

BENDING STRENGTH, STIFFNESS, AND STRESS-GRADE OF STRUCTURAL PINUS RADIATA: EFFECT OF KNOTS AND TIMBER DENSITY

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ABSTRACT

Australian-grown *Pinus radiata* D. Don (radiata pine) timber of 35 × 70 mm, 35 × 90 mm, and 45 × 90 mm cross-section was mechanically graded and then tested in bending to determine modulus of elasticity (MOE) and modulus of rupture (MOR). Knots contributing to failure were measured and classified and their knot area ratio calculated. The air-dry density of the timber was also determined.

Accuracy of prediction of MOR using MOE was shown to be independent of timber density but was improved by including knot area ratio, and sometimes knot position, in the regression.

Reductions in timber density and increases in knot size reduce theoretical mechanical stress-grade yields. Therefore a reduction in the market value of sawn structural timber is predicted if forest management aims to increase the rate of growth of plantation trees without compensatory attention to density and branch size.

When the radiata pine timber used in the study was graded to the normal Australian visual grading rules, it generally failed to meet normal bending strength requirements. A re-assessment of the grading rules is recommended.

INTRODUCTION

This study investigated the effect of knot size and timber density on bending strength, flexural stiffness, and, by implication, stress-grade recoveries in radiata pine scantling.

The main aim of grading timber for strength is to prevent material of inferior quality entering any one specified stress-grade. A stress-grade is usually defined as:

“The classification of a piece of timber for structural purposes by means of either visual or mechanical grading to indicate primarily the basic working stress in bending for purposes of design and, by implication, the basic working stresses for other properties normally used in engineering design. The stress grade is designated in a form such as ‘F7’ which indicates that, for such a grade of material, the basic working stress in bending is approximately 7 MPa” (SAA 1975).

Hence bending strength is of primary importance in the determination of a stress-grade. In general, the visual and mechanical grading systems use one or more measurable parameters to assign a stress-grade to timber, the primary parameters being knots in visual grading and flexural stiffness in mechanical grading.

Mechanical grading consists of three distinct steps. Firstly, timber stiffness is measured in a machine that sprays a colour on to the timber to indicate a stiffness range; secondly, a visual inspection is carried out for the detection of defects likely to reduce the shear strength or utility of the piece, or for excessive defects in the unmeasured section; and thirdly, a grade stamp is applied.

Visual grading "is accomplished from an examination of all four faces and the ends of the piece, in which the location as well as the size and nature of the knots and other features appearing on the surfaces are evaluated over the entire length" (ASTM 1974).

Mechanical grading uses measured stiffness as an indicator for strength and utilises the correlation that exists between short-span apparent modulus of elasticity (MOE) measured on the flat and modulus of rupture (MOR) measured on edge in order to predict strength. Mechanical grading programs are determined by the testing of full-sized sections of timber, followed by analysis of MOR results for specimens within various MOE ranges and then the assignment of a stress-grade (F grade) to timber within those MOE ranges (Anton 1977, 1981).

Until very recently, visual grading rules have been based entirely on the methods of ASTM D245-74, "Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber (ASTM 1974) –

"The development of these methods was based on extensive research in the United States covering tests of small clear specimens and of full-sized structural members. Detailed studies included the strength and variability of clear wood, and the effect on strength from various factors such as density, knots and other defects, seasoning, duration of stress, and temperature."

Direct application of these visual grading methods, however, without adequate verification of their accuracy by the testing of full-sized, graded, specimens has been under question for some years. Effects of density and, in particular, knot type and size on the strength of full-sized specimens are therefore of significance in the resolution of these arguments, at least for radiata pine.

MATERIALS AND METHODS

Approximately 300 mechanical stress-grading quality assurance test specimens (SAA 1978) of 35 × 90 mm cross-section were used initially to develop a standard method of notation and measurement. These specimens were routine samples from sawmills in New South Wales (Tumut and Bathurst), Australian Capital Territory, Victoria (Myrtleford), South Australia (Mount Gambier), and Tasmania (Scottsdale). A further 1200 pieces of 35 × 70 mm and 45 × 90 mm were obtained from grading operations in Bathurst, Myrtleford, Scottsdale, and Mt Gambier, with approximately equal representation from each State.

The Australian Standard for visually stress-graded radiata pine (SAA 1973) describes

most of the defects likely to be present in radiata pine scantling and was used as a basis for knot description. Recording of defect size and position was straightforward except where a combination of defects occurred and particularly when they were of differing types. In these specimens the size and position of the defect that contributed to the failure were determined after fracture. If more than one defect contributed to failure and the combination was not implicitly covered by the Australian Standard then the knot sizes were left unrecorded. It was not possible to describe some defects and they also were not recorded. Specimens that contained any growth rings with a diameter of less than 50 mm were excluded in line with the visual grading rules for radiata pine (SAA 1973).

Apparent MOE and MOR were determined in accordance with AS 1749, Appendix A (SAA 1978). MOE was determined with the specimen loaded at mid-span simply supported as a plank over a 914-mm span with the defective section in the middle. MOR was determined with the specimen loaded as a joist in four-point bending with the subjectively worst strength-reducing defect on the tension side. Span to depth ratio was about 14 to 1. After failure each specimen was checked against the recorded defect type to ensure the defect contributing to failure had been correctly recorded.

Density was determined for the 35 × 70-mm and 45 × 90-mm sizes by weighing the 1.5-m long specimens after they had been conditioned to approximately 12% moisture content. The density of the 35 × 90-mm specimens was determined from a section 140 × 22 × 22 mm in cross-section taken from each specimen for the evaluation of some clear timber properties as part of a separate project. These were also conditioned to approximately 12% moisture content.

Knot area was calculated using the normally accepted method of projecting the knot on to a cross-sectional plane. Knot area ratio (KAR) was calculated by dividing the total knot area by the cross-sectional area of the specimen.

RESULTS AND DISCUSSION

Knot types that were sufficiently well represented to permit separate analysis were margin, face, arris, and a special type of margin knot called margin/face (Fig. 1). Approximately 800 fell into this category and, as a grouping, it would represent around 70% of the defects in heart-excluded radiata pine scantling generally.

