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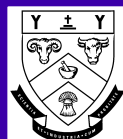
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# Nature of Knot Checks Developed During Seasoning of Radiata Pine Sawn Boards

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## ABSTRACT

One hundred and sixty radiata pine boards were dried using different methods (air drying, commercial kiln drying and laboratory kiln drying) to study the effect of knot, wood and seasoning variables on the nature of knot checking. Among the knot variables, the largest knot group (diameter >75 mm) was found associated with the highest check rate and the most severe checks. Medium size group (25 mm < diameter ≤ 75 mm) had significantly lower check rate. Face knots were significantly more liable to cracking than any type else. The major check directions of a knot generally ran across the symmetrical axes of the knot. In wood variables, due to lower number of medium size knots butt half had higher check rate than upper part of stem. After studying the density and check ratio of northern outer wood, southern outer wood and core wood, a reverse relation was found between the density and the check ratio. Final moisture content affected knot checking directly because it is proportional to shrinkage. Temperature did not show significant influence. Air dried timbers, especially those exposed to air without shield, had more severe checks than those exposed to other drying conditions. There were no relationships found among sawn pattern, dimensions of boards and check rate of knots.

Keywords: knots, checking, seasoning, temperature, shrinkage, stress, strength, radiata pine.

## INTRODUCTION

Knots have long been recognised as the most weakening factor of wood strength. The discontinuity of physical properties in the knotty area results in severe stress concentration during seasoning leading to initiation of cracks. Knot checks are generally present in structural boards and will propagate in later processes or in service. They may induce serious degradation and later fatigue failure (Bodig and Jayne, 1982; ASTM Standards for Testing and Material, 1974; Cramer and Goodman, 1982). Williamson (1982) studied the bending strength of knotty radiata boards and knots were found to be the major cause of strength variation. Grant et al. (1984) also conducted a similar study to predict modulus of rupture of radiata pine. A reassessment of grading rules was proposed after the study of Williamson (1982) and Grant et al. (1984).

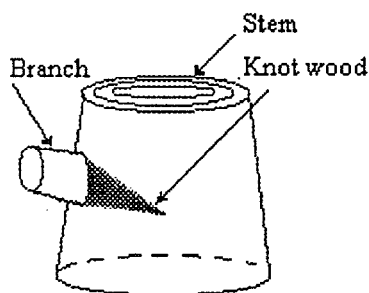
Radiata pine boards constitute more than 90% of the sawn timber in New Zealand and most of the radiata pine boards contain knots. Fenton (1967) recorded the diameter of the largest intergrown knot in each of his 299 radiata pine logs and found that the average of diameters of the largest intergrown knots was 67.5 mm. The knots of radiata pine sawn timber are comparatively larger than those generally found in other species. Moreover, grading rules allow knot diameter up to one-fourth the width in Grade 1 boards and 66% of the width in Grade 5 boards (New Zealand Ministry of Forestry, 1995). Because larger knots may produce more severe surface checks, knot checking of radiata pine sawn boards could be very serious and is the most common form of degradation (Kinimonth,1961). Material discontinuity caused by knot checking and associated grain deviation in knotty area has a dominant influence on mechanical properties of wood. Therefore, check initiation and the characteristics of knot checks can be regarded as considerably important.

### **OBJECTIVES AND SCOPE OF STUDY**

The objective of this research is to explore the drying behaviour of knots and the characteristics of knot checking in sawn radiata pine boards during seasoning. The main focus of this research is to investigate checking of intergrown knots as encased knots do not check during seasoning.

### **NATURE OF KNOTS**

The base of a branch embedded in the stem of a living tree is called knot wood. This forms the knot after being sawn. Cambia of knot wood grow inside the stem while the branch is alive and form an intergrown knot; which is also called a tight or red knot in literature. If the branch dies for some reason, then knot growth stops. This results in an encased knot. Clustered branches can result in knot groupings on a sawn board if the branches are closely located.



