LOG QUALITY AND THE STRENGTH AND STIFFNESS OF STRUCTURAL TIMBER

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ABSTRACT

A sample of 78 **Pinus radiata** D. Don logs was measured and sawn to maximise yields of 100 × 50-mm and 200 × 50-mm timber. The average bending strength and stiffness of the timber were found to depend on the basic density of the log but the lower fifth-percentile strength was more dependent on branch index. For the 28-year-old stand sampled, logs with a low branch index yielded 100 × 50-mm timber of No. 1 Framing grade strength without grading of the timber. When the timber was graded the influence of branch index on strength was reduced but logs with a large branch index yielded graded timber that was below strength.

Keywords: strength; stiffness; basic density; branch index; **Pinus radiata**.

INTRODUCTION

New Zealand's *Pinus radiata* resource is plantation grown and much of the timber is beginning to be cut from managed stands planted in the late 1950s. The tending of the trees in these managed stands has involved establishment, thinning, and pruning to achieve control of growth and log quality. More recently tree seed stock has been selected to produce adult trees of desired form, branching habit, wood density, and vigour. Planting of stands of improved stock began in 1969 and for the last 2 or 3 years seedlings have been entirely of seed orchard origin (M. J. Carson pers. comm.). Many years of research in silviculture and genetic selection have provided New Zealand's foresters with a blueprint for producing fast-grown *P. radiata* forests that maximise clearwood production (Bunn 1981).

Because the clearwood sawn from pruned butt logs is likely to be too valuable for construction, timber for structural purposes will be derived mostly from unpruned stands or the upper logs of pruned trees. These logs all contain branches, and branches produce knots in the timber that have a marked effect on timber properties (Bier 1985). To determine which logs yield the best structural timber it is desirable to predict the effects of these branches and other log variables on strength and stiffness since the performance of timber in buildings depends on these properties.

Already it is possible to predict visual and machine grade recoveries from a silvicultural stand model (Whiteside 1982) but this model does not predict strength and

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stiffness of sawn timber. Also, from data reported by Walford (1982) it is clear that the strength and stiffness of graded timber vary according to site. In other words, it is not enough to predict just grade recovery, because the strength and stiffness of given grades of timber may be different for logs with different properties. Strength and stiffness are described as follows.

The strength of a material is a measure of the maximum load it can sustain without failure. Safety requires that there are adequate margins between the stresses in a structure, and the lowest likely strength of the material. The strength of timber is variable and standard methods are used to calculate the near-minimum strength values required for design. International convention is to use the lower fifth-percentile strength which means that 19 out of 20 pieces in a population will have a strength above the lower limit (CIB-W18 1978). Safety and other design factors are then applied to this limit to obtain the required margin (Fig. 1).