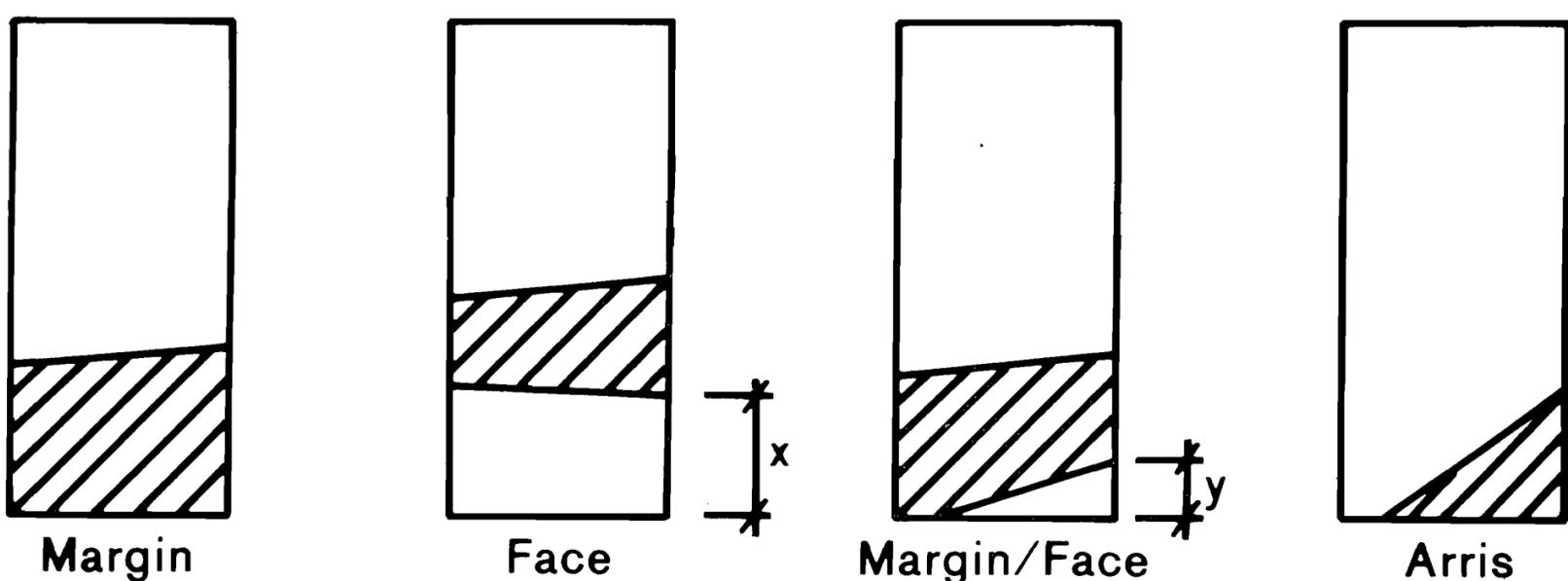


FIG. 1—Cross-sectional representation of the knot types included in the study.

Group univariate statistics of MOE, MOR, density, and KAR are given in Tables 1 to 4. Mean MOR (Table 2) was generally independent of cross-section except for the 35 × 70-mm and 45 × 90-mm margin/face knot groups, the 35 × 70-mm and 45 × 90-mm arris knot groups, and the 35 × 90-mm and 45 × 90-mm arris knot groups. Both the margin and margin/face knots had a similar, lower, mean strength than the face and arris knots because of a larger percentage of knots in the highest stressed area of the timber during testing.

There was no significant difference at the 1% level between mean density for any of the 12 groups (Table 3) indicating that timber density was independent of both cross-section and knot type groupings.

TABLE 1—Modulus of elasticity statistics for all groups (GPa)

Knot	Cross-section (mm)	N	Mean	s.d.	min.	max.	skew.	kurt.
Face	35 × 70	84	9.08	2.48	3.80	15.69	0.141	2.41
	35 × 90	92	9.32	2.58	4.82	16.23	0.203	2.81
	45 × 90	107	8.89	2.12	4.94	13.87	0.183	2.25
Margin	35 × 70	79	8.82	2.34	3.77	13.96	0.063	2.35
	35 × 90	47	9.13	2.63	4.30	14.99	0.309	2.48
	45 × 90	46	8.90	2.51	4.76	14.48	0.356	2.52
Margin/face	35 × 70	69	8.33	2.06	4.53	12.98	-0.018	2.15
	35 × 90	64	8.69	2.59	4.13	16.25	1.269	4.62
	45 × 90	101	8.19	2.10	4.05	13.94	0.291	2.67
Arris	35 × 70	31	9.34	2.58	3.79	13.81	-0.334	2.22
	35 × 90	41	9.29	2.44	4.74	16.18	0.777	3.37
	45 × 90	48	10.11	2.21	5.08	14.29	-0.310	2.66

TABLE 2—Modulus of rupture statistics for all groups (MPa)

Knot	Cross-section (mm)	N	Mean	s.d.	min.	max.	skew.	kurt.
Face	35 × 70	84	39.14	16.71	3.08	75.91	0.248	2.44
	35 × 90	92	41.30	18.68	7.14	88.71	0.402	2.72
	45 × 90	107	43.36	17.20	13.49	93.20	0.414	2.57
Margin	35 × 70	79	25.26	14.07	5.78	77.08	1.230	4.78
	35 × 90	47	27.14	14.53	5.23	62.21	0.578	2.53
	45 × 90	46	28.50	15.57	5.41	66.11	0.853	3.20
Margin/face	35 × 70	70	21.31	9.87	5.24	45.50	0.383	2.50
	35 × 90	64	24.86	11.82	10.49	68.63	1.634	6.02
	45 × 90	100	26.02	11.59	6.18	62.42	1.138	4.61
Arris	35 × 70	31	36.71	16.20	9.08	67.08	0.327	2.29
	35 × 90	41	37.80	13.57	11.22	67.64	0.479	2.89
	45 × 90	48	46.49	15.75	17.91	81.53	0.287	2.32

TABLE 3—Density statistics for all groups (kg/m³)

Knot	Cross-section (mm)	N	Mean	s.d.	min.	max.	skew.	kurt.
Face	35 × 70	84	524	54.2	402	679	0.294	3.49
	35 × 90	92	522	51.8	391	648	0.151	2.76
	45 × 90	107	521	49.0	404	645	-0.197	2.66
Margin	35 × 70	79	523	45.7	418	612	0.213	2.28
	35 × 90	47	508	54.3	383	668	0.338	3.77
	45 × 90	46	518	43.3	438	637	0.449	2.99
Margin/face	35 × 70	70	529	42.9	440	641	0.323	2.86
	35 × 90	64	515	62.6	362	673	0.136	3.02
	45 × 90	101	524	53.1	410	658	0.051	2.48
Arris	35 × 70	31	518	65.1	385	645	-0.078	2.32
	35 × 90	41	518	63.0	406	670	0.141	2.25
	45 × 90	48	531	38.2	469	610	0.254	2.16

TABLE 4—Knot area ratio statistics for all groups

Knot	Cross-section (mm)	N	Mean	s.d.	min.	max.	skew.	kurt.
Face	35 × 70	84	0.40	0.14	0.11	0.77	0.210	2.53
	35 × 90	92	0.33	0.13	0.08	0.63	0.225	2.48
	45 × 90	107	0.33	0.13	0.03	0.67	0.200	2.68
Margin	35 × 70	79	0.35	0.15	0.05	0.72	0.158	2.33
	35 × 90	47	0.27	0.16	0.06	0.62	0.711	2.52
	45 × 90	46	0.28	0.15	0.06	0.75	0.865	3.61
Margin/face	35 × 70	70	0.48	0.14	0.13	0.81	0.077	2.74
	35 × 90	64	0.39	0.12	0.10	0.61	-0.228	2.34
	45 × 90	101	0.41	0.13	0.14	0.78	0.262	3.01
Arris	35 × 70	31	0.15	0.11	0.01	0.40	0.642	2.75
	35 × 90	41	0.11	0.09	0.01	0.36	1.117	2.43
	45 × 90	48	0.11	0.10	0.01	0.42	1.402	4.48

Correlation matrices for the four knot types are given in Tables 5 to 8. The distance X in Table 5 (*see* Fig. 1, face knot) is the distance from the largest of the two face knots to the edge placed in tension during the modulus of rupture test. The distance Y in Table 7 (*see* Fig. 1, margin/face knot) was included because its addition to the regression of MOR on KAR improved the multiple correlation coefficient more than other measurements that could be taken for this complex knot type (*see below*).

The most important correlations were between MOE and MOR, MOE and density, MOE and KAR, MOR and KAR. To a lesser extent MOR was also correlated with density and to the measurements X and Y for the face and margin/face knots respec-

tively. For the margin knots (Table 6) the log transformation of MOR data increased the correlation coefficient between MOR and KAR significantly but not the correlation coefficient between MOR and MOE.

