Delta x_i} \quad (3.22)$$

On the other hand, the strain imposed on each layer to keep it at the same length as the timber board may be estimated as:

$$\varepsilon_i = \zeta_{ave} - \beta M_i \quad (3.23)$$

This physical picture is shown in Figure 3.11. This stress/strain model only takes into account shrinkage and elastic effects, omitting viscoelastic and mechano-sorptive strains. Salin (1992) and Brooke (1999) justified the use of this simple model since it gave adequate predictions of stresses and strains for their work in terms of cracking. In addition, Salin (1992) found that the uncertainty in an overall stress/strain model due to lack of data for viscoelastic and mechano-sorptive strain components created significant further uncertainty for predicting how much timber value is lost due to cracking. Overall, the use of the simple stress/strain model proved useful in the work of Salin (1992) and Brooke (1999).

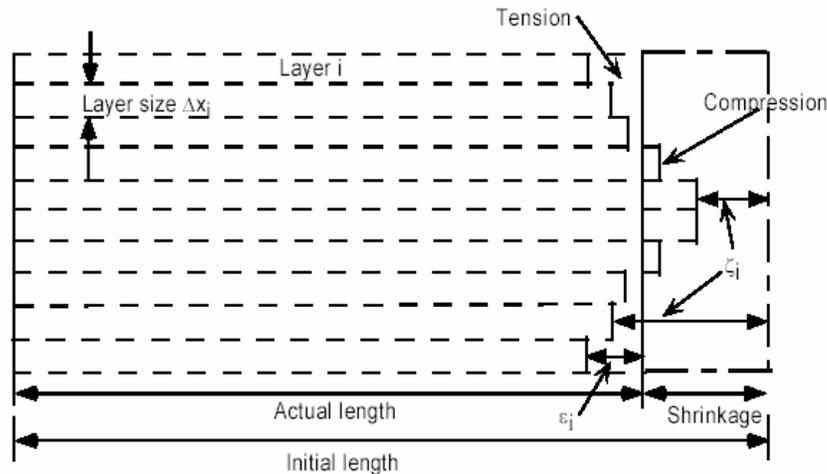


Figure 3.11. Stress-strain development during timber drying (Haque, 2002).

3.4 Drying Tunnel

Figure 3.12 shows the overall design of the pilot—scale batch dryer used for drying 800 mm long timber boards. This conventional kiln was used to produce controlled drying conditions with initial dry—bulb and wet—bulb temperatures of 55°C and 52°C, respectively, and an air velocity of 1.30 m/s around the boards. Manipulating the steam flowrate to a steam-injection system was used to control the wet—bulb temperature at its desired setpoint. The steam system consisted of a droplet removal system and six-point steam injection pipe over a 300 mm duct. The control mechanism for the dry—bulb temperature involved the flowrate adjustment of 100 kPa (gauge) steam to a finned heat exchanger using a control valve. An overall mean of the average moisture contents for each board was then used to determine if the set points of the dry—bulb and wet—bulb temperatures had to be altered, according to the drying schedule shown in Table 3.3. Overall, each experiment used the same change over times.

