CROSS-GRAIN EFFECT ON TENSILE STRENGTH AND BENDING STIFFNESS OF *PINUS RADIATA* STRUCTURAL LUMBER

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(Received for publication 14 February 1996; revision 16 March 1996)

ABSTRACT

Analysis of wood properties in 257 pieces of dried, dressed, 90 × 45-mm lumber, randomly selected from a sawing study on *Pinus radiata* D. Don logs from a 25-year-old stand in Kaingaroa Forest, indicated that grain deviation in the corewood zone could be severe (up to 18°). An assessment of kiln drying degrade showed a severe problem resulting from twist. Cross grain has also been implicated in strength reduction, and so a study was designed to provide preliminary data on the relative effects of wood density, knot area ratio, and spiral grain (cross grain in sawn lumber) on tensile strength and stiffness in structural lumber.

The most influential of the measured properties were knot area ratio and wood density, but cross grain also had a significant impact on tension strength of "in-grade" lumber. On the other hand, grain deviation led to only a small, though significant, reduction in stiffness (E plank). It is therefore unlikely that spiral grain in standing trees contributes strongly to the low stiffness of structural lumber from young *P. radiata* plantations.

Keywords: spiral grain; wood density; strength; stiffness; *Pinus radiata*.

INTRODUCTION

Recent research at the Forest Research Institute has highlighted the prominent pattern of spiral grain in the juvenile wood of *Pinus radiata* (Cown *et al.* 1991; Xin *et al.* 1995) and the impact of the resulting cross grain on drying degrade of lumber from juvenile wood (Haslett & McConchie 1986; Haslett *et al.* 1991, 1995; Cown *et al.* in prep.). Theoretical studies of the strength properties of wood have also shown a dramatic reduction in performance of clearwood with cross grain (Kollmann & Cote 1968). Cross grain also contributes to chipped and raised grain during moulding (Wilcox *et al.* 1991).

Sawing studies of *P. radiata* in New Zealand have identified small-end diameter, branch index, and density as the most significant criteria affecting the recovery of machine stress grades. However, some trials with "young" wood (20 years and less) have indicated grade recoveries even poorer than would otherwise be predicted (Haslett & McConchie 1986; Tsehaye *et al.* 1989). The high proportion of juvenile wood in *P. radiata* is associated not only with low wood density but also with high spiral grain and microfibril angles (Cown

1992; Donaldson 1992, 1995) which in turn may result in cross grain in the lumber and reduce the stiffness of structural members, independent of wood density.

The study reported here is a first attempt to measure the impact of spiral grain (cross grain) on some strength properties (tension and bending) of *P. radiata* lumber from a 25-year-old stand. Spiral grain patterns have been reported by Cown *et al.* (1991), drying degrade by Haslett *et al.* (1991), and mechanical properties by Walford (1994).

MATERIALS

Log Selection

Trees from Compartment 1013 in Kaingaroa Forest in the central North Island were selected as a source of logs for a 1991 sawing study. The plantation was about 25 years old and regarded as typical of the harvest at that time (Table 1).

TABLE 1–Stand history

Date	Operation
1965	Established at 2500 stems/ha
1968	Waste thinned to 1320 stems/ha
1971	Low pruned to 2.2 m (336 stems/ha)
1972	Waste thinned to 690 stems/ha
1973	Medium pruned to 4 m (260 stems/ha)
1974	High pruned to 5.8 m (275 stems/ha)
1975	Waste thinned to 350 stems/ha
1990	Sample trees felled

For this study, 50 trees were selected to cover the range of tree sizes in the stand, and 50 m^3 of unpruned logs (nominally 4.8 m long) were allocated to the sawing study, as far as possible evenly spread across the log grades (S1, S2, S3, L1, L2—Whiteside & Manley 1987). The pruned butt logs were allocated to a separate clearwood study and all unpruned logs were cant sawn and high-temperature dried at a sawmill in Rotorua to maximise the recovery of lumber in 100 × 50-mm structural sizes. A study of the drying characteristics revealed 36% rejection prior to planing, almost entirely due to twist (Haslett *et al.* 1991). After being planed to 90 × 45 mm, all the study boards (about 2000) were graded both visually and mechanically (using a Computermatic machine); the data were added to the NZ FRI Log and Timber Database and used to update computer models of sawn lumber yields (Cown *et al.* 1987).

