ESTIMATING TENSILE STRENGTH IN *PINUS RADIATA* STRUCTURAL TIMBER

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ABSTRACT

Altogether, 1862 *Pinus radiata* D.Don structural boards were tested in tension to examine five selected parameters of tensile strength, and to verify the code-assigned characteristic tensile strength values. Knot area ratio (KAR) alone does not predict tensile strength at the weakest point of the board; local bending stiffness at the failure point $E_{P,\ fail}$ shows a stronger correlation with tensile strength, and this presents a possibility for non-destructive estimation of tensile strength in *P. radiata* structural timber. The mean, 5th percentile, and characteristic strength in tension were studied for the test boards and the results indicated that the code values for current visual stress-grading systems of *P.radiata* need to be revised because the characteristic tensile strengths obtained from the tests were significantly lower than the values assigned in the standards.

Keywords: tensile strength; characteristic tensile strength; stiffness; knots; knot area ratio; visual stress-grading; machine stress-grading; code value; timber; *Pinus radiata*.

INTRODUCTION

Estimating strength, i.e., failure stress, in structural timber includes estimating the strength of a single board, and estimating the characteristic strength (the basic material strength defined in statistical terms) of a timber population. Designers and customers rely on such work to avoid structural failures. However, timber strength cannot be measured without destructive testing although proof loading can be used to cull out weaker boards. Consequently, non-destructive measurements involving stiffness and knots have been used to estimate the strength of structural timber, and they form an important part of machine stress-grading and visual stress-grading. This study aimed to:

(1) Evaluate stiffness and KAR (knot area ratio) as parameters of tensile strength in single boards of *Pinus radiata*:

(2) Verify the code-assigned characteristic tensile strength values in stress-grading systems for *P. radiata* populations.

The effect on tensile strength of other wood qualities and knot features, such as density, microfibril angle, slope of grain, knot location, knot types, was beyond the scope of this study.

The strength of a single board varies with the manner of loading. When a board is tested in axial tension, the entire length of the board is subjected to the same tensile force, thus the failure occurs at the weakest point regardless of where it is located. When tested in bending, however, the bending moment varies along the length of board, and so failure usually occurs in the region of maximum bending moment regardless of whether that is the weakest point in the whole length. In other words, bending failure does not necessarily occur at the weakest point along the full length of the board (Madsen 1992; Bodig & Jayne 1982). Therefore, tensile testing was chosen for this study because it has the advantage of identifying the strength at the weakest point in the full length of a member.

A number of practical approaches were used, including estimating strength according to the lowest local F-grade mark on the board (i.e., machine stress-grading), the maximum knot area ratio at any point along the board (i.e., visual stress-grading), or some combination of the two. Most previous studies have focused on strength behaviour in bending, and little information is available on estimating tensile strength in *P. radiata* structural timber (Gaunt *et al*. 1999; Addis Tsehaye *et al*. 1995, 1998; Cramer *et al*. 1988; Kunesh & Johnson 1972).

Estimating the strength in a single board from the lowest local F-grade mark is based on the relationship between local bending stiffness and local strength (New Zealand Ministry of Forestry 1995; AS/NZS 4063: 1992). If it is assumed that the lowest local F-grade mark on a board indicates the weakest zone of the board, the local strength at this zone provides an estimate for the tensile strength of the whole board. However, each F-grade mark corresponds to a range of local bending stiffness values as assigned by the Forestry Commission of New South Wales (1974) rather than to a single value. In practice, an individual board may have several "lowest local F-grade marks" along its length, if the bending stiffnesses at these locations all fall in the same grade range. When this happens, the local F-grade mark does not indicate the weakest zone, as there are a number of possibilities. In addition, a board may break unexpectedly at a higher local F-grade mark. Therefore, this study used the actual stiffness values rather than the F-grade colour mark to explore the likely estimator of tensile strength for each board. Local bending stiffness at the actual failure point of board was termed "local failure stiffness" ($E_{P,\ fail}$) in this study. The correlations between tensile strength, average stiffness in tension (E_T), the lowest local bending stiffness ($E_{P,min}$), and local failure stiffness ($E_{P,\ fail}$) are presented in this paper.

Knottiness is recognised as having a negative effect on the mechanical properties of timber (Xu 2000, in press; Pellicane & Franco 1994; Walker 1993; Samson 1993; Barrett & Kellogg 1991; Cramer *et al.* 1988; Buchanan 1986; Cramer & Goodman 1983). Knottiness is generally described by the local Knot Area Ratio (KAR) — namely, the ratio of the sum of projected cross-sectional areas of the knots to the cross-sectional area of the piece (BS 4978: 1988; AS 2858: 1986). The maximum KAR in the board is a major parameter used to judge the grade of the board in visual stress-grading systems (NZS 3603: 1993; BS 4978: 1988; AS 2858: 1986). In order to evaluate the accuracy of the prediction of tensile strength by KAR in a single board, both maximum KAR and KAR at the actual failure point were investigated before and after testing in tension. The correlations between tensile strength, maximum KAR, and KAR at the actual failure point are presented in this paper.