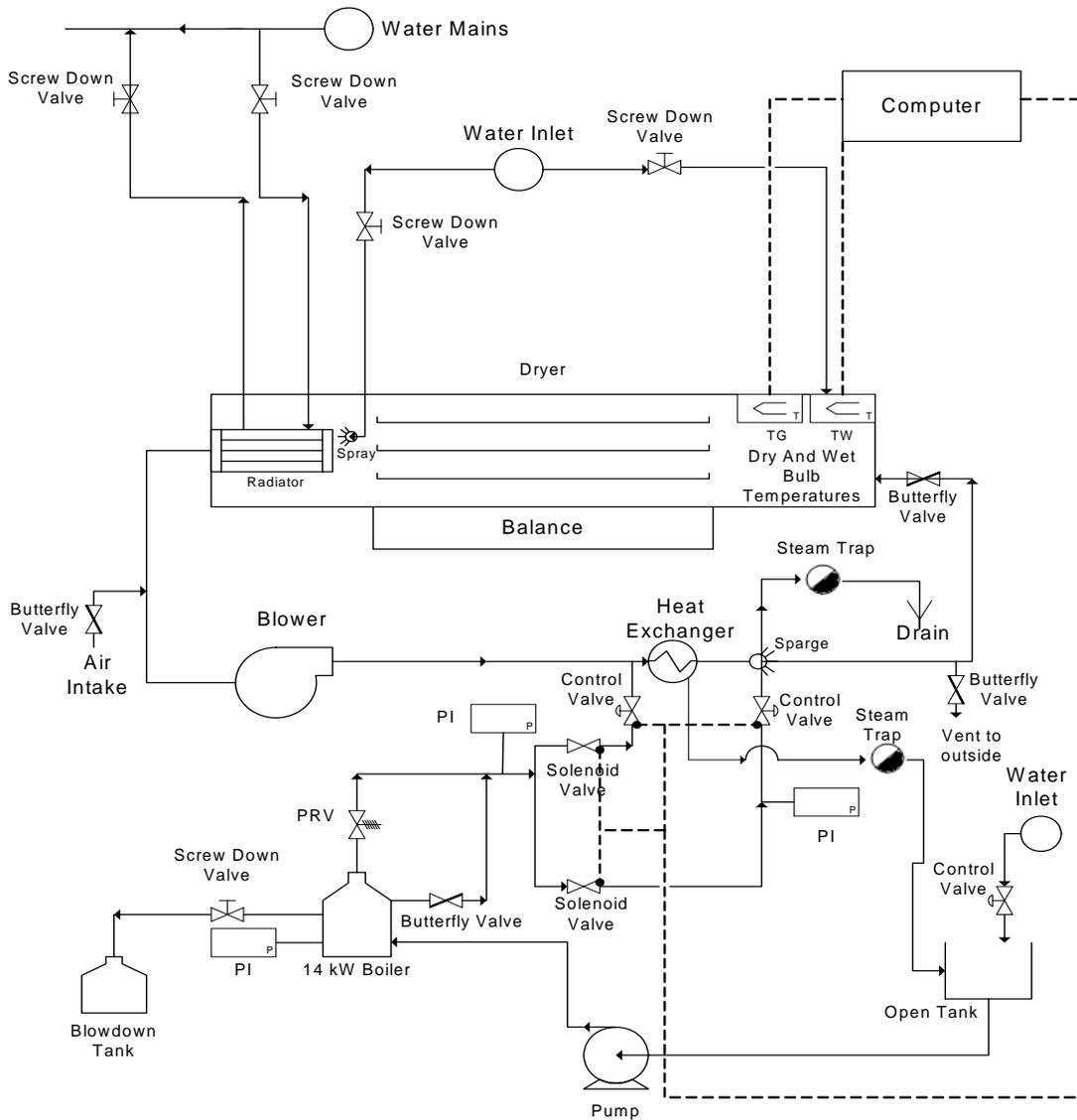


Figure 3.12. Schematic diagram of the timber drying tunnel.

3.5 Modulus of Elasticity

Tensile tests have been conducted rather than three—point bending tests to measure the modulus of elasticity perpendicular to the grain of the green and the dried timber samples. Tensile tests have the disadvantage that they are very sensitive to small imperfections in the wood, which sometimes makes three-point bending tests preferable. Despite this,

tensile tests have been used in previous work (Brooke, 1999; Haque, 2002; Jönsson and Thelandersson, 2003) because they are simple, cheaper, and fully standardized (Cornell Center for Materials Research, 2005), and this test involves a simple tensile stress field inside the specimens. The work of Evans *et al.* (2000) preferred to use three—point static bending due to the lower sensitivity to small imperfections in the timber, an advantage of this method. A disadvantage of the three—point static bending test is that it places the timber in both tension and compression. Therefore, the average of the tensile and compressive properties is measured, rather than just the how the timber performs in tension, which is most relevant to the cracking of wood in timber drying.

‘Dog bone’ samples were unwrapped from their protective plastic just before testing to prevent significant moisture loss from the green samples. The dried ‘dog bone’ samples did not require wrapping and were tested as cut. The recorded testing room temperature was 20°C. The bottom grip of the INSTRON 5567 was fastened to hold the sample in place, and the top grip, before tightening it by hand, was positioned by lowering the moveable crosshead enough to hold the top end of the specimen. For every test, a zero load condition was applied by pressing the appropriate button located on the INSTRON 5567 testing machine. Thereafter, the clip—on extensometer was fastened to the sample by holding the two finger joints together, to settle the cup—and—cone arrangement into its set gauge length of 23.62 mm. The clip gauge was maintained at a zero reading (zero extension) despite the clip gauge being attached to the sample. This was achieved by the clip gauge being held in place by a knife—edge and clip that fitted on each side of the sample. The gauge was zeroed, with it in place, using the calibration button on the

control panel, to ensure that both the extensometer and the load cell were zeroed at the beginning of each test. The gauge length of the moveable crosshead was also reset, allowing it to return to its initial position at the end of each run.