Specimen Selection

All lumber from the sample logs was visually and mechanically graded in 90 × 45-mm cross section and in lengths up to 4.8 m. The test results have been reported by Walford (1994). A subsample of 4.8-m pieces (300) was randomly selected for a cross-grain study. Each piece was cut to yield two specimens 1850 and 2950 mm long to obtain a comparison of the mechanical properties of "long" and "short" pieces. In cutting the two specimens from each piece, no account was taken of the position of the visual grade-determining defect. This is in accord with the Australian/New Zealand standard (AS/NZS 4063) for the in-grade evaluation of timber.

METHODS

Strength Testing

After short-term storage in the laboratory at an equilibrium moisture content of 12%, the specimens were subjected to tension tests. The tension testing machine in the FRI Timber Engineering Laboratory was used to load the pieces in tension parallel to the grain at a rate to produce failure in 1 to 3 minutes from the commencement of loading. The grips of the tension testing machine covered 600 mm at each end of the specimens so that the length between grips was 650 mm for short specimens and 1750 mm for long specimens. Maximum load, position of failure, and defects at the fracture were recorded.

The maximum tensile stress (MTS) was computed from the expression:

$$MTS = P/BD \quad (MPa)$$

where: P = maximum load (in Newtons)
B = thickness (mm)
D = width (mm)

Stiffness Testing

Each sample was passed through a Computermatic stress grading machine. This instrument measures the change in deflection under load at 150-mm intervals along the piece by loading the lumber on the flat at midspan over a span of 914 mm with a constant load of 1443 Newtons. Using the deflection at midspan, the modulus of elasticity (MOE) is calculated from the expression:

$$MOE = PL^3/(4d\,B^3\,D) \quad (GPa)$$

where: P = applied load (in kiloNewtons)
d = deflection at midspan (mm)
B = thickness of lumber (mm)
D = width of lumber (mm)
L = span (mm)

The MOE measured when the point of fracture in the tension test was at midspan in the stress grading machine was used in the subsequent analysis. It should be noted that this value of MOE was not necessarily the minimum value in the original length but simply the value corresponding to the fracture point in the particular sample

Measurement of Wood Properties

Basic density, average ring width, and moisture content were measured on a specimen cut from defect-free lumber taken from near the fracture. Also, on each sample the slope of grain to the longitudinal axis was measured on the face and edge in defect-free wood near the point of failure. A combined slope was computed as the square root of the sum of the squares of the individual slopes, and taken to be the cross grain in the piece.

Knot area ratio (KAR) is defined as the ratio of the projected cross-sectional area of knots in a length equal to the width of the piece, to the cross-sectional area of the piece. KAR was calculated at the defect nearest the point of failure using knot diagrams. Outer KAR was calculated in the same way as KAR but considering only the outer 25% of the width on the more defective edge.

Statistical Analyses

Correlation coefficients between the maximum tensile strength (MTS), and bending stiffness (MOE) and a number of wood properties (KAR, largest knot, basic wood density, moisture content, and grain angle) were obtained for both short and long samples. Samples which failed in the grips of the test machine were excluded from the analysis of MTS. Multiple regressions were carried out with KAR, density, and grain angle as independent variables and MTS and MOE as dependent variables. Tests for differences between the regressions obtained for short and long samples were performed.

RESULTS

Means, minima, maxima, and coefficients of variation (CVs) of wood and strength properties for the short and long samples are reported in Table 2, and correlations between strength and wood properties are given in Table 3. Knot size as measured by knot area ratio had the most significant correlation with tensile strength. Outer knot area ratio and diameter of the largest branch were also significant, although less so than the knot area ratio of the cross section. These were followed by density, which was significant only for long samples. Grain angle showed a significant negative correlation with tensile strength for the short samples.

Density had the highest correlation with MOE, knot size also being significant but only for the long samples. Grain angle had no significant correlation with MOE.

TABLE 2–Means, minima, maxima, and coefficients of variation of wood properties.