Effects of Density and KAR on MOE and Mechanical Grade

Multiple regressions of MOE on density and KAR showed that for all four knot types and the three specimen cross-sections both density and KAR were highly significant. Coefficients of determination were generally in the range 0.6 to 0.7. Sample sizes were from about 50 to 100 (*see* Tables 1 to 4). As expected, MOE decreased as density decreased and as KAR increased.

TABLE 5—Correlation matrix for face knots. All coefficients shown were significant at the 1% level

	Cross-section (mm)	MOE	MOR	Density	KAR
MOR	35 × 70	0.71	1		
	35 × 90	0.64	1		
	45 × 90	0.70	1		
Density	35 × 70	0.62	0.30	1	
	35 × 90	0.55	0.27	1	
	45 × 90	0.54	0.40	1	
KAR	35 × 70	-0.59	-0.65	ns	1
	35 × 90	-0.51	-0.57	ns	1
	45 × 90	-0.48	-0.56	ns	1
X	35 × 70	0.32	0.47	ns	-0.45
	35 × 90	ns	0.47	ns	-0.29
	45 × 90	ns	0.48	ns	ns

TABLE 6—Correlation matrix for margin knots. All coefficients shown were significant at the 1% level

	Cross-section (mm)	MOE	MOR	Density	KAR
MOR	35 × 70	0.84	1		
	35 × 90	0.75	1		
	45 × 90	0.87	1		
Density	35 × 70	0.44	0.33	1	
	35 × 90	0.67	0.39	1	
	45 × 90	0.58	0.44	1	
KAR	35 × 70	-0.77	-0.81	ns	1
	35 × 90	-0.59	-0.76	ns	1
	45 × 90	-0.75	-0.75	ns	1
ln (MOR)	35 × 70	0.88	0.94	0.33	-0.88
	35 × 90	0.77	0.95	0.36	-0.87
	45 × 90	0.86	0.94	ns	-0.81

TABLE 7—Correlation matrix for margin/face knots. All coefficients shown were significant at the 1% level

	Cross-section (mm)	MOE	MOR	Density	KAR
MOR	35 × 70	0.66	1		
	35 × 90	0.70	1		
	45 × 90	0.71	1		
Density	35 × 70	ns	ns	1	
	35 × 90	0.62	0.50	1	
	45 × 90	0.59	0.35	1	
KAR	35 × 70	-0.66	-0.64	0.31	1
	35 × 90	-0.62	-0.49	ns	1
	45 × 90	-0.56	-0.56	ns	1
Y	35 × 70	ns	0.42	ns	ns
	35 × 90	-0.34	ns	ns	0.47
	45 × 90	ns	0.36	ns	ns

TABLE 8—Correlation matrix for arris knots. All coefficients shown were significant at the 1% level

	Cross-section (mm)	MOE	MOR	Density
MOR	35 × 70	0.78	1	
	35 × 90	0.81	1	
	45 × 90	0.78	1	
Density	35 × 70	0.64	0.51	1
	35 × 90	0.64	0.56	1
	45 × 90	0.64	0.57	1
KAR	35 × 70	-0.57	-0.71	ns
	35 × 90	ns	-0.47	ns
	45 × 90	-0.66	-0.59	ns

Statistical tests showed that there were no significant differences between the regression coefficients for any of the 12 regression models but that there were differences in the intercepts. Data were therefore pooled to derive a best estimate of the population regression coefficients for density and KAR. These were found to be 0.02446 and -10.209 for density and KAR respectively. Based on this over-all coefficient, revised estimates of the intercepts were calculated for each cross-section and these are given in Table 9. For example, the regression model for 35 × 90-mm face knots was:

$$\text{MOE} = 0.02446 \times \text{density} - 10.209 \times \text{KAR} - 0.09$$

Stress-grading machines measure the MOE parameter, and the high correlation with MOR is utilised in the assignment of stress-grades. Mechanical grade is therefore directly related to MOE, with the assigned stress-grade decreasing as MOE decreases.

TABLE 9—Intercepts of multiple regressions of MOE on density and KAR

Cross-section (mm)	Intercept			
	Margin	Face	Margin/Face	Arris
35 × 70	-0.43	+0.30	+0.20	-1.83
35 × 90	-0.51	-0.09	+0.09	-2.23
45 × 90	-0.91	-0.53	-0.43	-1.75

The effect of density and KAR on stress-grade for the 35 × 90-mm specimens with face knots is depicted in Fig. 2. Regression lines are shown for mean density and plus and minus 1 and plus and minus 2 standard deviations from the mean. The dotted lines are the mechanical stress-grade MOE limits and the dot on the mean density line represents timber with average density and average KAR. This graph has great importance because it shows that the grade of timber with average KAR of 0.33 and average density of about 520 is F8 and can be affected by small changes in density or KAR.

For example, if, as a result of a particular silvicultural treatment, the density of radiata pine decreased by about 10% (i.e., 1 s.d.) compared to a control stand with properties similar to the timber in this study, then the average stress-grade of 35 × 90-mm timber with face knots produced from the treated stand would be expected to be one grade lower at F5 resulting in poorer over-all grade yields. Conversely, if density increased then over-all grade yields would improve.

Assuming that MOE and density data are normally distributed (reasonable because skewness was generally low and kurtosis was close to 3 as it is for the normal distribution) and assuming that the standard deviation of the density data remains constant as density decreases, theoretical grade yields can be calculated. This was done by determining the probability of occurrence within each of the MOE ranges that defines the particular F grade by calculating areas under the normal distribution probability density function. This probability is the required percentage yield in the grade.

A standardised value was determined for the recovered timber based on the normally accepted grade pricing relativities of 1.25 for F11, 1.15 for F8, 1.00 for F5, 0.80 for F4, and 0.50 for Reject. The value was calculated by multiplying the fraction in each grade by the pricing relativity and summing these data for all grades. This value could be used to determine current mill-door product values by multiplying it by the rate (\$/m³) for F5 grade timber.

Calculated grade yields and values for timber with face knots are shown in Table 10. The three stands represent a control stand (with average timber density) and two other stands – one where timber density is 10% higher than the control and another where timber density is 10% lower than the control. The better grade yields in the stand with higher wood density can be seen clearly and this is reflected in the 4–7% higher value of that stand. The stand with lower timber density had poorer grade yields and from 7% to 10% lower values than the control.