The data logger started its measurements of parameters, such as time (seconds), load (N) from the load cell, and strain (%) from the clip gauge, once the instruments had been zeroed. Once the values from the clip gauge and the load cell stabilized, the test was initiated with the crosshead starting to move upwards. The strain rate applied was 2 mm/min, close to the accepted strain rate value of 2.5 mm/min listed in the ASTM Standard Designation: D 143—83 (section 107) method of testing for specimens across (perpendicular) to the grain. The test ended when the specimen broke, which was easily noticed and heard. The INSTRON 5567 was reset, the specimen taken out, and the data logger halted until the next test was initiated, following the same procedure. Thereafter, the broken specimens were re-wrapped for moisture content determination, using the oven—drying method.

3.6 Shrinkage

There are a variety of ways that shrinkage measurements for timber have been conducted in the past. Poku *et al.* (2001) measured the dimensions of the samples that were soaked for 72 hours in water, and then the dimensions of the same samples after being oven—dried for 48 hours. From these measurements, Poku *et al.* (2001) calculated the radial and tangential shrinkages of these samples based on the dimensions that were measured at soaked and oven—dried conditions. Likewise, Shupe *et al.* (1995a, 1995b) simply

measured the dimensions of the timber disks from swollen conditions to oven—dry conditions using a digital caliper. For this project, rectangular blocks of timber were used, as cut from the boards, rather than disks. The method applied to measure shrinkage was the one described in the work of Kingston and Risdon (1961) for their study of Australian and other woods using specimens with dimensions 25 mm × 25 mm × 100 mm. In addition, since blackbutt is a type of Australian timber, this method was chosen due to the fact that all shrinkage figures for Australian timbers published in Bootle (1983) are based on this procedure.

Three points were marked along the four longitudinal faces of each shrinkage sample, as shown in Figure 3.13. Each shrinkage sample was placed between the two digital gauge heads and measured at each point. Tangential and then radial shrinkages were measured for each sample between the green moisture content and the air—dried condition at 12% moisture content. Figure 3.14 shows the directions in which the tangential and radial shrinkages were measured.

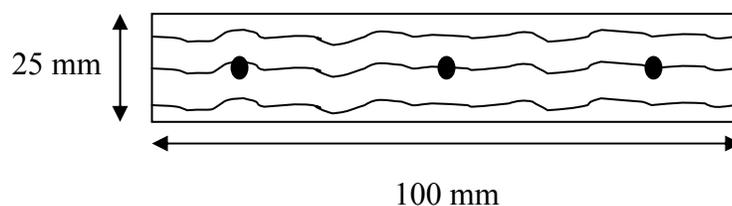


Figure 3.13. Shrinkage sample (top view) showing three points marked on one of the longitudinal faces. Three points were also marked on the remaining three longitudinal faces.

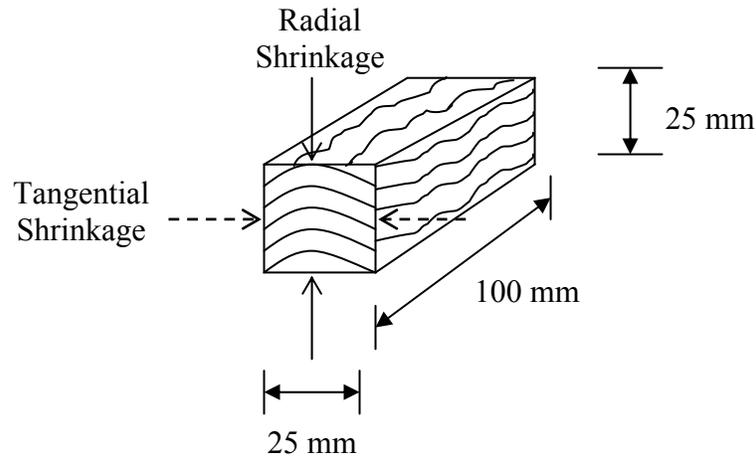


Figure 3.14. Direction showing how the gauge heads were positioned to measure tangential and radial shrinkages.

3.7 Conclusions

The properties of two *regrowth* blackbutt logs (36 boards) and two *plantation* blackbutt logs (24 boards), have been measured and analysed for the *within—tree* variation of timber properties. In a separate set of experiments, two boards were taken from each log, from a total of 12 *regrowth* logs and 10 *plantation* logs, to study the *between—tree* variability of the timber properties of blackbutt timber. The sample size chosen for each assessment was based on the sample size used in previous work that has studied timber properties *within* and *between trees*, given the desirability of using the largest sample sizes possible for the best statistical estimates of variability, while maintaining a realistic time frame for this project. After measuring the timber properties for *regrowth* and *plantation* blackbutt timber, the variability of these properties *within* and *between trees* has been quantified in the following chapters, and analysed to assess if a correlation

exists between the physical (initial moisture content, basic density), the transport (diffusion coefficient), and the mechanical properties (modulus of elasticity, shrinkage).