**Figure 1. knot wood in a stem**

The anatomical structure of a branch is similar to that of the stem and the knot wood appears like an elliptic cone with its vertex at the pith of tree stem (Beijing Forest University, 1982;

Kininmonth and Whitehouse, 1991). The knot wood remains in sawn boards present different shapes depending upon the cutting angle, which is defined as the angle of cutting plane to the symmetric axis of knot wood (Figure 2).

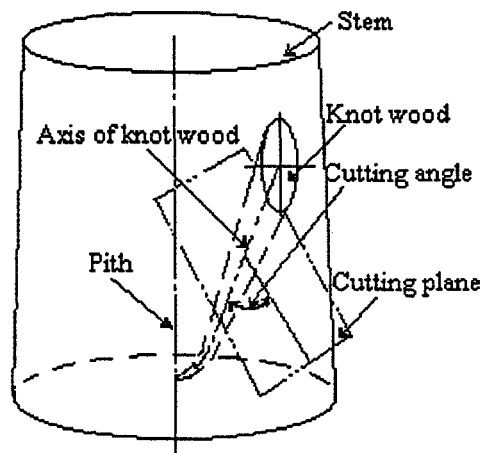


Figure 2. Cutting angle

An oval knot can be formed if cutting angle is between semi-vertex angle and  $90^{\circ}$ , otherwise the knots are spikes. Oval knots have an elliptic boundary, whereas boundaries of spikes are hyperbolic or parabolic. In practice, the long-narrow elliptic knots are called spikes as well.

Three dimensional positions of knots present on sawn lumber are divided into face, margin, aris and other types (Figure 3).

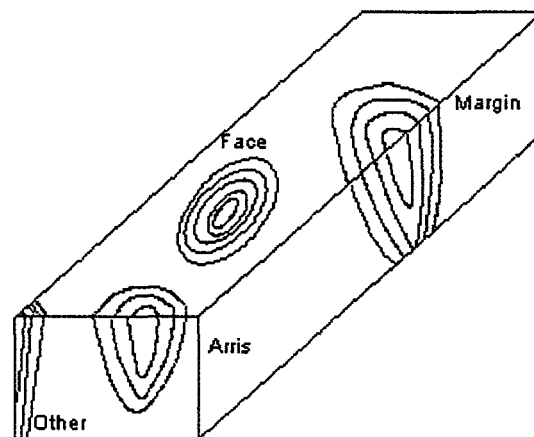


Figure 3. Different knot types presented in board

Face knots lie completely inside the surfaces of sawn board and normally have oval shapes. A margin knot intersects with the edge of the board surfaces and consists of one spike and two

partial ovals. An arris also touches the edge of board, but only have one spike and one oval. Rest knot types are all called other.

### *PHYSICAL PROPERTIES AND DRYING BEHAVIOUR OF KNOTS*

Knot wood is compressed by the surrounding wood during growth, so it is denser and contains more lignin than clear wood, which results in its higher density and lower moisture content. Kinimonth (1961) studied 30 knots with the diameter from 25 to 75 mm isolated from surrounding wood of 25 mm thick radiata pine boards. The average green moisture content of knot wood was 45.2% (dry-basis) and specific gravity was 0.69, whereas the average green moisture content of surrounding wood was 141.7% (dry-basis) and specific gravity was 0.42. Knot wood can always be readily distinguished from the surrounding wood by its darker colour, which results from its high level of resinification. The resin content was found to have a significant inverse correlation with shrinkage. From green to 12% moisture content, the average volumetric shrinkage of radiata pine knot (14.6% resin content in average) is 5.3%, compared with 6.5% volumetric shrinkage of clear wood whose average resin content is 2.0% (Clifton, 1985).

During seasoning, knot is dried faster than surrounding wood, which is because of not only the lower moisture content of knot wood, but also the higher speed of moisture movement along its own longitudinal direction (Walker, 1993). Therefore, shrinkage occurs in knot wood when the surrounding wood is still above fibre saturation point. Surface checks in sawn boards can first start in the knotty area by shrinkage induced stresses. The validation of this is supported by the observation that knots begin to crack after a short period of seasoning (Kinimonth, 1961).

