SPIRAL GRAIN IN CANTERBURY *PINUS RADIATA*: WITHIN- AND BETWEEN-TREE VARIATIONS AND EFFECT ON MECHANICAL PROPERTIES

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ABSTRACT

A study of spiral grain in Canterbury-grown *Pinus radiata* D.Don revealed that spiral grain varies significantly both within the tree and between trees; bending strength and stiffness decrease with an increase in the angle of spiral grain; corewood stiffness is less sensitive to spiral grain than outerwood stiffness; and spiral grain downgrades a significant proportion of the sawmill output from Canterbury-grown *P. radiata*.

Keywords: spiral grain; modulus of elasticity; bending strength; within-tree variation; between-tree variation; corewood; outerwood; *Pinus radiata*.

INTRODUCTION

The consequences of spiral grain are encountered in the form of twist in dry timber, distortion in plywood sheets, short-grained failure of timber under stress, and surfacing problems during machining (J.M.Harris unpubl. data). Bendtsen (1978) reported that the instability associated with spiral grain, coupled with the abnormal longitudinal shrinkage of corewood and excessive amount of compression wood, are responsible for the poor reputation of solid wood products from rapid-grown plantation timber. Indeed some have argued that spiral grain is the most serious single defect in plantation-grown softwoods (Harris 1989).

The effects of grain deviation on compressive, bending, and tensile strength parallel to the grain are indicated in Fig. 1. The effects of grain deviation from the axis of the tree or the length of a board can be described (USDA 1987) using the empirical Hankinson equation:

$$P_\theta = (P_0 \,.\, P_{90})/(P_0 \,.\, \mathrm{Sin}^N\theta + P_{90} \,.\, \mathrm{Cos}^N\theta) \qquad [1]$$

where: P_θ = property value for wood in which the grain angle is inclined at an angle, θ, to the direction of the load;
P_0 = property value parallel to the grain ($\theta = 0°$);
P_{90} = property value perpendicular to the grain ($\theta = 90°$); and
N = a constant for the particular strength property.

The values for N and associated ratios of P_{90}/P_0 are given in the USDA Wood Handbook (USDA 1987, pp. 4–29) as follows:

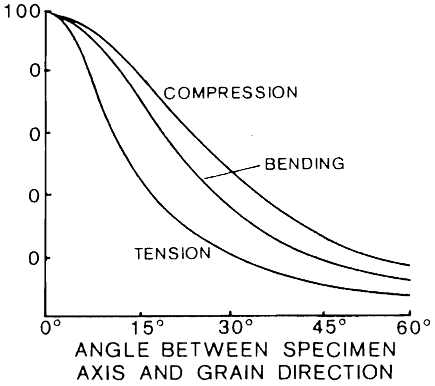

FIG. 1–Effect of grain angle on strength properties (reproduced with permission from Harris 1989).

Property	Values of N	Values of P_{90}/P_0
Tensile strength	1.5–2.0	0.04–0.07
Compressive strength	2.0–2.5	0.03–0.4
Bending strength	1.5–2.0	0.04–0.1
Modulus of elasticity	2.0	0.04–0.12
Toughness	1.5–2.0.	0.06–0.1

For each property a wide range of values can be obtained, depending on the values assigned to P_{90}/P_0, or N.

Bier (1984) examined strength and stiffness properties of *P. radiata* plywood at 0°, 15°, 30°, and 45° angles to the face grain. He demonstrated that Hankinson's equation can be used for the modulus of elasticity of wood at any angle and obtained a ratio of 0.05 for E_{90}/E_0 which gave the best fit. However, concerning strength properties, he observed that beyond the limit of proportionality the relationship between stress and strain becomes difficult to determine. Failure loads are dependent not only on the magnitude of the direct stresses parallel and perpendicular to the grain, but also the shear stress. Hankinson's formula does not include a shear stress term.

Even with the modulus of elasticity, Hankinson's equation is useful only when a wide range of values for grain angle (such as those of Bier 1984) is available to predict the modulus of elasticity perpendicular to the grain (E_{90}). As will be shown later, in the current experiment the range of values for spiral grain is too small to justify the use of Hankinson's equation; instead, linear equations are used.