In order to sort timber into populations to which characteristic strengths could be assigned, two basic systems, i.e., machine stress-grading and visual stress-grading, were used.

The common procedure in machine stress-grading systems is to sort a source population of timber into sub-populations according to selected stiffness cut-off values that are applied to the lowest local bending stiffness within each piece. In practice, the cut-off values are adjusted so that the properties of the sub-populations satisfy the characteristic values assigned to established grades, and the sub-populations are then branded accordingly. The properties of the source population of timber may change. If that happens, for whatever reason, operators of the machine stress-grading system are expected to adjust the cut-off values in order to produce timber grades with consistent properties, as monitored by a quality control system. This study considered the lowest local bending stiffness ($E_{P,min}$) as the parameter for sorting timber. Other parameters (for example, average E_P or E_j) were beyond the scope of this study.

The two visual stress-grading systems that were evaluated were the Australian structural-grades (AS 2858: 1986) and New Zealand framing-grades (Engineering grade, No.1 Framing, and No.2 Framing). Australian structural-grades (AS 2858: 1986) define the grades according to visual defects and then derive the code values for the characteristic strengths from an assumed relationship between the visual stress-grades and the corresponding F-grades (Appendix, Table A2).

Regarding the MGP (machine-graded pine) system, the Australian Standard (AS 1720.1: 1997) gives only three grades (MGP 15, 12, and 10) that have high characteristic tensile strengths. However, compared to most other softwood species, New Zealand *P. radiata* structural timber can show low stiffness and strength, especially when the boards are cut from corewood (Xu & Walker in press; Sorensson *et al*. 1997; Shelbourne 1997). In order to resolve this problem, lower MGP grades have been proposed, namely MGP 8 and MGP 6 (Walford 2001; Gaunt *et al*. 1999). In this study, the characteristic tensile strengths R_K calculated from the measured data were compared with the assigned code values for characteristic tensile strength in F-grades, Australian structural-grades, MGP-grades, and New Zealand No.1 Framing and No.2 Framing. It was thought that a comparison between the derived and assigned characteristic tensile strengths could provide useful information for improving the existing design codes.

MATERIALS AND METHODS

Selection of Materials

Sixty-two 27-year-old, thinned, unpruned, *P. radiata* trees were randomly selected from a single stand on the Mamaku Plateau in the central North Island of New Zealand. All stems were cut to give 4.2-m logs, and the average large-end diameters were butt logs 384 mm, middle logs 315 mm, top logs 284 mm, and upper-top logs 250 mm (Fig. 1).

All logs were live-sawn to give a 100-mm-thick central cant and a series of 40-mm-thick flitches. Further sawing involved cutting 100 × 40-mm boards from the cants and flitches as shown in Fig. 2. The study yielded 1988 dressed 90 × 35 × 4200-mm (width × thickness × length) structural boards for machine stress-grading and tensile testing. Full details concerning sawing and subsequent processing have been published by Xu (2000) and Xu & Walker (in press).