Stresses caused by uneven shrinkage could result in radial or circular cracks around intergrown knots. Moreover, encased knots are liable to become loose, especially if their diameter is larger than 20 mm (Kinimonth and Whitehouse 1991). After drying 150 mm x 25 mm and 200 mm x 25 mm dressed knotty boards, Kinimonth (1961) found that the larger knots produce more severe surface checks than the smaller ones. Among seasoning variables, final moisture content was found to have a dominant effect on knot checking. The lower the final moisture content, the more severe is checking. On the contrary, higher temperature (77<sup>0</sup> C) did not make more severe checks, compared to those at lower temperature (54<sup>0</sup> C and air-seasoning). In fact, checking in air-seasoning was significantly severe than that in kiln drying according to his experimental data.

Seasoning variables have been studied by Kininmonth (1961) and some data were presented in his unpublished report. However, further study is necessary to understand how and why seasoning variables influence knot checking. In addition, wood variables, such as density, moisture content, radial distance from pith and vertical position, and knot variables, such as knot size, knot shape and knot type, have not been well investigated.

## MATERIALS AND METHODS

### MATERIALS

All laboratory drying samples were rough sawn at the Mahoe sawmill, Christchurch from a 6.5 meter long single radiata pine log with 400 mm DBH (diameter at the breast height) obtained from the west coast of the Canterbury Province. The log was cut into 70 x 25, 70 x 50, 100 x 40, 150 x 20, 150 x 25, 150 x 35, 150 x 40 and 150 x 50 mm boards. The transverse positions of sawn boards are shown in Figure 4. The boards labelled E<sub>i</sub> were located at the eastern part of the tree and W<sub>i</sub> faced west of the growth location. M1 to M10 is along the direction from north to south. Each rectangle of Figure 4 represents 6 boards, which are cut from the vertical positions 0~1 m, 1~2m, 2~3m, 3~4m, 4~5m and 5~6m. Therefore, 120 boards were prepared.