Harris (unpubl.data) observed that while spiral grain is extremely common in corewood of *P. radiata*, it has been neglected by the timber industry in New Zealand because (a) spiral grain is confined to corewood which in turn is guarded against by the grading rules; (b) spiral grain in *P. radiata* seldom reaches extreme values, frequently lying within the range 5–10°; and (c) the climate over most of New Zealand is maritime in nature, so that dry timber shipped from one place to another would not normally encounter large differences in equilibrium moisture content.

The objectives of this paper are to examine (a) variations in spiral grain with changes in the vertical and radial positions within the tree; (b) the effect of spiral grain on the stiffness and strength properties of timber; and (c) the effect of spiral grain on the grade outturn of commercial timber.

MATERIALS AND METHOD

Preparation of Experimental Material

Forty eight unpruned trees from a 25-year-old stand established on the Canterbury Plains near Dunsandel in the South Island of New Zealand were milled to give 915 90 × 35 mm dried (12% m.c.), dressed, machine stress graded boards, 3.6 m long. Each board was identified according to log type (butt, middle, top) and distance from the pith (positions 1 to 4). For each board the modulus of elasticity and tensile strength were measured by testing in tension to failure. Subsequently a clearwood sample adjacent to the failure zone was cut and its unextracted air-dry density (12% m.c.) determined. Also a blank 0.75 to 1.50 m long was cut from which 300-mm-long, 20 × 20-mm, clearwood bending specimens were obtained in accordance with the British Standard (BS 373: 1957) and bending strength and modulus of elasticity were determined.

Measurement of Spiral Grain

The angle of spiral grain was measured on the tangential face of clearwood (20 × 20 × 300 mm) specimens cut from each of the 915 boards tested in tension. Details concerning the procedures of sample preparation have been reported fully by Addis Tsehaye (1995) and Addis Tsehaye *et al.* (1995).

The spiral grain angle for each clearwood specimen was measured using the technique described by Harris (1989 p.48) (Fig. 2). If the slope of grain on the tangential face is expressed as the ratio AB:BO, and that for the radial face as BC:BO, then the combined slope of grain DO is represented by BD:BO. Therefore, the true slope of grain (1/C) was calculated using the following formula:

$$1/C = \sqrt{[(1/F)^2 + (1/E)^2]} \qquad [2]$$

where: $1/F$ = slope of grain on face
$1/E$ = slope of grain on edge

RESULTS AND DISCUSSION

Variation of Spiral Grain with Position Within the Tree

The mean and upper 10-percentile values of the angle of spiral grain for all the 915 specimens on the basis of the four positions relative to the pith and the three log types are summarised in Tables 1 and 2.

Harris (unpubl. data) indicated that spiral grain peaked around the third growth ring and declined thereafter such that the "zero angle" point occurred about 15 rings from the pith. A recent re-evaluation by Cown *et al.* (1991) argued that spiral grain in *P. radiata* is even more significant than had been appreciated previously (Harris 1989). This study of 25-year-old *P. radiata* trees from Kaingaroa Forest revealed that angles in excess of 5° are frequently maintained within the first 10 growth rings from the pith and the decline is more gradual than previously suggested. Further, Cown *et al.* (1991) stated that 5° grain deviation is the critical point above which twist sufficient to down-grade the timber according to the New Zealand

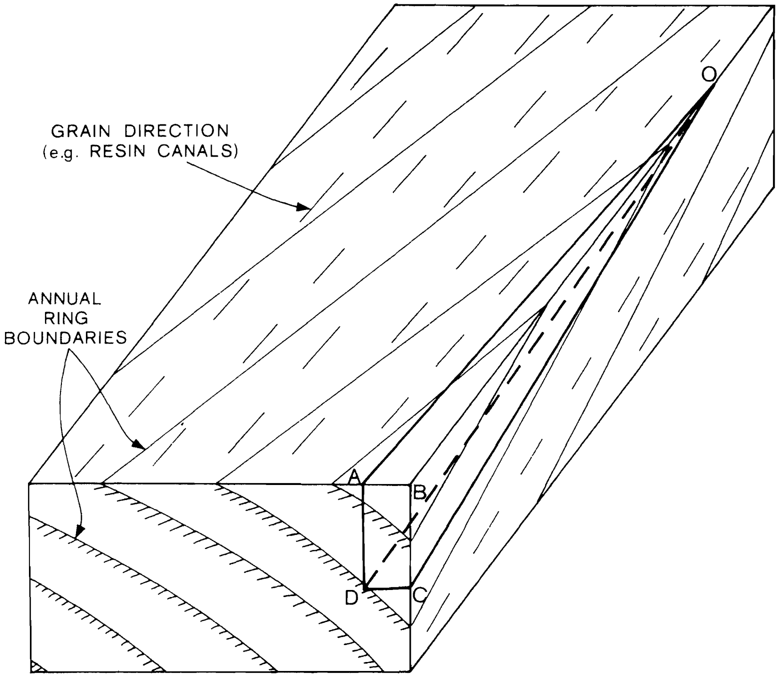

FIG. 2–Measuring of the slope of grain in sawn timber (reproduced with permission from Harris 1989).