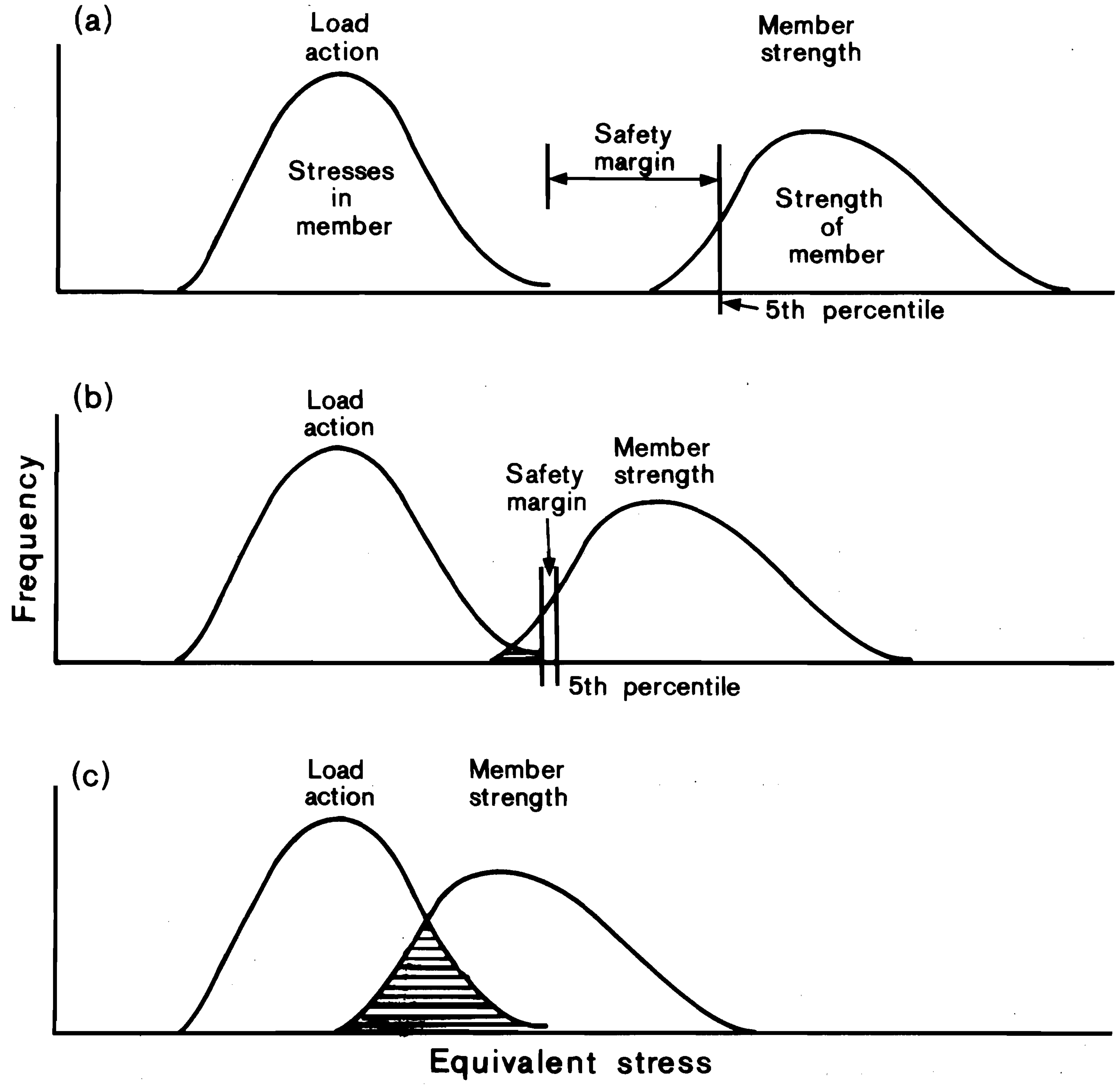

FIG. 1—Load stress and strength distributions for a structural member —
(a) Over-designed (margin too large)
(b) Acceptable margin
(c) Under-designed (stresses exceed strength for part of the distributions).

Material stiffness determines how far components in the structure deflect when they carry load. Excessive deflection or sag is visually unacceptable and can cause damage to other components. For example, a beam supporting a roof over a window would crack the glass if it was allowed to deflect too far. Though some pieces deflect more than others, an average value of stiffness is adequate for design since the differences in deflection relative to the total are often imperceptible.

The two log parameters that promise the most useful prediction of both strength and stiffness are basic density and branch index. Extensive density surveys (Cown & McConchie 1983) have identified and classified low-, medium-, and high-density sites, as well as the likely density of logs of different ages from those sites. Branch index is an easily measured external characteristic being the average of the largest branch in each of the four quadrants of a log. Bier (1985) derived relationships that expressed the **average** strength and stiffness of the timber from **each** log as a function of the branch index and basic density of the log.

However, to ensure adequate safety margins, it is essential to analyse the strength data at **near minimum**, not average values. To establish a reliable fifth-percentile for a population of graded timber, a large sample is normally required. (Madsen (1981) recommended a minimum of 200 specimens per grade tested.) This is impossible for individual logs containing a relatively small number of pieces. To obtain reasonable samples, logs of similar properties must be grouped together. Moreover, if relationships are determined from groups of logs they more closely represent what occurs in practice where graded timber is derived from a quantity of logs, and not individual specimens. This becomes more important now that log grades have been promulgated (Whiteside & Manley 1985) whereby sawmillers may convert logs of a limited range of properties into sawn timber, rather than milling all the logs from a site. Though such grouping is seen as desirable for ease of milling, the grouping of logs of similar properties into log grades may affect timber properties.

The analyses in this paper are a preliminary study of the effects of branch index on the strength and stiffness of timber from a single stand of logs of low to medium basic wood density. They probably represent the lower bound for the Bay of Plenty region and provide a stepping stone for further investigation across the resource.