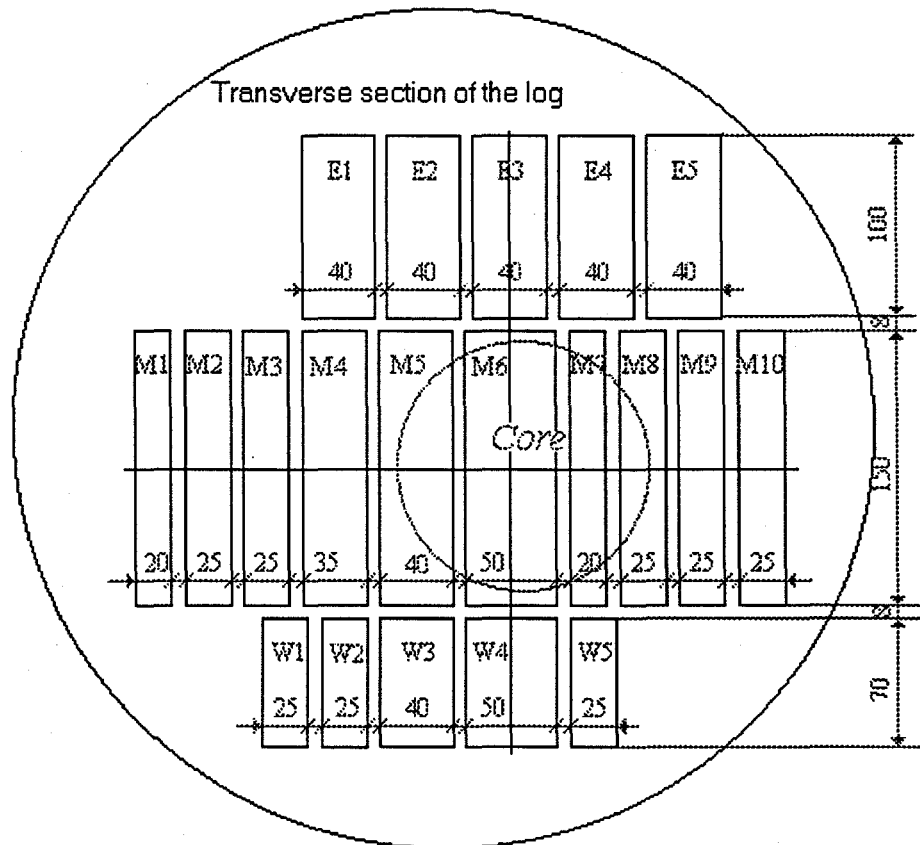


Figure 4. Transverse positions of sawn boards

The rough sawn boards were dressed at the carpenters' workshop of Lincoln University immediately after sawn. One face of all laboratory drying boards were meshed with 100 mm x 50 mm fine rectangular grid and additional 10 mm x 10 mm, 20 mm x 20 mm squares were marked in knotty areas so as to observe the behaviour of knots more precisely and measure the drying deformation more accurately. Moisture content, density, height and radial position, global direction and number of knots on each board were recorded. In addition to the experiments, check characteristics were observed from the eight 100 mm x 50 mm air-dried boards and the thirty-two 100 mm x 50 mm commercial kiln-dried boards.

### *SEASONING APPARATUS AND METHODS*

The laboratory samples were dried in a laboratory kiln with a double glazed window and kiln capacity of 1.5 x 1.8 x 2.1 m<sup>3</sup>. Conditioned air was supplied to kiln by an Aminco-air Unit ( ). The dry-bulb temperature and the relative humidity were set to 70<sup>0</sup> C and 60% respectively, and air velocity within chamber was about 2 m/s. The drying conditions including temperature and relative humidity were recorded every 15 minutes using the CR-10-X ( ) data logger attached to a notebook computer.

Boards were stacked 50 mm apart on sticks to allow uniform air flow over surfaces of boards. Boards were dried for two weeks to an average 12% final moisture content. Moisture content was measured before and after the seasoning by oven drying 10 mm thick samples that were cut 200 mm from the ends of boards.

Air-dried boards had been exposed to outside weather for about one year without cover and their average moisture content observed was 16%. Commercial kiln-dried boards were dried at 98<sup>0</sup> C dry-bulb temperature and 10<sup>0</sup> C wet-bulb depression for 5 days to reach an average of 12% final moisture content.

### *MEASUREMENTS*

Shrinkage, warping and dimensions of check were measured at fixed positions using a pair of digital callipers with an accuracy of 0.01 mm. These measurements were taken before and after drying, and each measurement was repeated twice and the average of readings were recorded.

Moisture content and dry-based density were taken according to ASTM D 2395 standard using sections cross cut from the boards having 10 mm in thickness and located 200 mm from the



ends of boards. Samples were weighed on a digital balance having an accuracy 0.0001 g soon after cutting and oven dried to constant weight at 105<sup>0</sup> C for 24 hours. The dried samples were first weighed for the calculation of moisture content and then covered with a thin coat of paraffin wax. The volume was measured by weighing the coated wood piece in water and the density was determined.

According to grading rules of New Zealand and Australia, Knot Area Rate (KAR) is employed to express the ratio of knot size to the width of board surface. Knot is projected on the transverse section of board and the knot projection is divided by the area of transverse section (New Zealand Ministry of Forestry, 1995). Another technique of measuring knot size was developed by American Society for Testing and Materials (1974), where knot size was defined as the greatest dimension of circumscribed box in a structural beam. The later technique is easy to use and is adopted in this study.

## RESULTS AND DISCUSSION

### 1. Knot variables

Seventy one percent of experimental boards were found knotty during this study. Higher knotty ratio was observed in timber yard. Knotty boards are the majority of saw-mill products and an inevitable problem encountered in timber drying.

#### *Knot size*

Knot size is defined as the largest dimension of circumscribed box of the knot. Knot size counted from the 120 laboratory-dried boards ranged from 5 mm to 120 mm in diameter. Statistically knot number against size follows a GAMMA distribution (location parameter =0, shape parameter =1.09072, scale parameter =6.15420, goodness-of-fit at 0.1 level, predictor interval = 4 mm) after analysing the data with software UNFIT II (Law and Vincent,1993). Mode of the frequency distribution is 29 with knot size 10~15 mm, which means that large amount of knots have their size ranged adjacent to 10~15 mm. Figure 5 and Table 1 further shows that 53% of knots can be classified into small size group (diameter  $\leq$  25 mm).