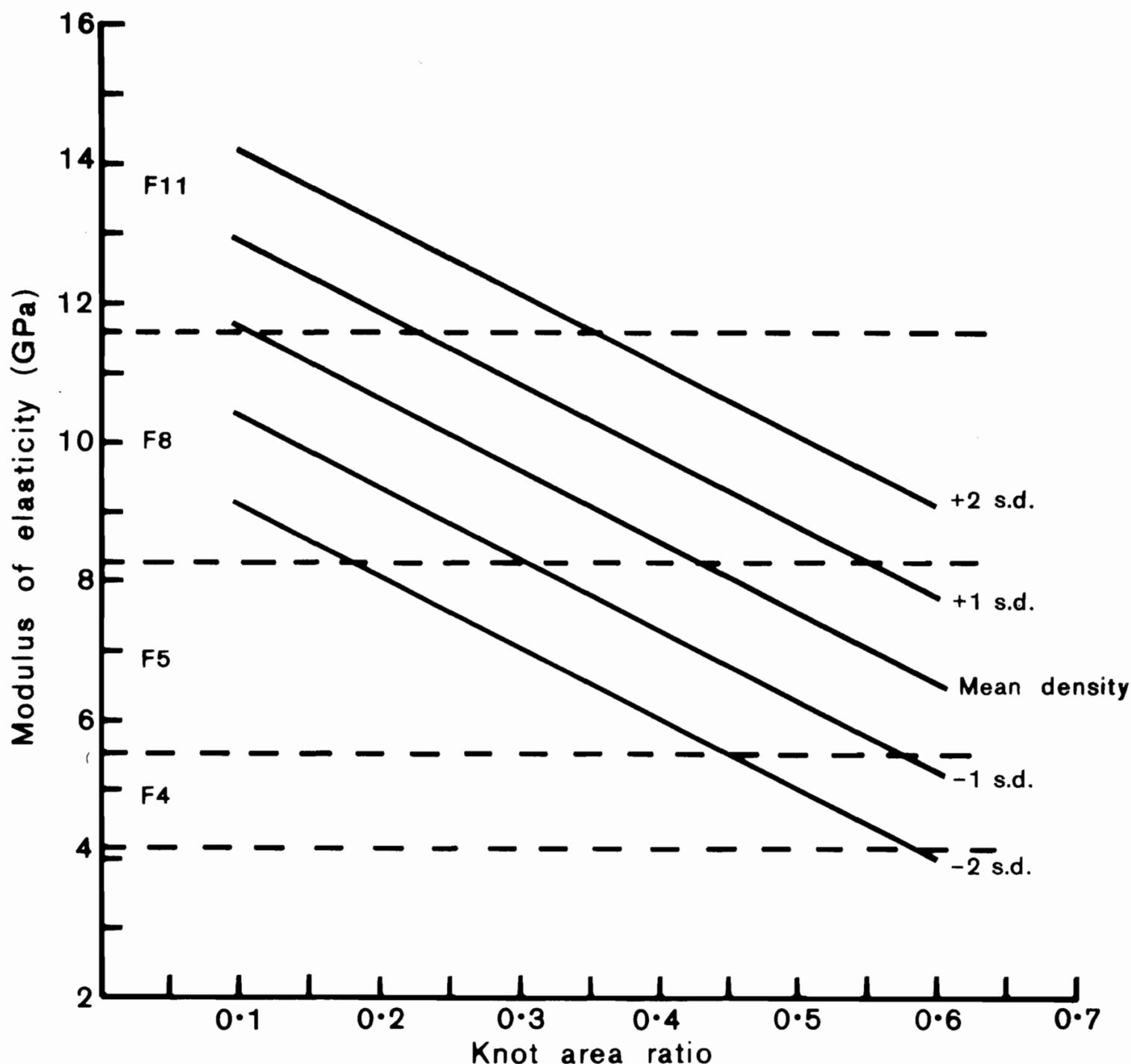


FIG. 2—Effect of density and knot area ratio on modulus of elasticity for 35 × 90-mm radiata pine with face knots. The relationship is drawn for the mean density and for ± 1 and ± 2 standard deviations from the mean. Mechanical stress-grade modulus of elasticity boundaries are shown dotted.

TABLE 10—Calculated stress-grade yields and standardised timber values for radiata pine timber with face knots. The three theoretical stands were a control with average density, one with timber with 10% lower density, and one with timber with 10% higher density

Cross-section (mm)	Relative wood density in stand	Stress-grade yield (%)					Standardised value
		F11	F8	F5	F4	Reject	
35 × 70	High density	17	50	25	6	2	1.10
35 × 70	Control	16	31	35	12	6	1.03
35 × 70	Low density	6	21	38	19	16	0.93
35 × 90	High density	32	48	17	2	1	1.14
35 × 90	Control	19	46	28	5	2	1.10
35 × 90	Low density	8	38	37	10	7	1.02
45 × 90	High density	71	18	9	1	1	1.20
45 × 90	Control	51	25	18	3	3	1.14
45 × 90	Low density	28	26	30	6	10	1.05

To gauge the effect of branch size changes on stress-grade yields and values, density was held constant and the branch size differences (from the control with average knot size) required to produce the grade yields of Table 10 were determined. These are shown in complete form in Table 11 and represent a branch size change of around plus and minus 30–40%. Similar trends would be expected to occur for the other defect types because of the similarity in the relationships and in the density statistics across all knot types and cross-sections.

It can be assumed, therefore, that a decrease of 10% in average timber density will lead to a general 7–10% decrease in mechanically graded timber value and to significantly poorer grade recoveries. Equivalent results would be obtained if, instead of density decreasing, knot size increased by between 30% and 44%. Conversely, a 10% increase in density or a 33% decrease in knot size would lead to a general increase in mechanically graded timber value of between 4% and 7% and also result in significantly better grade yields thus improving the utilisation potential of the resource.

Grant (1980), in a study of the sawn recovery of 5-m logs cut from radiata pine trees in the A.C.T., found that for commercially mature trees log value per cubic metre of product was dependent upon log position in the tree and also upon the maximum branch size per log, with the effect of branch size on value diminishing as log position (height) increased. Using his results, a 40% increase in branch size for the butt and second logs reduced the log values by 8% for the butt log and 6% for the second log. These results are similar to those found in the present study.

Combined Effects of MOE, KAR and Knot Position, and Density on MOR

MOE was highly correlated with MOR with coefficients of determination (CD) ranging from approximately 0.5 for face and margin/face knots to 0.6 for arris knots and 0.7 for margin knots (Tables 5 to 8).

The CD for face knots improved significantly to around 0.6 (i.e., by 0.2) when KAR and the distance X (Fig. 1) were introduced as additional independent variables.

TABLE 11—Calculated stress-grade yields and standardised timber values for radiata pine timber with face knots. The three theoretical stands were a control with average knot size, one with timber with smaller knots, and one with timber with larger knots

Cross-section (mm)	Relative knot size in stand	Stress-grade yield (%)					Standardised value
		F11	F8	F5	F4	Reject	
35 × 70	-33%	17	50	25	6	2	1.10
35 × 70	Control	16	31	35	12	6	1.03
35 × 70	+30%	6	21	38	19	16	0.93
35 × 90	-33%	32	48	17	2	1	1.14
35 × 90	Control	19	46	28	5	2	1.10
35 × 90	+44%	8	38	37	10	7	1.02
45 × 90	-32%	71	18	9	1	1	1.20
45 × 90	Control	51	25	18	3	3	1.14
45 × 90	+36%	28	26	30	6	10	1.05

The CD for margin knots improved significantly to around 0.75 (i.e., by 0.05) when KAR was introduced and again to 0.85 (i.e., by 0.15 over-all) when MOR was logarithmically transformed. The CD for margin/face knots improved significantly to around 0.7 (i.e., by 0.2) when KAR and the distance Y (Fig. 1) were introduced as additional independent variables. The distance Y was found to be generally more significant in this regression than any of the other possible measurements that could be taken of this knot type. The CD for arris knots improved to around 0.7 (i.e., by 0.1) when KAR was introduced as another independent variable.

The improvements in CD when the KAR and knot position measurements (X or Y) are introduced into the regression of MOR on MOE range from 0.1 for face and arris knots to 0.15 for margin knots and 0.2 for margin/face knots. These results indicate that some improvement in the accuracy of prediction of MOR using mechanical grading would be achieved if KAR for all four knot types and knot position for face and margin/face knots could be determined. The complexity, however, of measuring these parameters with the degree of accuracy and repeatability required would be considerable if attempted in a mill grading situation.

For radiata pine in New Zealand, G. B. Walford (unpubl. data) found CD of 0.55 to 0.60 for the regression of MOR on MOE and a 0.15 improvement when knot area in a specified section of the outer margin of the timber cross-section was included in the regression. These results are similar to those found here for margin knots. Regression equations are given in Appendix 1.