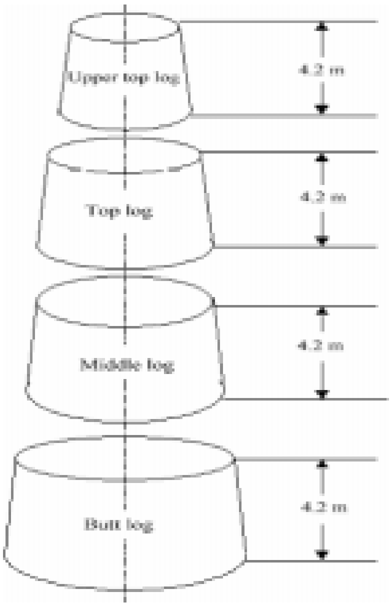

FIG. 1–Cutting pattern for stems

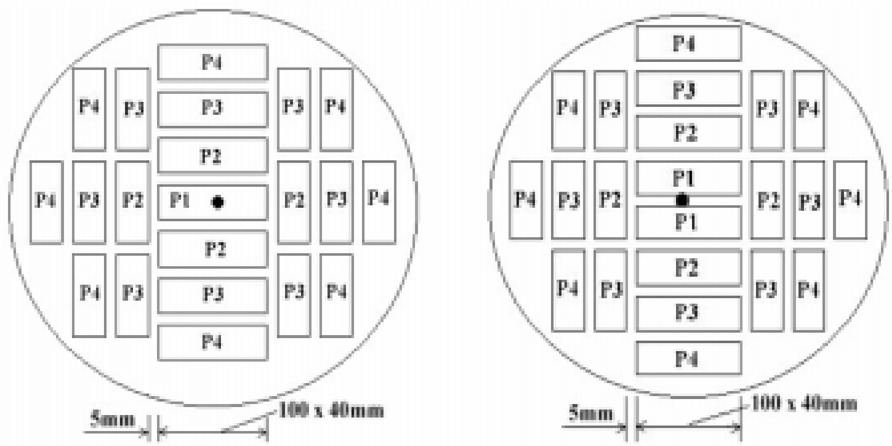

FIG.2–Two sawing patterns used in this study. The numbering of the boards indicates their relative distance from the pith. The thickness of the saw blade was 5 mm.

Of the 1988 boards tested, 1862 were used for the analysis of tensile strength. The failure stress of the other 126 boards could not be identified accurately as tensile strength because of either damage during machine stress-grading (69 boards) or failure occurring in the grips of the tensile testing machine (57 boards). Therefore, these 126 boards were excluded from all analyses.

Only 1589 of 1862 boards could be used for the analysis of local failure stiffness because some boards failed in their ungraded ends, i.e., "end failure". During machine stress-grading, local bending stiffness in the first 0.65 m and the last 0.65 m of the board could not be measured because of the distance between the supporting rollers in the grader. Excluding the 0.45-m grip length of the tensile testing machine, this meant that local failure stiffness could not be obtained where failure occurred in the 0.2m before the first local bending stiffness reading and the 0.2 m after the last local bending stiffness reading. In order to obtain comparisons between the parameters, all other analyses for estimating tensile strength in a single board were based on data from the same 1589 boards.

"End failure" did not affect the analysis of characteristic tensile strength because:

(1) The lowest local bending stiffness that allowed for the 0.65-m ungraded ends was selected as the parameter for sorting timber in the F-grades and MGP-grades;

(2) The maximum KAR in the board (excluding the length of the grips) was the parameter for sorting timber in the Australian structural-grades and New Zealand Framing grades, which did not need to consider the local bending stiffness values.

Machine Stress-grading

When an average 12% moisture content was reached, the boards were machine stress-graded using a MPC Computermatic stress grader (MK5 system) to obtain the local stiffness value from bending as a plank (E_P). No allowance was made for shear deformation. In the first section, a transducer on the infeed outrigger arm measures the natural bow in the unloaded board. Then, the board immediately enters the testing section where it is flexed between two rollers 0.914 m apart by applying a small constant force (900N) at mid-span and measuring the deflection. The true deflection is determined from the measured deflection under load and the natural bow in the unloaded board, and is used to calculate the modulus of elasticity.

The boards were fed through the machine immediately after the stress grader had been re-calibrated. Local bending stiffness (or local bending modulus of elasticity) was determined at 152-mm intervals along the length of the board as the board passed through the grader, and these values were recorded on computer. At the same time, the local bending stiffness grades were automatically colour-marked along the board. The lowest local bending stiffness value along the length of a board determined the F-grade of the board.

Tensile Test

The average stiffness in tension and the ultimate tensile strength (UTS) of each board were measured using a tensile testing machine. The net span of the tensile test machine between the two, 0.45-m-long, hydraulically operated grips was set at 3.3 m. A 200-kN-capacity hydraulic ram provided the axial tensile force to the board. A load cell, which was connected in line with the tensile machine and the ram, measured the tensile load continuously and transferred the data to a computer during the tensile test (Xu 2000). Once the board broke, the dimensions of the cross-section at the failure zone were measured immediately and the tensile strength for each board was calculated.

Maximum KAR, KAR at Failure Point, and Local Failure Stiffness

Before destructive testing, the KARs for the different knot types in each board were measured to obtain the maximum KAR in the board. Then the estimated weakest point was predicted using the Australian Standard (AS 2858: 1986) and this point was marked on the surface of the board.

After destructive testing, the local bending stiffness value at the failure point was confirmed by matching the local F-grade colour mark at the failure point to the original data that had been recorded during machine stress-grading of that board. The KAR at the actual failure point was re-measured to study the features at the failure point in the board. Any "grip failure" tests were excluded from this study.