About half of the knots checked during seasoning. The maximum width and length of checks are 1.88 mm and 120 mm respectively. Large-size knot group (diameter  $\geq$  75 mm) has the highest proportion of checked knots, which is slightly higher than that of small-size knot group, but significantly higher than the check rate of medium-size knot group (25 mm < diameter < 75 mm). Length of the largest check of a knot is normally positively proportional to its diameter of the knot, which means that larger knots generally suffer more severe damage than smaller ones.

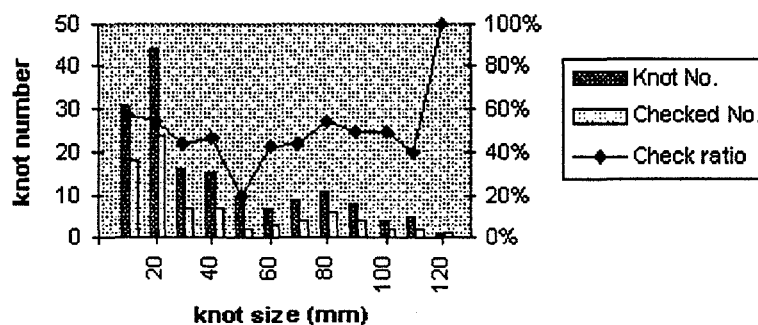


Figure 5. Number of knots and checked knots vs knot size

Dimension	Frequency of knot			Width of check				Length of check		
	Frequency of knots	Frequency of checked	Check ratio	<0.5 mm	0.5~1mm	1~1.5mm	>1.5mm	< D/2	D/2~D	>D
small	85	46	54.1%	40	6	0	0	4	37	5
medium	52	21	40.4%	10	4	5	2	1	16	4
large	24	13	54.2%	5	1	7	0	1	9	3
total	161	80	50%	55	11	12	2	6	62	12

Small: diameter less than 25 mm, Medium: diameter between 25 mm and 75 mm, Large: diameter larger than 75 mm, D= diameter. (Data are obtained from all knots in laboratory-dried boards.)

Table 1. Effect of knot size on check severity

### *Knot Shapes*

Knot shapes including oval and spike refer to two dimensional geometrical figures of knots. Spike knots appear like parabolic or hyperbolic and oval knots are approximately elliptic. The symmetric axis of a spike knot is the zone of stress concentration and sometimes is the weakest part when spike contains the pith of knot wood. Consequently, spike knots almost always are torn up first along their symmetric axis. Under extreme tensile stresses, an oval knot breaks down first at the weakest part by separating ray tissues, the same as the end splits developing. Checks of oval knots first and mainly occur in radial direction of the knots, and sometimes associate with circular checks if the stresses further grow. The check directions can be further specified when an oval knot is approximated as an ellipse because checks initiate in the order of stress intensity. Check normally starts along the major axis of the elliptic oval, later another check may run in minor axis orientation, or just an arbitrary radial direction. Circular checks also can be found around knots, but they are not as often as radial checks.

### *Knot types*

Knot types including face, margin, arris and other refer the position of knots on the board and the three dimensional shapes of knots.  $\chi^2$  test ( $\chi^2=13.26 > \chi^2_{0.01}=9.210$ ) of checked and unchecked knots in type groups shows that face knots have a significantly high check ratio (Table 2). Face knots are those with their boundary totally lying on the surface of boards. Therefore, the only way for face knots to release stresses is to pull fibre apart. Margin and arris, on the other hand, can release drying stresses by bending the whole board warp. Checking of other type is not significant and will not be discussed in detail.