Timber Grading Rules (NZS3631:1988) is very likely to occur, even with appropriate restraint during drying.

The angle of spiral grain decreased significantly measured radially from the pith to the cambium (Table 1). These results are in agreement with those reported by Cown *et al.* (1991) for *P. radiata*. The radial variations are also similar in magnitude to the results of a recent study by Lausberg (1995) who examined spiral grain within the first 11 growth rings on both 10-mm-core and 50-mm-disc samples taken at breast height on 15 *P. radiata* trees from Kaingaroa and Tairua Forests. He reported that spiral grain increased from average values of 4.5° to 6.5° degrees between growth rings 1 and 6, then decreased to a minimum of 3° out to growth ring 11.

TABLE 1–A summary of the mean and the upper 10-percentile values of the angle of spiral grain based on positions relative to the pith.

Position relative to the pith	N	Angle of spiral grain (°)		Percentage of boards
		Mean	Upper 10-percentile	≥6°
1 (Boxed-pith)	206	4.2	7.3	26.2
2	440	2.8	6.3	13.0
3	250	1.9	4.4	1.6
4 (Adjacent to cambium)	19	1.8	–	0.0
All	915	2.9	6.3	12.6

In this study, position 1 referred to as corewood and positions 2–4 as outerwood.

TABLE 2–A summary of the mean and upper 10-percentile values of the angle of spiral grain based on log type.

Log type	N	Angle of spiral grain (°)		Percentage of boards ≥6°
		Mean	Upper 10-percentile	
Top	221	2.9	6.3	11.8
Middle	295	3.3	6.8	14.9
Butt	399	2.5	6.0	11.3
All	915	2.9	6.3	12.6

However, unlike Cown *et al.* (1991) we observed no obvious variation up the stem, i.e., from the butt to the top log (Table 2).

Effects of the Angle of Spiral Grain on Wood Properties

Whole tree properties

Linear regression analysis between spiral grain and bending strength, and spiral grain and stiffness gives the following equations:

$$\mathrm{MOR} = 72.09 - 1.91\mathrm{SG} \qquad [3]$$

$$\mathrm{MOE} = 8.56 - 0.23\mathrm{SG} \qquad [4]$$

where: MOR is modulus of rupture (MPa)
MOE is modulus of elasticity (GPa), and
SG is angle of spiral grain (degrees).

Weak correlations were observed with the above equations: only 16% of the variation ($r = -0.40$) in the bending strength and 10% of the variation ($r = -0.32$) in the modulus of elasticity of clearwood specimens could be attributed to variation in the angle of spiral grain. The low R^2 values were not unexpected as (a) the variation in grain angle observed was quite limited, so the observed effects would be small and (b) the relationship between grain angle and mechanical properties of wood should be interpreted more properly by non-linear equations such as Equation 1.

The implications of an increase in the angle of spiral grain on wood properties can be determined simply by ranking the wood properties according to spiral grain. For example, to examine the clearwood data further all 915 data points for bending strength, modulus of elasticity, and density were sorted into 11 classes of 1° angles of spiral grain. A summary of mean angle of spiral grain, bending strength, modulus of elasticity, and density for each of these classes is presented in Table 3.

There was a decrease in bending strength and stiffness with increasing spiral grain (Table 3). For example, the bending strength was 81% of the value for straight-grained timber when the grain angle was 6° and 66% of the value for straight-grained timber for a spiral grain of 10°. Stiffness is 80% of the straight grained values when the grain angle is 6° and 63% of the value for straight grained timber for a spiral grain of 10°. These percentage values are similar to those obtained using Equations 3 and 4.

TABLE 3–Distribution of mean angle of spiral grain, modulus of rupture (MOR), modulus of elasticity (MOE), and density on the basis of 1° angle of spiral grain classes.