The inclusion of density as another independent variable in the regressions of MOR on MOE, KAR, and knot position for face and margin/face knots showed that density did not contribute significantly to the relationships, a result also found by Walford (1981) in his work on radiata pine in New Zealand. This indicates that if MOE is measured (as in mechanical stress-grading) then measurement of timber density is superfluous if we are attempting to predict MOR. Prediction of MOR would, however, be improved if KAR and knot position for face and margin/face knot types are taken into account in addition to the measurement of MOE.

The substitution of density for MOE in the above relationships produced poorer correlations for all cross-sections and knot types. The regression equations are given in Appendix 2.

Effect of KAR on MOR – an Evaluation of the Visual Grading Rules for Radiata pine

Data for the three cross-sections for each knot type were pooled for the investigation of the effect of KAR on MOR. This was considered justified because in practice there are no differences in grading rules for any of the cross-section sizes considered here. Differences between the individual regressions of KAR on MOR were in fact small or non-significant (as with the face knots).

The regressions and lower 1%, 2.5%, and 5% exclusion lines (determined from the regression lines by using a reduction of 2.33, 1.96, and 1.64 standard errors of MOR respectively) for all four knot types together with the actual data values are shown in Fig. 3 to 6.

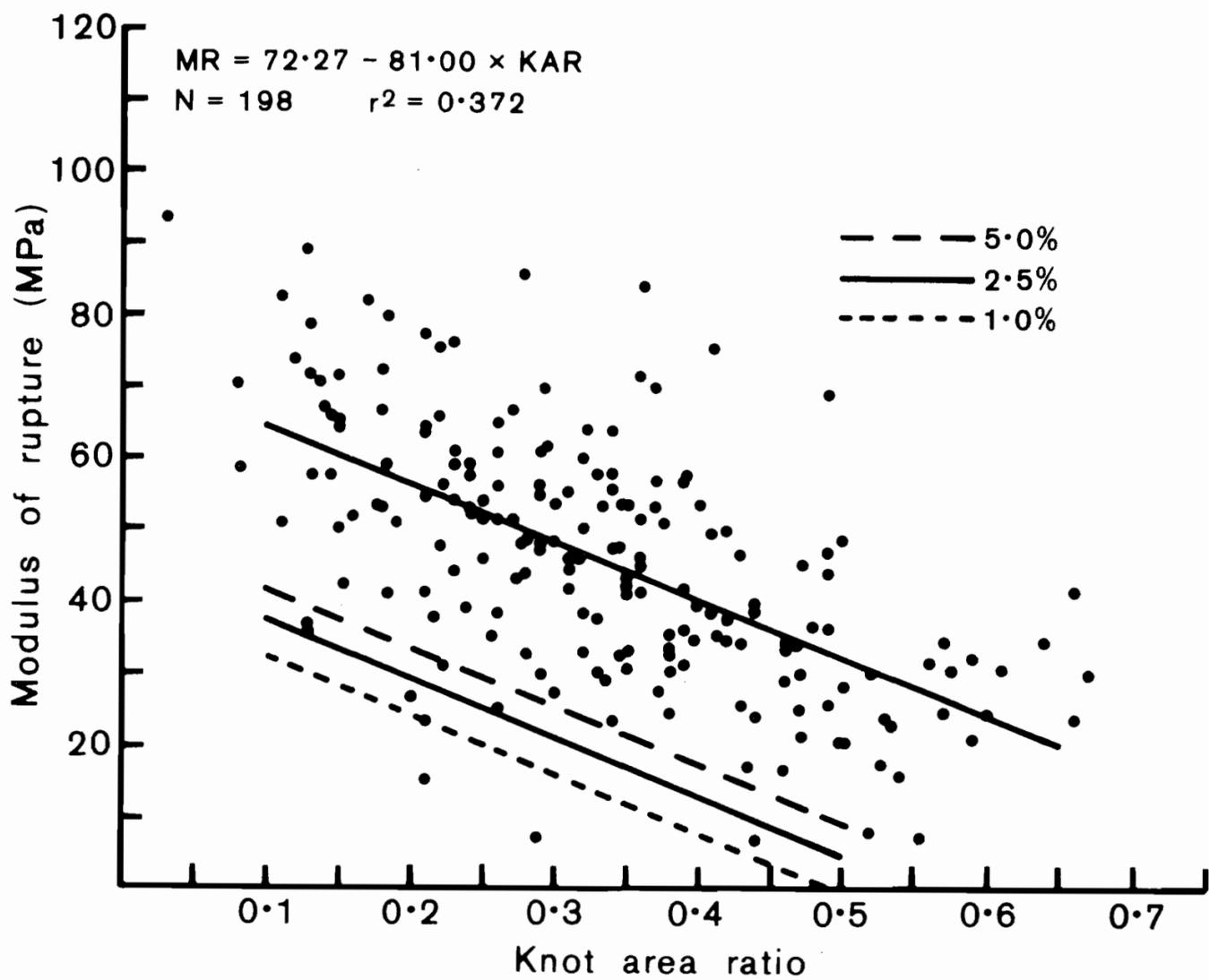


FIG. 3—Relationship between modulus of rupture and knot area ratio for face knots for the three cross-sections pooled.