Knot type	Frequency of knots	Frequency checked	Percentage checked
Face	86	54	63%
Margin& arris	69	25	36%
Other	6	1	16%

Table 2. Effect of knot types on checking rate

#### A). Check directions on margin and arris knots

A margin contains two ovals and one spike, whereas an arris knot consists of one spike and one oval, sometimes an arris may have two ovals. The geometrical combination makes the major checks of a margin or an arris run through the symmetric plane of knots (Figure 6), which crosses the symmetric axes of oval and spike where the zones of stress concentrations are. About 74% checks of margin and arris knots followed this pattern in this study.

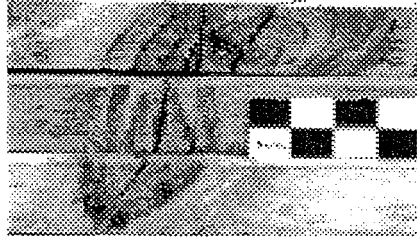


Figure 6. Direction of checks in margin and arris knots

#### B) Check direction of small face knots (diameter < 25 mm)

Small face knots are approximately round. Differences of diameters are negligible. In this case, shrinkage induced stresses are almost evenly exerted to the boundary of knots. Fibres of the tree exert much larger constraint in grain direction than in other directions. Therefore, stresses along fibre direction mainly are released in the way of separating the knot into two halves. As shown in Table 3, about 78% checks of small knots develop almost perpendicular to the grain direction of the board (Figure 7).



Figure 7. Direction of check in small face knots

#### C) Check direction of face knot

Knot shapes are not always regular, but face knot can be regarded as approximately elliptic shaped oval. As seen in Figure 8, the largest check goes along its major axis where stresses concentrate more severely than other radial directions of the knot. 92% face knots were observed following this description, especially when the major axis of ellipse is far longer than the minor axis (Table 3).

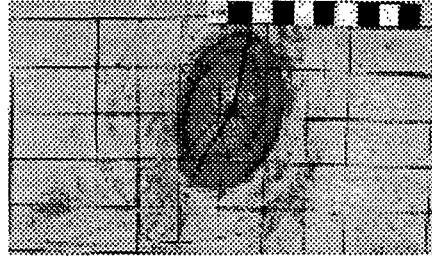


Figure 8. Direction of check in elliptical face knots

The hypothesis examined by experimental (Table 3) data is that knot checking obeys the law of mechanics and runs through the symmetric axes of the broken knot where the zones of stress concentrations are.

Knot Shapes	Number of checked knots			Number of support the hypothesis			%
	air-drying	commercial kiln drying	laboratory kiln drying	air-drying	commercial kiln drying	laboratory kiln drying	
Elliptic face	16	76	13	16	68	13	92%
Margin & arris	32	16	25	20	12	22	74%
Small face	12	64	47	11	48	37	78%
Total	301			247			82%

Table 3. Number of knots supporting the description of check directions

## 2. Wood Variables

The number of checked knots was 32 in the upper half of stem versus 48 in the butt (Table 4). Because knots of medium size group have a significantly lower check rate, a lower check rate in upper half of stem can be attributed to its higher number of medium size knots, which were 38% of total 73 knot in upper half of stem, whereas 28% medium size knots among total 88 knots in butt half.

The knot numbers in northern half and southern half of stem were 113 and 48 respectively. Correspondingly number of checked knots in northern part was twice greater than that in southern part (Table 4). In the south hemisphere, the northern part of a tree gets more sun and develops more branches. Besides the down-hill half of a tree has the advantage of assimilating more nutrition in mountainous area. The studied log was from a tree with its north facing down hill. This geographic condition makes the difference of growth features in the two halves remarkable.

	Number of checked	Number of total knots	Check rate
Upper half	32	73	43.8%
Butt half	48	88	54.5%
Northern half	53	113	46.9%
Southern half	27	48	56.3%

Table 4. Number of knots and check rate in the halves of stem

There was a reverse relation between density and check rate in group M1~M10 boards (Figure 4), which were cut to the same width from the middle of log. Density of northern outer wood of this radiata tree was  $470.5 \text{ kg/m}^3$  (dry-basis, standard deviation [stdev]= 47.8, minimum value [min]= 421.6, maximum value [max]=542.7), which was higher than  $401.4 \text{ kg/m}^3$  (stdev =11.2, min= 383.8, max = 416.6) of southern outer wood and  $368.4 \text{ kg/m}^3$  (stdev = 33.4, min= 344.9, max=437.6) of core wood. Correspondingly the check rates of north (M1~M4), south (M9~M10) and core (M5~M8) were 0.46, 0.50 and 0.60.