Class	N	Angle of spiral grain (°)	MOR (MPa)	MOE (GPa)	Density (kg/m^3)
Straight grain	294	0.0	72.8 (11.5)	8.6 (1.7)	480 (40.3)
1–1.9°	47	1.4 (0.3)	68.0 (15.1)	8.4 (1.9)	471 (46.1)
2–2.9°	110	2.4 (0.3)	67.4 (12.0)	7.9 (1.7)	468 (36.3)
3–3.9°	152	3.4 (0.3)	66.5 (11.6)	7.7 (1.7)	471 (36.5)
4–4.9°	122	4.3 (0.3)	63.3 (9.5)	7.7 (1.6)	459 (35.5)
5–5.9°	76	5.4 (0.3)	61.0 (10.4)	7.5 (1.6)	461 (41.6)
6–6.9°	55	6.4 (0.3)	59.2 (7.6)	6.9 (1.5)	469 (36.3)
7–7.9°	31	7.3 (0.3)	56.6 (8.1)	6.6 (1.4)	465 (43.1)
8–8.9°	20	8.4 (0.3)	59.4 (9.5)	6.9 (1.7)	475 (37.1)
9–9.9°	6	9.3 (0.3)	53.1 (6.8)	6.7 (1.7)	453 (27.7)
10–10.9°	2	10.5	48.4	5.4	495
All	915	2.9 (2.5)	66.8 (12.2)	7.9 (1.8)	471 (39.4)

Value in parentheses is the standard deviation.

Corewood v. *outerwood properties*

The radial distribution of spiral grain within the tree (Table 1) showed that the boxed-pith contained material with a mean spiral grain angle of 4.2° compared with that of 2.8° directly outside the boxed-pith and 1.8° near the bark in the outerwood. Further, over 26% of the boxed-pith material had spiral grain in the critical range ≥6° while only 13% of the outerwood material has a similar angle of spiral grain.

The corewood (in this specific instance corewood is taken to be the wood in position 1 which contains the first 7–8 growth rings) and outerwood could be treated separately (Table 1). The differences that became apparent when the relationship between spiral grain and modulus of elasticity for corewood and outerwood was analysed separately are revealed in Fig. 3 and Equations 5a and 5b. Only a linear equation was considered since the range of θ ($\leq 11°$) was too limited to expect Hankinson's formula to be any more useful. As can be seen from Equation 5(a) corewood stiffness was less sensitive to spiral grain (with a slope of –0.05) than outerwood stiffness (with a slope of –0.17). The reason for such different behaviour of corewood and outerwood arises from the inherent differences in anatomical characteristics between the two. In the corewood spiral grain has a complementary role to other major factors such as a larger microfibril angle, thinner cell wall, lower cellulose content, and lower percentages of latewood, all of which tend to reduce extremes of anisotropy parallel and perpendicular to the grain.

$$MOE_{cw} = 6.35 - 0.05SG_{cw} \qquad [5a]$$

$$MOE_{ow} = 8.86 - 0.17SG_{ow} \qquad [5b]$$

where: MOE_{cw} is modulus of elasticity of corewood (GPa);
MOE_{ow} is modulus of elasticity of outerwood (GPa);
SG_{cw} is angle of spiral grain of corewood (degrees); and
SG_{ow} is angle of spiral grain of outerwood (degrees).

This greater initial decline in stiffness with increasing grain angle in the outerwood than in the corewood (–0.17 *v.* –0.05) implies a greater difference between E_{90} and E_0 in

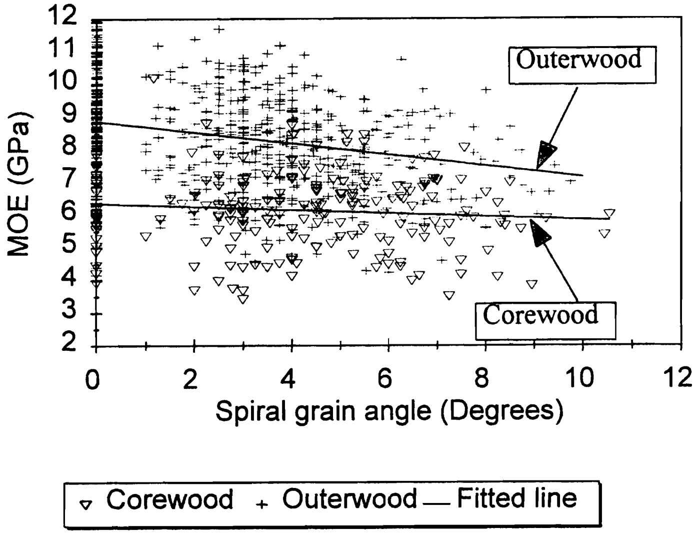

FIG. 3–The effect of spiral grain on modulus of elasticity; corewood and outerwood separated. Note that outerwood is more sensitive (r = –0.29) to spiral grain than is the corewood (r = –0.07).