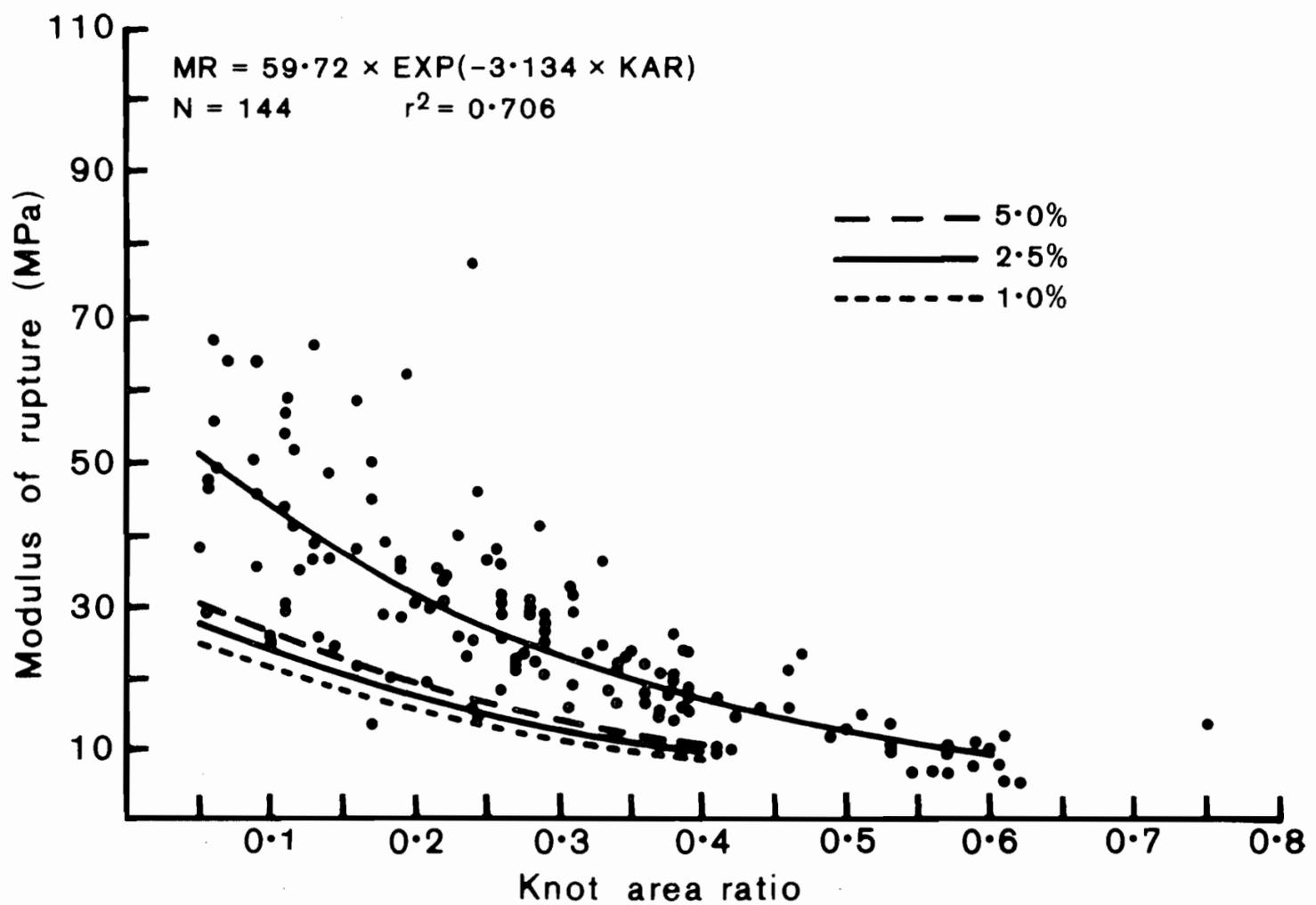


FIG. 4—Relationship between modulus of rupture and knot area ratio for margin knots for the three cross-sections pooled.

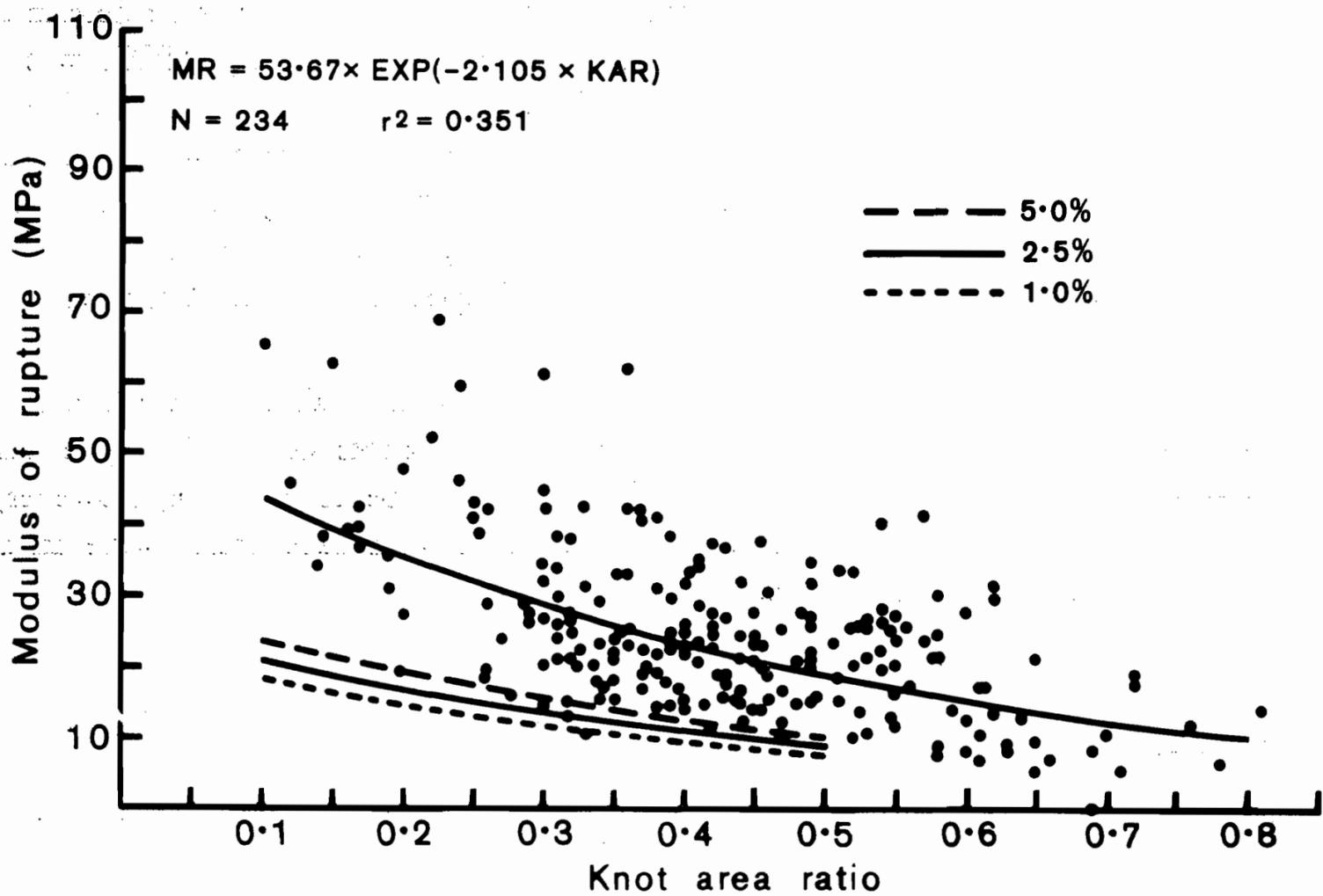


FIG. 5—Relationship between modulus of rupture and knot area ratio for margin/face knots for the three cross-sections pooled.