As seen in Figure 4, boards that labelled with  $M_i$  were flat sawn, and labelled  $E_i$  and  $W_i$  were quarter sawn or intermediate sawn. In Figure 9, the rates of checked knots in all sawn patterns are represented using bar graphs and the thicknesses of boards are denoted by the plot of rhombus-dot line. There is no correlation that can be seen among check rate, dimensions and sawn pattern of boards from Figure 9.

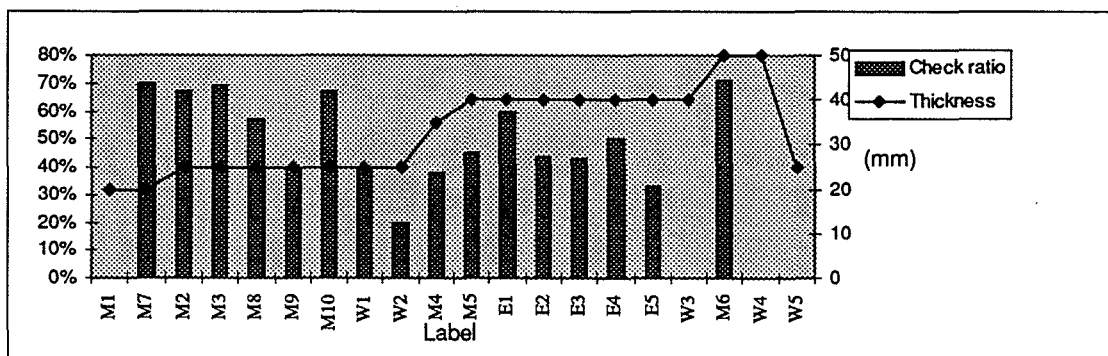


Figure 9. Check rates of different sawn patterns

### 3. Seasoning variables

#### Moisture content

The average moisture content of the experimental clear wood was 87.08% with standard deviation 28.49% and varied from 44.88% to 171.98%. The tree was fell in summer and one week was spent for transportation and processing before putting into the kiln. Moisture content was a little lower than the original though the boards were wrapped in plastic all the time.

In living tree, the mass flow is transported through fibres along the longitudinal direction of stem. Therefore, moisture is removed from this direction through the ends of sawn boards much faster than other directions, and the ends attain the lowest moisture content. Due to high resinification, moisture content of knot wood is lower than that of surrounding wood. After felling, the moisture in stem is protected by the bark, while longitudinal direction of knots is exposed to air. Moisture keeps moving from knots fast and it is even accelerated after sawing. Moisture content of knots must be lower than that of clear wood when timbers are stacked in kiln. Reading of a hydrometer showed that average moisture content of knots before drying was 36.66% and ranged from 23.32% to 55.13%. At this moment, checking had not occurred yet.

Final moisture content is an important indicator of check intensity. As knots dry faster than clear wood, it shrinks earlier than the surrounding wood. It was observed that most knot checks were initiated in the early several hours, when the shrinkage of surrounding wood had not occurred. At the initial stage, two factors, shrinkage of knots and restraint from surrounding wood, could have dominant influences. High shrinkage of knots produces large stresses, but high constraint makes the stress hard to release. In other words, the stress exerted on knots keeps increasing as moisture releases until knots crack. When wood in the surrounding of knot shrinks, stresses are induced and exerted on knots. If knots have checked already, stress concentrations build up at the tip of checks and tear up checks further as explained by fracture mechanics. Because shrinkage of wood is inversely proportional to moisture content. Therefore, lower moisture content definitely produces more shrinkage, thus higher stresses and more checks. As a matter of fact, it was observed that the number of checked knots and severity of checks increase with moisture removing during drying.