MATERIAL AND METHODS

Logs

The sample was cut from Cpt 1250 in Kaingaroa State Forest and has been fully described by Bier (1985). Selection of the 78 logs was random with respect to branch index and density to avoid distortion of the distribution of timber strengths. All logs were measured in the forest using established procedures (Whiteside 1982) to obtain end diameters, branch index (BI), and sweep. Basic density was determined from a disc cut from the upper end of each log. Logs less than 350 mm small-end diameter were sawn to maximise 100 × 50-mm framing timber. Larger logs were sawn to yield 200 × 50-mm material.

Timber

Timber was kiln dried to a target moisture content of 16% and then machined to dry dressed sizes (90 × 45 mm and 180 × 45 mm).

Test procedures have been described by Bier (1985). The 100 × 50-mm timber was cut into 1.8-m lengths and tested over a span of 1.62 m whereas the 200 × 50-mm sticks were tested over a span of 3.24 m, first at one end and, if sufficient length remained after failure, again at the other end. These spans represent typical span to depth ratios for bending members in service. This procedure yielded an average of about two and a half tests per 100 × 50-mm stick and one and a half per 200 × 50-mm stick, totals of 888 and 562 respectively.

From a plot of load against deflection for each piece the Modulus of Elasticity (EJ) was calculated. This is a measure of the stiffness of the timber. The higher the EJ, the stiffer the timber, and the less will be its deflection under load in a structure. The maximum load was recorded and the Modulus of Rupture (RJ) calculated. The RJ value is a measure of the strength of the material and this cannot be exceeded by the stresses caused by loading of real structures.

Analyses

Pieces of 100 × 50-mm timber from the logs cut to maximise 200 × 50-mm were excluded from the samples because different sizes have different strengths. Hence, properties of 100 × 50-mm timber were analysed for the small logs, and 200 × 50-mm timber for the large logs.

Individual log properties: In the earlier study (Bier 1985), the average RJ and EJ and the minimum RJ of all pieces in each log were determined. For this study, the RJ values were fitted to a 3-parameter Weibull distribution (Pierce 1976) to determine a lower fifth-percentile exclusion limit for each log. Although the number of specimens in each sample was small, each log provided a data point for determining the effect of branch index on cut-of-log properties. For No. 1 Framing and better grade pieces in each log, average EJ values were calculated. However, there were not enough pieces "in-grade" to determine fifth-percentiles of RJ from individual logs for graded timber.

Grouped log properties: Samples incorporated test values for pieces from logs with branch indices over discrete ranges to provide a reasonable number of specimens and determine at least five fifth-percentiles. Average EJ and RJ were calculated and the fifth-percentile RJ was determined as above for each group of logs. The analyses were carried out for both cut-of-log material and timber graded No. 1 Framing and better. The cut-of-log analysis provided a direct comparison between the results of grouping and individual log data.

RESULTS

The distributions of small-end diameter and branch indices are summarised in Fig. 2 and 3 respectively. The mean basic density was 389 kg/m^3 with a standard deviation of 24.7 kg/m^3.