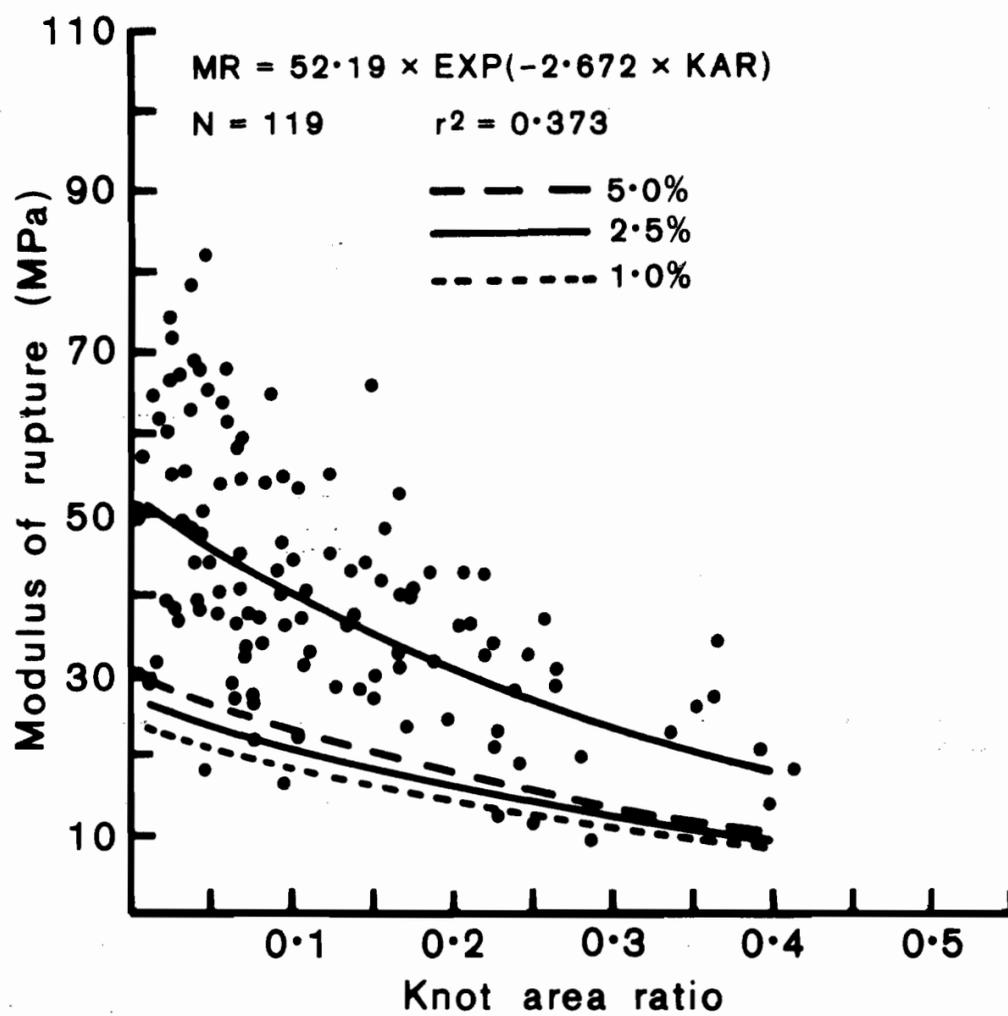


FIG. 6—Relationship between modulus of rupture and knot area ratio for arris knots for the three cross-sections pooled.

KAR for the minimum MOR values permitted in each stress-grade were determined from the 5% lower exclusion lines. The value chosen for minimum MOR was 2.2 times the basic working stress in bending and is the normally accepted value for visually graded timber. These data are given in Table 12 together with the KAR equivalent to the knot size limits specified in the current visual grading rules (SAA 1973). Also included are the levels for F14 and F11 grades from a proposed draft combined softwood standard to cover most softwood species used in Australia (SAA 1983).

The maximum KAR used for the margin/face knot in Table 12 are the limits specified for margin knots in AS1490 because they are knots of similar type. Also, AS1490 specifies a limit as to how close a face knot can be to an edge; however, it was found that only one or two non-critical specimens with face knots were in this category and so these were not excluded.

TABLE 12—Calculated 5th percentile values of KAR and the maximum KAR permitted by AS1490 and the draft combined softwood standard for the various knot types. F_b is the basic working stress in bending specified in AS1720 (SAA 1975)

Stress-grade	$F_b \times 2.2$ (MPa)	Calculated KAR at 5th percentile	Max. KAR permitted
Face knot			
F14*	30.8	0.23	0.25‡
F11*	24.2	0.31	0.33‡
F8†	18.9	0.38	0.40‡
F7†	15.2	0.42	0.50‡
F5†	12.1	0.46	0.66‡
Margin knot			
F14*	30.8	—	0.15‡
F11*	24.2	0.13	0.25‡
F8†	18.9	0.21	0.33‡
F7†	15.2	0.28	0.40‡
F5†	12.1	0.35	0.40‡
Margin/face knot			
F14*	30.8	—	0.15‡
F11*	24.2	0.08	0.25‡
F8†	18.9	0.20	0.33‡
F7†	15.2	0.30	0.40‡
F5†	12.1	0.41	0.40 OK
Arris knot			
F14*	30.8	—	0.08‡
F11*	24.2	0.08	0.13‡
F8†	18.9	0.17	0.17 OK
F7†	15.2	0.25	0.20 OK
F5†	12.1	0.34	0.20 OK

* Extra grade permitted in the draft softwood standard

† Grade permitted by AS1490

‡ KAR too large at 5th percentile level.

- GRANT, D. J. 1980: The influence of age, site and stocking density of plantations on grade and monetary recovery of radiata pine scantlings and boards. M.Sc. Thesis, Australian National University, Canberra.
- SAA 1973: AS1490-1973, Visually Graded Radiata Pine Scantling (amended 1977). Standards Association of Australia.
- 1975: AS1720-1975, Timber Engineering Code. Standards Association of Australia.
- 1978: AS1748, AS1749-1978, Mechanically Stress Graded Timber and Rules for Mechanical Stress Grading of Timber. Standards Association of Australia.
- 1983: TM/101/83-3, Draft Standard for Timber - Seasoned Softwood - Visually Stress Graded. Standards Association of Australia.
- WALFORD, G. B. 1981: Combined visual and mechanical grading of *Pinus radiata*. **New Zealand Journal of Forestry Science** 11: 298-303.

In almost every grade and for all knot types, the maximum KAR permitted by AS1490 exceeded the KAR value calculated from the 5% lower exclusion lines. The only exceptions were for arris knots in the F8, F7, and F5 grades and for the margin/face knots in the F5 grade.

These results indicate that if the current and proposed draft visual grading rules were used to grade the timber used in this study then a large percentage of the timber would be graded one or two F grades too high. Generally, the margin and margin/face knots would be graded two grades high and the face knots one grade high. The F14 and F11 arris knots would also be graded one grade too high. This conclusion can be extended to cover radiata pine in general because of the extensive nature of the sampling.

CONCLUSION

This work has shown that changes in density and knot size will significantly affect mechanical stress-grade yields in radiata pine.

Forest managers will need to be cautious in their management of plantations for the production of structural timber when they consider using practices aimed at simply increasing the rate of growth without the use of treatments that may compensate for the adverse effects. Increasing the rate of growth may have the effect of reducing the value of the standing timber per unit volume and may lead to timber utilisation problems in the future. This would be because of poorer grade yields due to reductions in the density of standing timber (trees will reach marketable size more quickly and will have lower over-all density due to both age and rate of growth effects) and because the trees will have larger branches.

Accuracy of prediction of modulus of rupture using modulus of elasticity (as in mechanical grading) was shown to be independent of timber density, the modulus of elasticity fully accounting for variations in density. Knot area ratio and sometimes knot position were found to significantly improve the prediction of modulus of rupture when added to the regression of modulus of rupture on modulus of elasticity.

For the most common knot types and timber cross-sections, radiata pine timber graded to the normal visual grading rules will fail to meet normal strength requirements. For margin knots the grading was found to be two F grades too high and for the other types it was generally one F grade too high. A re-assessment of the visual grading rules for this species is therefore warranted.

REFERENCES

- ANTON, A. 1977: Mechanical stress grading of timber and derivation of basic working stresses. Proceedings of the 18th Forest Products Research Conference, Melbourne.
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APPENDIX 1

REGRESSIONS OF MODULUS OF ELASTICITY, KNOT AREA RATIO,
AND KNOT POSITION ON MODULUS OF RUPTURE

The coefficient of determination and the standard deviation respectively are shown after the equation (MOE and MOR = MPa; X and Y = mm).