outerwood than in corewood. One might expect this as the smaller microfibril angle in the outerwood exaggerates the axial to transverse stiffness ratio (*see* Cave 1969, Fig. 4 and 5). The gradual decrease in microfibril angle from pith to cambium first examined in detail for *P. radiata* by Wardrop & Dadswell (1949) is consistent with Equations 5a and 5b. Indeed, the observed differences in the slope demonstrate that the E_{90}/E_0 ratio should not be considered a constant for a fast-grown plantation species (with its enlarged juvenile core) even for a single site. Thus we reach the conclusion that the anisotropic effects of spiral grain are reduced in corewood. This is not surprising as deviation away from the longitudinal would imply a reduction in anisotropy as longitudinal stiffness would be approaching transverse values.

Effect of Spiral Grain on the Grade Outturn

Concerning the impact of spiral grain on the grade outturn of sawn timber, a 6° (equivalent to a slope of grain 1:10) grain deviation is the critical point above which twist is sufficient to downgrade an Engineering grade timber to No.1 Framing according to the New Zealand Standard (NZS3631: 1988). Appropriate restraint during drying will mitigate its worst effects but will not wholly overcome the problem.

The effect of spiral grain angle on the grade outturn can be estimated for the current material. Spiral grain in clearwood (20 × 20 × 300-mm) specimens reflects the nature of this property in the 90 × 35-mm graded boards from which the clearwood specimens had been cut. Thus, from a total of 915 graded boards, 115 (13%) had a spiral grain angle ≥6° (Table 3): 13% of the sawn timber should be downgraded. In fact, very few pieces (<10) were distorted badly. This could be attributed to slow air-drying with weighted stacks and horticultural net used to mitigate worst effects of the dry north-westerly winds in Canterbury. Further, the airdried timber was dressed from a nominal green 100 × 40 mm to 90 × 35 mm, which would remove some of the twist from the dried boards.

There are two issues: strength and stiffness for structural uses are of less importance; distortion affects the fitness of timber for all uses and is a major problem. Cown (1992) noted that there is evidence that spiral grain is detrimental to the economics of processing, i.e., its presence lowers the value of timber. Haslett *et al.* (1991) estimated that excessive twist reduces the value of timber by \$40/m^3, and so with sawn timber production in excess of 2 million m^3/year, spiral grain is a significant problem.

Between-tree Variation

The between-tree variation in spiral grain was examined using those samples with large grain angle values of ≥6° . This approach emphasised the significance of extreme values rather than mean values. When the 115 pieces with spiral grain angles ≥6° were assigned to the 48 trees, just five trees accounted for 25% of all the specimens giving this extreme value. Even with these five trees only a quarter of their timber was liable to warp, mainly from near the pith. This indicates that some selection of clones for reduced spiral grain should be possible.

CONCLUSIONS

The following can be deduced about spiral grain in Canterbury-grown *P. radiata* timber:

(1) There is a decrease in both bending strength and stiffness with an increase in the angle of spiral grain;

(2) If the 6° angle of spiral grain is the critical point in relation to degrade, a modest proportion (i.e., about 13%) of the sawmill output from Canterbury-grown *P. radiata* will be down graded;

(3) Concerning the between-tree variation in spiral grain, among the 48 trees six trees had "no spiral grain" of 6° or more, while only five trees accounted for 25% of all the timber with this excessive value; some selection of clones for reduced spiral grain should be possible (if priorities in tree breeding allow);

(4) The mean angle of spiral grain varies with radial positions in the tree: it decreases significantly on moving radially from the pith to the cambium, but appears constant up the height of the tree;

(5) The difference between the effect of spiral grain on corewood and outerwood properties indicates that corewood and outerwood should be treated separately.

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