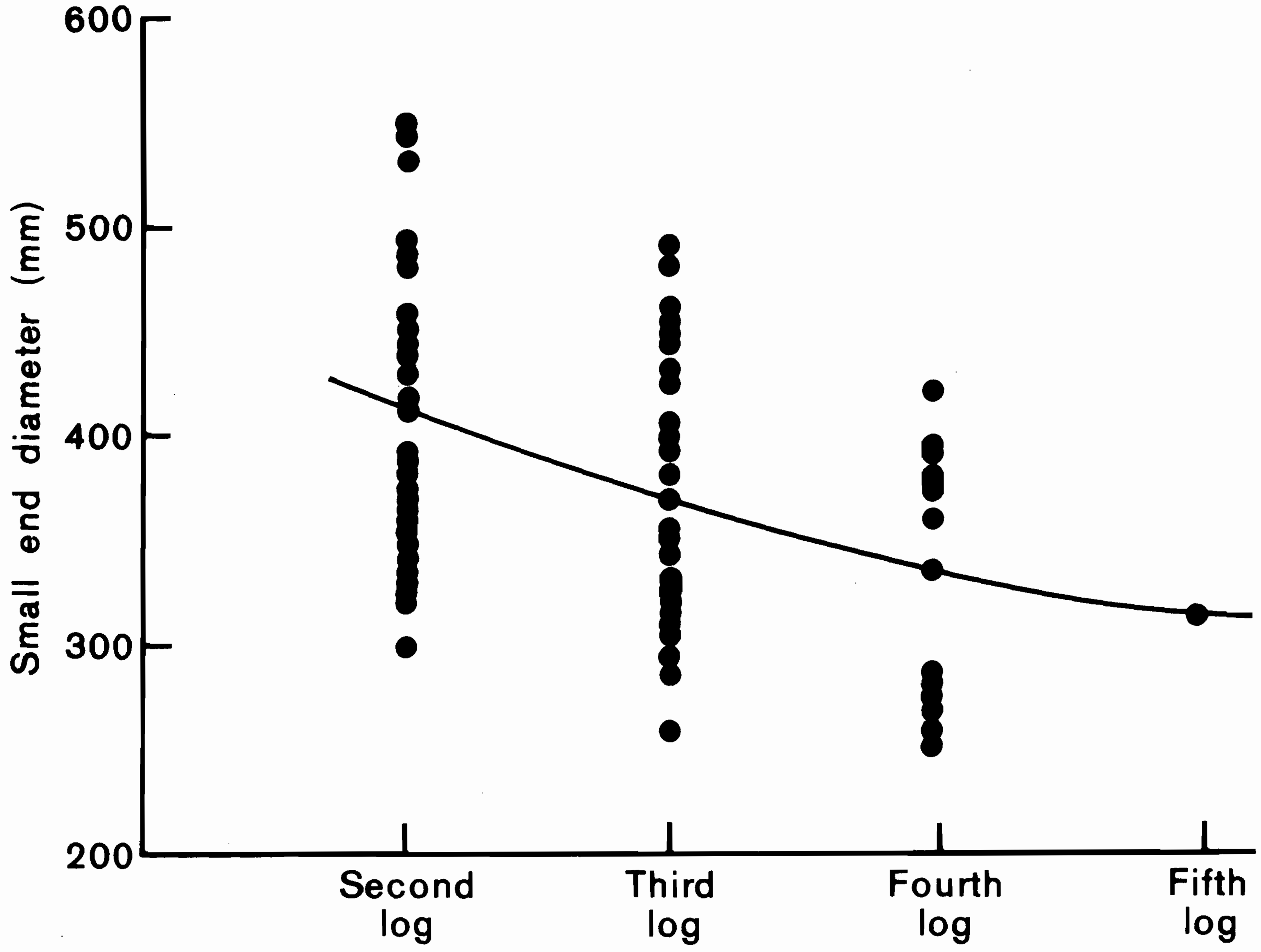

FIG. 2—Small-end diameters of the upper logs of the 28-year-old trees.