### *Temperature and drying methods*

Higher temperatures did not lead to more severe check damage in boards, on the contrary, the most severe knot checks were found on air-dried boards, especially those at the top of piles in the timber yard. An experiment was designed to illustrate check propagation during seasons. Thirty kiln-dried boards (12% moisture content) were fully soaked with water by immersing in a water tub for one week. The average width of boards was recovered to about 97% of original dimensions in green status. The unrecovered portion was due to collapse of wood cells during seasoning. These boards were re-dried at 70<sup>0</sup> C dry-bulb temperature and 60% relative humidity for 48 hours reaching the final moisture content of 15~ 17%. Owing to diminishing shrinkage, warping was reduced almost half of the original amount. However, the checks

increased significantly. Circular checks appeared this time and the number of checked knots increased about 22%. Moreover, the length of check increased and maximum increment was about 50% (126 mm versus 85 mm). As shown in Figure 10, the part circled with white ink is the expansion of check during second seasoning. This process is repeated many times within timber exposed to air during seasons. In wet days, timbers swell due to moisture adsorption. Checks contain more water than anywhere else when it rains, thus the surrounding area of a knot swells more. The swollen part shrinks unevenly because of moisture gradient and different shrinkage coefficients on sunny day. The original checks are much more liable to propagate due to stress concentration at the tips. Cyclic stresses release and exertion can also result in fatigue effect that accelerates check propagation. Crack tip effect and fatigue effect both work during air-seasoning and make knot checking more severe than that in other drying methods.

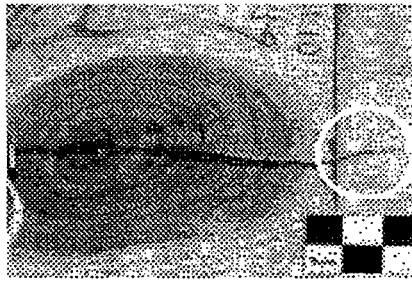


Figure 10. Demonstration of cyclic drying effect

## SUMMARY AND CONCLUSIONS

Most radiata pine sawn boards contain knots and the knot size of radiata pine is relatively larger than those generally found in other species. In knot size groups, small size knots had the highest number, where medium size knots had the lowest check rate and large size knots suffered the most severe check damage.

Spike knots appear like parabolic or hyperbolic and oval knots are approximately elliptic. Spike knots usually check first and mainly along its symmetric axis, where is the zone of stress concentration and contains the pith of knot wood sometimes. The checks of oval knots initiate in the radial directions of knots by separating ray tissues of knot wood. The major check of an oval knot normally goes through the major axis of the knot and further development of drying stress may produce the second largest check in minor axis, arbitrary radial directions or circular orientation.

Among all knot types, face knot is significantly liable to check than rest of knot types, because the only way for face knots to release stress is to separate fibre apart. Margin and arris knots



can release their stresses both by making checks and warps. The check directions of knots are determined by their geometrical shapes. The major checks of margin and arris knots run cross the major symmetric planes, which consists of the symmetric axis of the spike and the major axes of the oval knots. Knots of small size group are almost round and have their checks approximately perpendicular to the grain orientation. Like spike, the major check of an elliptic face knot is along its major axis.

Due to the high number of medium size knots, upper half of stem had a lower check rate than that of butt. The advantage of assimilating sun and nutrition led to the northern half of stem growing much more branches, thus forming more knots and checked knots, though the check rate in the southern of stem was higher. Core wood (density=368.4 kg/m<sup>3</sup>), southern outer wood (density= 401.4 kg/m<sup>3</sup>) and northern outer wood (density=470.5 kg/m<sup>3</sup>) showed progressively increasing checking ratios, which indicated a reverse relation between checking and density. There was no correlation found among check rate, dimensions and sawn pattern of boards.

Most checks of knots initiated in the first several hours during drying and the number of checked knots kept growing with moisture desorption, because lower moisture content leads to more shrinkage and induces higher stresses. Temperature did not show a significant influence on knot checking. During seasons, the cyclic weather changes resulted in crack tip effect and fatigue effect on air-drying boards and made air-dried boards without cover produce the lowest drying quality.

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