Face knots

$$35 \times 70\text{-mm MOR} = 3.22 \times \text{MOE} - 33.0 \times \text{KAR} + 0.343 \times X + 17.88 \quad (0.61, 10.60)$$

$$35 \times 90\text{-mm MOR} = 3.52 \times \text{MOE} - 32.4 \times \text{KAR} + 0.604 \times X + 9.38 \quad (0.60, 11.97)$$

$$45 \times 90\text{-mm MOR} = 4.36 \times \text{MOE} - 29.2 \times \text{KAR} + 0.465 \times X + 6.11 \quad (0.66, 10.14)$$

There were no significant differences in regression models for the three cross-sections and the appropriate model was found to be:

$$\text{MOR} = 3.666 \times \text{MOE} - 30.17 \times \text{KAR} + 0.4884 \times X + 10.75$$

Margin knots

$$35 \times 70\text{-mm } \ln(\text{MOR}) = 0.1200 \times \text{MOE} - 1.806 \times \text{KAR} + 2.65 \quad (0.88, 0.197)$$

$$35 \times 90\text{-mm } \ln(\text{MOR}) = 0.0915 \times \text{MOE} - 2.32 \times \text{KAR} + 2.94 \quad (0.85, 0.239)$$

$$45 \times 90\text{-mm } \ln(\text{MOR}) = 0.1384 \times \text{MOE} - 1.47 \times \text{KAR} + 2.37 \quad (0.81, 0.268)$$

There were significant differences in the intercepts of the regression models for the different cross-sections but not in the coefficients. The appropriate models were:

$$35 \times 70\text{-mm } \ln(\text{MOR}) = 0.11144 \times \text{MOE} - 1.9469 \times \text{KAR} + 2.7752$$

$$35 \times 90\text{-mm } \ln(\text{MOR}) = 0.11144 \times \text{MOE} - 1.9469 \times \text{KAR} + 2.6521$$

$$45 \times 90\text{-mm } \ln(\text{MOR}) = 0.11144 \times \text{MOE} - 1.9469 \times \text{KAR} + 2.7478$$

Margin/face knots

$$35 \times 70\text{-mm MOR} = 2.04 \times \text{MOE} - 23.5 \times \text{KAR} + 0.453 \times Y + 10.76 \quad (0.71, 5.44)$$

$$35 \times 90\text{-mm MOR} = 3.11 \times \text{MOE} - 29.2 \times \text{KAR} + 0.499 \times Y - 0.12 \quad (0.69, 6.79)$$

$$45 \times 90\text{-mm MOR} = 3.18 \times \text{MOE} - 28.2 \times \text{KAR} + 0.376 \times Y + 4.66 \quad (0.73, 6.24)$$

There were significant differences in the intercepts of the regressions but not in the coefficients. The appropriate models were:

$$35 \times 70\text{-mm MOR} = 2.824 \times \text{MOE} - 25.45 \times \text{KAR} + 0.4110 \times Y + 5.75$$

$$35 \times 90\text{-mm MOR} = 2.824 \times \text{MOE} - 25.45 \times \text{KAR} + 0.4110 \times Y + 2.57$$

$$45 \times 90\text{-mm MOR} = 2.824 \times \text{MOE} - 25.45 \times \text{KAR} + 0.4110 \times Y + 5.79$$

Arris knots

$$35 \times 70\text{-mm MOR} = 3.48 \times \text{MOE} - 59.90 \times \text{KAR} + 13.00 \quad (0.71, 8.98)$$

$$35 \times 90\text{-mm MOR} = 4.10 \times \text{MOE} - 45.23 \times \text{KAR} + 4.81 \quad (0.74, 7.12)$$

$$45 \times 90\text{-mm MOR} = 4.93 \times \text{MOE} - 21.40 \times \text{KAR} + 1.10 \quad (0.61, 9.99)$$

There were significant differences in the intercepts of the regressions but not in the coefficients. The appropriate models were:

$$35 \times 70\text{-mm MOR} = 4.130 \times \text{MOE} - 42.04 \times \text{KAR} + 4.33$$

$$35 \times 90\text{-mm MOR} = 4.130 \times \text{MOE} - 42.04 \times \text{KAR} + 4.21$$

$$45 \times 90\text{-mm MOR} = 4.130 \times \text{MOE} - 42.04 \times \text{KAR} + 9.32$$

APPENDIX 2

REGRESSIONS OF DENSITY, KNOT AREA RATIO, AND KNOT POSITION ON MODULUS OF RUPTURE

The coefficient of determination and the standard deviation respectively are shown after the equation (MOR = MPa; density (D) = kg/m³; X and Y = mm).

Face knots

$$35 \times 70\text{-mm MOR} = 0.0793 \times D - 61.2 \times \text{KAR} + 0.418 \times X + 15.63 \quad (0.53, 11.68)$$

$$35 \times 90\text{-mm MOR} = 0.0987 \times D - 69.3 \times \text{KAR} + 0.584 \times X + 3.17 \quad (0.50, 13.40)$$

$$45 \times 90\text{-mm MOR} = 0.1412 \times D - 67.2 \times \text{KAR} + 0.448 \times X - 16.05 \quad (0.60, 10.99)$$

There were no significant differences in regression models for the three cross-sections and the appropriate model was found to be:

$$\text{MOR} = 0.1063 \times D - 64.78 \times \text{KAR} + 0.4910 \times X + 0.50$$

Margin knots

$$35 \times 70\text{-mm } \ln(\text{MOR}) = 0.002595 \times D - 3.11 \times \text{KAR} + 2.81 \quad (0.82, 0.241)$$

$$35 \times 90\text{-mm } \ln(\text{MOR}) = 0.003290 \times D - 3.10 \times \text{KAR} + 2.31 \quad (0.84, 0.252)$$

$$45 \times 90\text{-mm } \ln(\text{MOR}) = 0.003290 \times D - 3.04 \times \text{KAR} + 2.34 \quad (0.72, 0.325)$$

There were significant differences in the intercepts of the regression models for the different cross-sections but not in the coefficients. The appropriate models were:

$$35 \times 70\text{-mm } \ln(\text{MOR}) = 0.002997 \times D - 3.089 \times \text{KAR} + 2.5868$$

$$35 \times 90\text{-mm } \ln(\text{MOR}) = 0.002997 \times D - 3.089 \times \text{KAR} + 2.4583$$

$$45 \times 90\text{-mm } \ln(\text{MOR}) = 0.002997 \times D - 3.089 \times \text{KAR} + 2.5070$$

Margin/face knots

$$35 \times 70\text{-mm MOR} = 0.0534 \times D - 51.0 \times \text{KAR} + 0.447 \times Y + 12.62 \quad (0.63, 6.10)$$

$$35 \times 90\text{-mm MOR} = 0.0878 \times D - 64.9 \times \text{KAR} + 0.464 \times Y - 3.64 \quad (0.62, 7.51)$$

$$45 \times 90\text{-mm MOR} = 0.0746 \times D - 56.4 \times \text{KAR} + 0.391 \times Y + 2.88 \quad (0.62, 7.36)$$

There were significant differences in the intercepts of the regressions but not in the coefficients. The models were:

$$35 \times 70\text{-mm MOR} = 0.0769 \times D - 57.07 \times \text{KAR} + 0.4126 \times Y + 3.53$$

$$35 \times 90\text{-mm MOR} = 0.0769 \times D - 57.07 \times \text{KAR} + 0.4126 \times Y - 0.11$$

$$45 \times 90\text{-mm MOR} = 0.0769 \times D - 57.07 \times \text{KAR} + 0.4126 \times Y + 1.60$$

Arris knots

$$35 \times 70\text{-mm MOR} = 0.0931 \times D - 95.60 \times \text{KAR} + 2.56 \quad (0.64, 10.90)$$

$$35 \times 90\text{-mm MOR} = 0.1195 \times D - 72.13 \times \text{KAR} - 15.96 \quad (0.53, 9.51)$$

$$45 \times 90\text{-mm MOR} = 0.1915 \times D - 77.90 \times \text{KAR} - 46.66 \quad (0.55, 10.81)$$

There were significant differences in the intercepts of the regressions but not in the coefficients. The appropriate models were:

$$35 \times 70\text{-mm MOR} = 0.1251 \times D - 82.64 \times \text{KAR} - 15.92$$

$$35 \times 90\text{-mm MOR} = 0.1251 \times D - 82.64 \times \text{KAR} - 17.64$$

$$45 \times 90\text{-mm MOR} = 0.1251 \times D - 82.64 \times \text{KAR} - 10.85$$