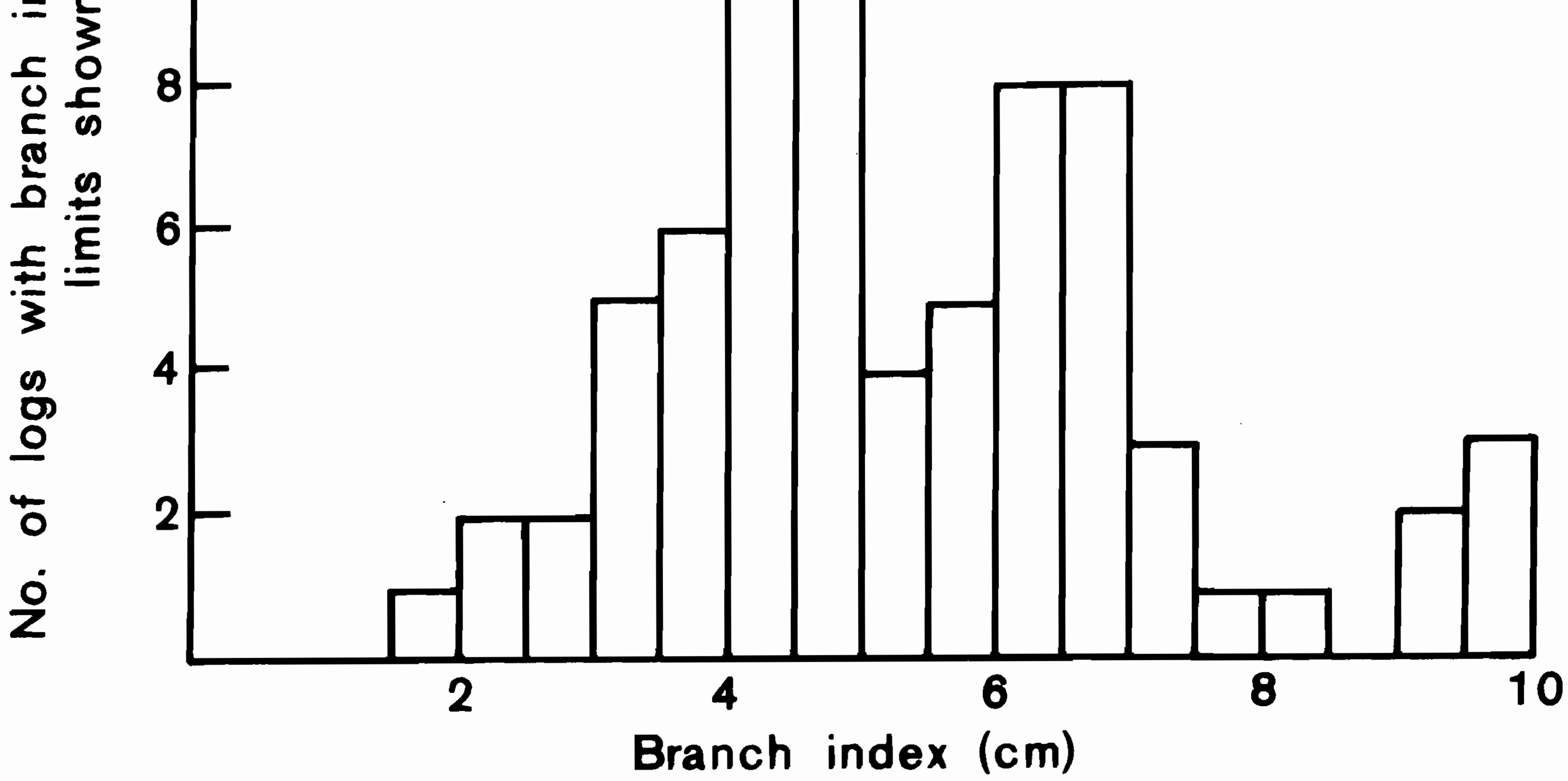

FIG. 3—Branch-size distribution for the upper logs of the 28-year-old trees.

Timber from Individual Logs

Strength

The previous study showed that average properties are more highly correlated with basic density than are the near-minimum properties, with the best prediction of minimum strength obtained with branch index (BI) and basic density (BD) together. Stepwise linear regression of the fifth-percentile strength of individual logs (5% RJ) on these two variables and their product (BI × BD) yielded only simple regression equations, with branch index being the significant variable. Subsequently the simple regression equations in Table 1 were obtained. The residual standard error for all the equations was about 4.2. However, for 100 × 50-mm timber the correlation for 5% RJ on BI and BD was very similar to that for the minimum RJ determined in the previous study ($r^2 = 0.27$ and 0.15 respectively) but for the 200 × 50-mm timber the correlation was less. This is due in part to the smaller number of pieces in each log for the larger size. Very few logs had in excess of 25 pieces. For small samples the fifth percentile is not as reliable as the fifth percentile determined from a large sample. Either a greater number of individual logs with similar branch index and density would be required or logs could be grouped (as in the next section) to provide larger samples.

TABLE 1—Simple regression equations showing dependence of the fifth-percentile strengths (MPa) on three log variables for timber from individual logs

Size 100 × 50 mm 28 logs	r^2	Size 200 × 50 mm 50 logs	r^2
Equation (1)		Equation (2)	
5% RJ = 21.1 — 1.89 BI	0.25**	5% RJ = 13.3 — 0.74 BI	0.11*
5% RJ = —14.2 + 0.070 BD	0.16*	5% RJ = —9.50 + 0.048 BD	0.07
5% RJ = 19.5 — 0.0039 BI×BD	0.16*	5% RJ = 12.8 — 0.0017 BI×BD	0.08*

* significant at $p \leq 0.05$
** significant at $p \leq 0.01$

Stiffness

For cut-of-log timber, basic density accounted for 30% and 37% of the variation in stiffness for 100 and 200 × 50-mm timber respectively (Table 2). This was slightly reduced in the graded timber, more so in the smaller size. Branch index accounted for only 8% and 18% of the stiffness variation and this reduced to 6% for both sizes after grading. A lowering of the log quality by a branch index of 5 cm would produce less than a 10% lowering of the modulus of elasticity for No. 1 Framing grade. This is unlikely to cause problems in practice.