Wood property	Short samples				Long samples			
	Mean	Min	Max	CV (%)	Mean	Min	Max	CV (%)
Knot area ratio	0.342	0	1.0	61	0.407	0	0.80	44
Outer knot area ratio	0.325	0	0.99	72	0.411	0	0.91	49
Largest knot (mm)	26.0	0	53.3	57	30.7	0	54.2	40
Basic density (kg/m^3)	381	329	474	8.4	376	291	463	8.3
Moisture content (%)	11.7	8.7	16.7	11.6	11.7	9.8	15.8	11.6
Grain angle (degrees)	5.03	0	17.8	58	5.97	0	14.3	52
MOE (GPa)	6.23	1.67	11.8	32	5.71	1.95	9.82	27
MTS (MPa)	17.8	1.2	52.7	54	12.7	1.6	51.7	58
Number of samples	127				126			

TABLE 3–Correlation coefficients between strength and wood properties.

Wood property	Short samples		Long samples	
	MTS	MOE	MTS	MOE
Knot area ratio	–0.57**	–0.14	–0.67**	–0.44**
Outer knot area ratio	–0.56**	–0.08	–0.57**	–0.39**
Largest branch	–0.51**	–0.05	–0.56**	–0.26**
Density	0.15	0.36**	0.23**	0.40**
Grain angle	–0.20*	–0.14	–0.15	–0.15
Moisture content	0.18*	0.03	0.32**	0.12

* significant at the 5% level
** significant at the 1% level

Multiple regressions relating MOE and MTS to wood properties are given below, with standard errors of the coefficients in parentheses. The square root of the mean square error (Root MSE) is also given for each equation to provide a measure of the unexplained variation.

MTS for short samples:

$$\underset{(8.2)}{\mathrm{MTS} = 10.6} - \underset{(3)}{27}\ \mathrm{KAR} + \underset{(0.021)}{0.051}\ \mathrm{Density} - \underset{(0.23)}{0.65}\ \mathrm{Grain\ angle} \qquad R^2 = 0.40 \quad \mathrm{Root\ MSE} = 7.5$$

MTS for long samples:

$$\underset{(6.1)}{\mathrm{MTS} = 13.2} - \underset{(3)}{27}\ \mathrm{KAR} + \underset{(0.015)}{0.034}\ \mathrm{Density} - \underset{(0.15)}{0.38}\ \mathrm{Grain\ angle} \qquad R^2 = 0.51 \quad \mathrm{Root\ MSE} = 5.3$$

MTS, short and long samples combined:

$$\mathrm{MTS} = A - \underset{(2)}{27}\ \mathrm{KAR} + \underset{(0.013)}{0.043}\ \mathrm{Density} - \underset{(0.14)}{0.50}\ \mathrm{Grain\ angle} \qquad R^2 = 0.48 \quad \mathrm{Root\ MSE} = 6.5$$

where $A = 12.9$ for short samples
$A = 10.3$ for long samples

MOE for short samples:

$$\underset{(1.8)}{\mathrm{MOE} = -1.4} - \underset{(0.7)}{1.6}\ \mathrm{KAR} + \underset{(0.005)}{0.022}\ \mathrm{Density} - \underset{(0.057)}{0.072}\ \mathrm{Grain\ angle} \qquad R^2 = 0.17 \quad \mathrm{Root\ MSE} = 1.8$$

MOE for long samples:

$$\underset{(1.4)}{\mathrm{MOE} = 1.3} - \underset{(0.6)}{3.4}\ \mathrm{KAR} + \underset{(0.003)}{0.017}\ \mathrm{Density} - \underset{(0.036)}{0.068}\ \mathrm{Grain\ angle} \qquad R^2 = 0.33 \quad \mathrm{Root\ MSE} = 1.3$$

MOE, short and long samples combined:

$$\underset{(1.2)}{\mathrm{MOE} = -0.4} - \underset{(0.5)}{2.4}\ \mathrm{KAR} + \underset{(0.003)}{0.020}\ \mathrm{Density} - \underset{(0.025)}{0.074}\ \mathrm{Grain\ angle} \qquad R^2 = 0.23 \quad \mathrm{Root\ MSE} = 1.6$$

In the multiple regression equations for MTS, knot area ratio and density were highly significant ($p<0.01$) for both long and short samples. Grain angle also had a significant effect ($p = 0.014$ for long samples and $p = 0.006$ for short samples). Thus, although the correlation between grain angle and MTS was not significant for long samples, and only barely significant for short samples (Table 3), once knot size and density were taken into account, the impact of grain angle on MTS became clearly apparent. The coefficients for the three independent variables in the regressions for long and short samples did not differ significantly, but the intercept was significantly lower for long than for short samples ($p<0.01$). A combined equation for MTS with separate intercepts for long and short samples was therefore fitted and showed grain angle to be highly significant ($p=0.0003$).

For MOE, density was highly significant for both short and long samples ($p<0.01$), KAR was also significant ($p<0.01$ for long samples and $p = 0.04$ for short samples), but grain angle was not significant. However, as the equations for long and short samples did not differ significantly, a regression on the combined samples was fitted. In this equation, grain angle proved to be significant, although only marginally ($p=0.025$).

DISCUSSION

These results show that tensile strength of *P. radiata* lumber is significantly affected by knot size, density, and spiral grain. The most important factor is knot size, with tensile strength being inversely proportional to the knot area ratio at the point of failure. In other words, the strength is proportional to the cross-sectional proportion of sound wood. The linear regression predicts a tensile strength of approximately zero for a knot area ratio of 0.85 and above. Logically, this cannot be true so the true relationship is probably one that is asymptotic to zero strength at a KAR of 1.0. Density also has an important effect on tensile strength. The equations predict that a 10% reduction in density will cause an 11% reduction in tensile strength.

Although of less importance than knot size or density, grain angle also significantly affects tensile strength. The regression equations indicate that an increase in grain angle of 1° reduces tensile strength by about 3.3%. The effect was similar in both long and short samples and was clearly apparent despite the presence of knots.

It is possible to estimate reduction in tensile strength due to grain angle using Hankinson's formula. This requires values for tensile strength parallel to and perpendicular to the grain. A reduction in strength of approximately 40% at a grain angle of 10° was obtained for two pine species by Winter (1944—*see* Kollmann & Cote 1968). The regression equations derived in this study predicted a reduction of 33% at this angle. Although slightly smaller than the theoretical results, these results indicate that spiral grain can still have an important effect on tensile strength. Theory also suggests that the effect of grain angle on strength is non-linear, with an angle of less than 3° having little effect. In this study, no departure from linearity could be detected, possibly because of the considerable remaining unexplained variability. This unexplained variability may be due largely to the acknowledged limitations of using KAR to represent the effects of knots on strength properties.

Overall, tensile strength was lower in the long samples than in the short samples, even after adjusting for knot size, density, and grain angle. This was probably because there was more chance of a serious defect occurring in the longer samples (Madsen 1992).

In contrast to tensile strength, bending stiffness is affected by properties along the span of the test sample (i.e., grain slope, density) rather than just at the point of failure (i.e., KAR). Thus it could be expected that grain slope will be better correlated with MOE than with tensile strength, while KAR should be better correlated with tensile strength than with MOE. In this study, the correlations with MOE were much weaker than those for tensile strength, except for density, with R^2 values of only 0.2 to 0.3. Density and knot size had significant effects but the influence of grain angle was only marginally significant. The regression equation for the combined short and long samples suggests that an increase in grain angle of 1° reduces bending stiffness by about 1.2%. Based on these results, it is unlikely that spiral grain contributed greatly to the poor machine grade recovery in studies of young lumber.

The properties of juvenile *P. radiata* lumber are of some concern to wood users. The link between spiral grain (cross grain) and drying degrade is now well established, and drying schedule developments have been targeted at reducing losses from this source. The documented low stiffness of wood from near the pith also poses a potential problem for some structural uses, particularly as affected members may not be detected in visual grading, and the causes are yet to be fully explained. Experimental data from clearwood tests (Cave & Walker 1994; Donaldson 1995) indicate that, in addition to wood density, microfibril angle is significantly implicated in determining the stiffness of juvenile wood. Several reports have documented the patterns of variation in microfibril angle in *P. radiata* (Donaldson 1992; Donaldson & Burdon 1995). Unfortunately, the labour-intensive nature of microfibril angle measurement has precluded its routine inclusion in large in-grade studies.

Future research will emphasise the role of features such as spiral grain, microfibril angle, and compression wood in addition to the more traditional wood characteristics such as growth rate, knot area ratio, and average wood density.

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