Timber from Groups of Logs

The properties of the material from groups of logs with branch indices between specified limits are summarised in Table 3. The mean branch index was determined as the average of the branch index of the pieces in the samples.

TABLE 2—Regression equations showing the dependence of modulus of elasticity EJ (GPa) on log variables for timber from individual logs

Regressions	r^2	t	Residual s.e.
Size 100 × 50 mm			
Cut-of-log timber - 28 logs			
$EJ = 0.857 + 0.0164\ BD$	0.30	(3.34)	0.71
$EJ = 8.0 - 0.178\ BI$	0.08	(−1.45)	0.81
$EJ = 1.75 + 0.0156\ BD - 0.133\ BI$	0.34	(3.18, −1.25)	0.70
No. 1 Framing grade timber - 28 logs			
$EJ = 1.76 + 0.0154\ BD$	0.18	(2.38)	0.91
$EJ = 8.57 - 0.196\ BI$	0.06	(−1.3)	0.97
Equation (3)			
$EJ = 2.73 + 0.0148\ BD - 0.170\ BI$	0.22	(2.3, −1.2)	0.90
Size 200 × 50 mm			
Cut-of-log timber - 50 logs			
$EJ = -3.66 + 0.0273\ BD$	0.37	(5.32)	0.83
$EJ = 8.29 - 0.234\ BI$	0.18	(−3.25)	0.95
$EJ = -1.72 + 0.025\ BD - 0.19\ BI$	0.48	(5.3, −3.2)	0.76
No. 1 Framing grade timber - 44 logs			
$EJ = -4.32 + 0.0314\ BD$	0.31	(4.36)	1.07
$EJ = 8.91 - 0.177\ BI$	0.06	(−1.7)	1.24
Equation (4)			
$EJ = -3.11 + 0.0299\ BD - 0.114\ BI$	0.34	(4.1, −1.3)	0.90

The fifth-percentile strengths of the samples are plotted in Fig. 4 as a function of branch index. The current basic working stress for design with No. 1 Framing grade is 6 MPa and this, when safety and load duration factors are removed corresponds to a fifth-percentile value of 13.3 MPa (Fig. 4).

Some timber from logs with extremely high branch index was very weak. This is reflected in the low fifth-percentiles for both cut-of-log and graded timber. One log with a BI of 9.75 yielded nine sticks of timber of which three broke in handling before being tested. None of the remaining pieces was No. 1 Framing grade. Regression of strength and stiffness on branch index is given in Table 4, using values from Table 3.

The Equations (5) and (6) for cut-of-log timber are remarkably similar to Equations (1) and (2) for individual logs in Table 1. Grouping has therefore not affected the relationship between strength and branch index. Only the cut-of-log regressions are significant, and there is a substantial strength reduction with increasing branch size of 100 × 50-mm material, with the strength of 100 × 50-mm timber from logs with a BI of 6 cm being about two-thirds the strength from logs with a BI of 3 cm.

TABLE 3—Statistics of timber samples obtained for groups of logs with branch indices between specified limits

Range of branch index (cm)	No. of logs	Mean basic density (kg/m³)	Mean branch index (cm)	Fifth-percentile RJ (MPa)	Mean RJ (MPa)	Mean EJ (GPa)	No. of pieces	No. 1 Framing grade (%)
				100 × 50-mm cut-of-log				
2.25-3.0	6	391	2.68	15.6	35.1	7.70	118	—
3.5 -4.0	6	390	3.70	12.0	29.9	7.34	115	—
4.25-4.5	7	393	4.48	11.3	31.3	6.87	108	—
4.75-5.75	5	383	5.16	12.7	32.8	7.51	93	—
6.25-6.5	4	377	6.40	8.4	27.9	6.63	87	—
				100 × 50-mm No. 1 Framing grade				
2.25-3.0	6	391	2.68	19.9	37.0	7.96	102	86
3.5- 4.0	6	390	3.70	13.8	32.2	7.74	65	56
4.25-4.5	7	393	4.48	17.2	36.2	7.69	61	56
4.75-5.75	5	383	5.21	18.2	37.0	7.98	39	42
6.25-6.5	4	377	6.35	10.7	30.9	6.70	46	53
				200 × 50-mm cut-of-log				
1.75-4.0	10	388	3.51	10.8	25.6	6.41	98	—
4.25-4.5	9	404	4.34	9.8	28.4	7.78	94	—
4.75-5.75	9	385	5.28	8.4	22.7	6.84	101	—
6,0 -7.75	12	385	6.37	6.4	22.3	6.30	132	—
7.0 -9.75	10	386	8.27	7.3	21.4	6.30	110	—
				200 × 50-mm No. 1 Framing grade				
1.75 -4.0	10	388	3.38	13.1	30.1	7.60	55	56
4.25 -4.5	9	404	4.35	14.1	33.1	8.33	53	56
4.75 -5.75	9	385	5.20	14.0	29.7	7.90	33	33
6.0 -7.75	12	385	6.38	14.9	31.3	7.81	36	27
7.0 -9.75	10	386	8.40	9.9	27.9	7.66	20	18

Grading of the timber has reduced the dependence on branch index since the worst pieces have been graded out. Nevertheless, for both sizes the strengths of the No. 1 Framing grade samples with the largest branch index are below that implied by the code value in spite of grading (20% for 100 × 50-mm and 27% for 200 × 50-mm) (points a and b on Fig. 4). For low branch index (point c), ungraded 100 x 50-mm has a fifth-percentile strength above 13.3 MPa.

The stiffness of timber is more highly correlated with density than with any knot characteristics (Bier 1985). This was also shown in the analysis of data from individual logs. The lack of dependence on branch index for the grouped logs is therefore not

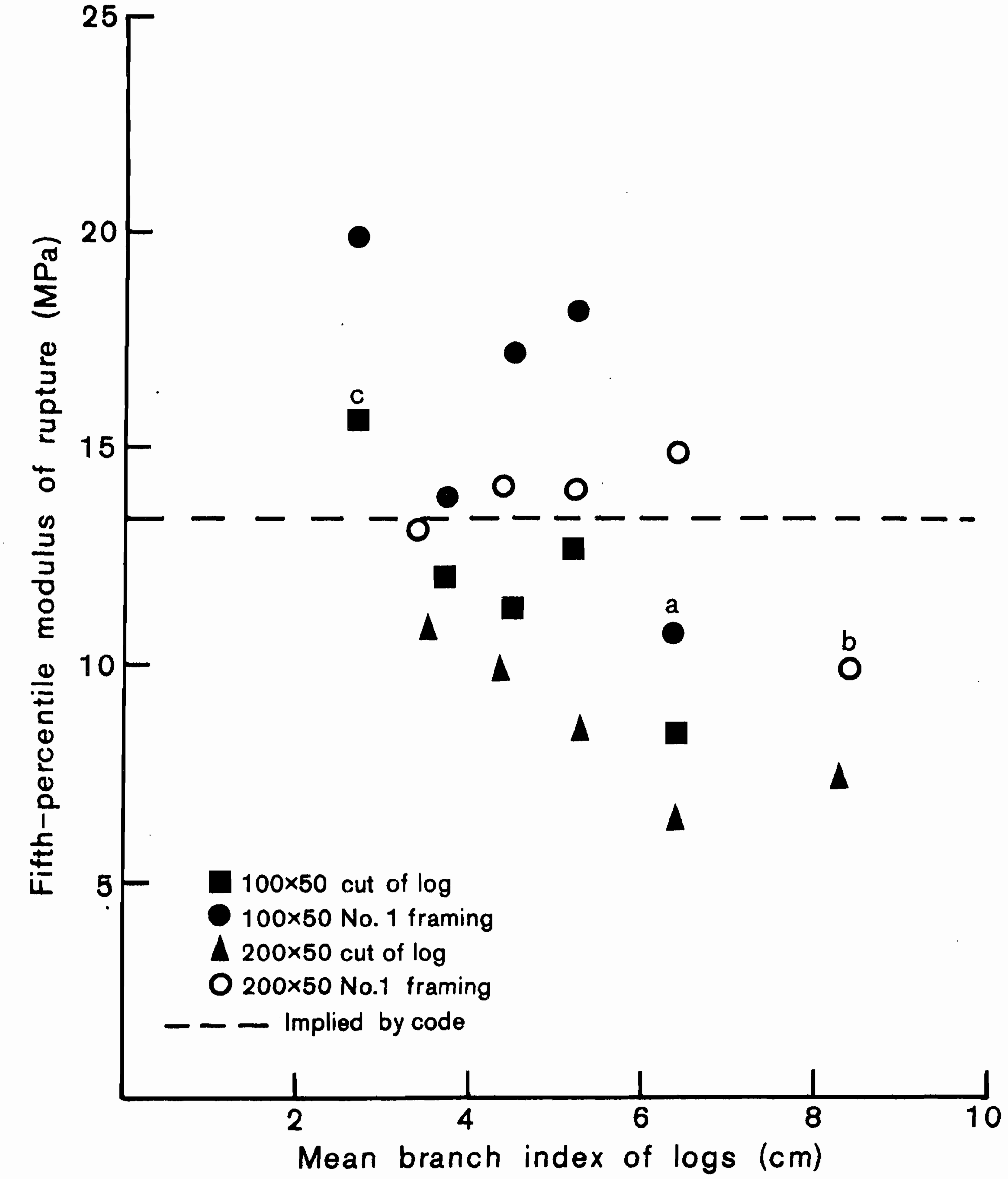

FIG. 4—Effect of branch index on fifth-percentile strength. Points a and b are for graded timber, with fifth-percentile strengths below that implied by the code. Point c shows ungraded timber with fifth-percentile strength above the code value.

TABLE 4—Regression of fifth-percentile strength and mean stiffness on branch index for timber from groups of logs with branch index between specified limits

Regressions		r^2	
Strength			
Cut-of-log			
100 × 50 mm	5% RJ = 19.3 − 1.62 BI	0.77*	Equation (5)
200 × 50 mm	5% RJ = 13.1 − 0.815 BI	0.71†	Equation (6)
No. 1 Framing grade			
100 × 50 mm	5% RJ = 23.7 − 1.73 BI	0.43 ns	
200 × 50 mm	5% RJ = 16.6 + 0.616 BI	0.36 ns	
Stiffness			
Cut-of-log			
100 × 50 mm	EJ = 8.27 − 0.237 BI	0.56 ns	
200 × 50 mm	EJ = 8.11 − 0.232	0.50 ns	
No. 1 Framing grade			
100 × 50 mm	EJ = 8.85 − 0.28 BI	0.53 ns	
200 × 50 mm	EJ = 8.09 + 0.04 BI	0.08 ns	

* significant at $p \leq 0.05$
† significant at $p \leq 0.10$
ns not significant

surprising. The lower modulus of elasticity for large branch index in the 100 × 50-mm size may be attributed to the lower mean basic density for that sample.

DISCUSSION

Strength

Framing timber of the two sizes tested is a major component of the domestic structural timber market. Observations therefore may have commercial implications. Cut-of-log 100 × 50-mm timber from logs with a branch index less than about 3 or 4 is above the strength implied by the code stress. This is without any grading rule being applied to the timber. In other words, if logs were graded to sufficient quality, grading of the timber for structural strength might not be required.

Conversely, timber graded as No. 1 Framing grade may have fifth-percentile strength below 13.3 MPa if it is obtained from a group of logs with a high branch index. This is not to say that all the timber from poorer quality logs will be below strength, but that some lower strength pieces will not have been identified by the No. 1 Framing grade rules. The large branches contribute to more-extensive grain deviations around the knots in the timber. Even clear timber cut from adjacent to such a branch can have extensive local grain deviation that is difficult to detect and has drastic effects on the strength of the timber in bending or tension. Though it may be intended that larger branch log grades should be used for the production of short clears, such clears could be used for fingerjointed glue-laminated timber stock and there are then implications for glue-laminated beam strength. If, in production, better logs are assigned for other products the strength of both sawn and glue-laminated structural timber will be adversely affected.

Stiffness

Because stiffness is dependent on density, the lowest site density class will determine the worst EJ value. Substituting (from Cown & McConchie 1983) the BD for low-site-density class (390 kg/m^3) and a high branch index (say, 9) in Equations (3) and (4), values of EJ of 7 GPa and 7.5 GPa are calculated for the two sizes.

An E value even 10% lower than the current code value of 8 GPa is unlikely to cause problems in practice, and most structural timber will be derived from a range of branch indices, with few logs with a branch index as high as 9 cm. However, should significant quantities of structural timber come from high-branch-index logs from low-density sites, a closer analysis could be warranted.

CONCLUSIONS

Structural timber will need to be obtained from logs of adequate quality if strength levels are to be maintained. Current grading rules do not effectively remove the influence of branch index on the fifth-percentile strength of timber obtained from logs with a large branch index. For these poorer quality logs, better sawn-timber grading rules are required. The best structural timber comes from high-density logs with low branch index and, if the log quality is very good, there may be no need for grading of the timber.

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