Characteristic Tensile Strength for the Population Being Studied

Boards were sorted into several populations according to the cut-off limits of $E_{P,\,min}$ for the machine stress-grading systems as well as according to the maximum KAR of the board for visual stress-grading systems. Then the characteristic tensile strength for the population being studied was calculated using the formula (AS/NZS 4063: 1992):

$$R_K = \left[1 - \left[\frac{2.7V_R}{\sqrt{n}} \right] \right] R_{0.05} \tag{1}$$

where

V_R = coefficient of variation of the measured data;
n = sample size;
$R_{0.05}$ = the 5th percentile of the measured data.
$\left[1 - \left[\frac{2.7V_R}{\sqrt{n}} \right] \right]$ provides a 75% confidence for the derived percentile values (AS/NZS 4063:1992).

The calculation of 5% percentile value in this study followed the method presented in the Standard (Appendix C in AS/NZS 4063:1992).

Finally, the results (R_K) were compared with the code values of characteristic tensile strength in different grading systems.

RESULTS AND DISCUSSION

Estimating Tensile Strength in a Single Board

Five parameters that might be expected to relate to tensile strength in a single board were studied. They were maximum KAR, the KAR at actual failure point, average stiffness in tension, the lowest local bending stiffness, and local failure stiffness, i.e., local bending stiffness at the actual failure point in the board. All analyses were based on data from the same 1589 boards.

The experimental results showed that nearly 99% of the tested boards failed at a knot, which confirmed that knots are an important factor affecting the tensile strength in *P. radiata* structural timber. However, the poor correlations between tensile strength and maximum KAR ($R^2 = 0.21$), and between tensile strength and KAR at the actual failure point ($R^2 = 0.19$) suggest that KAR alone is not a good predictor of tensile strength in structural timber (Fig.3 and Fig. 4).

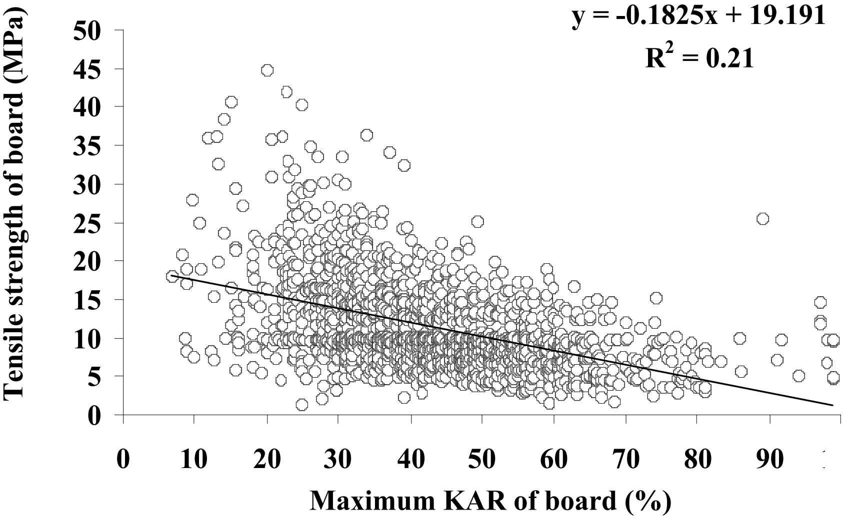

FIG. 3–The correlation between tensile strength and maximum KAR (data from 1589 boards).

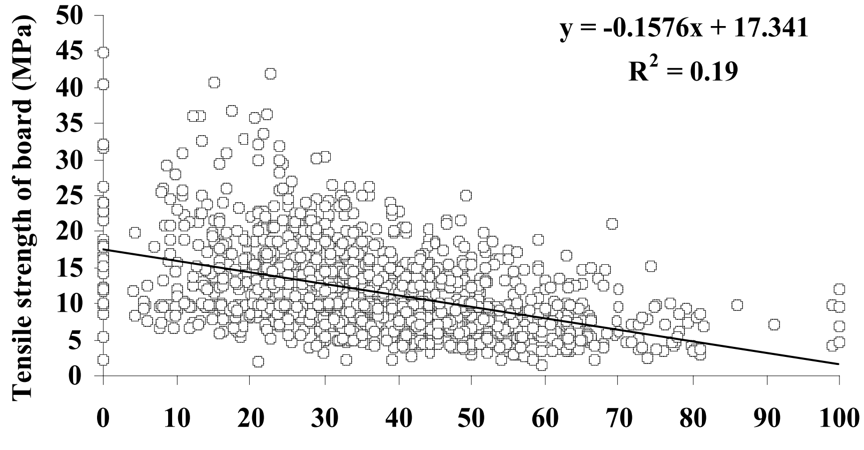

FIG.4–The correlation between tensile strength and KAR at the actual failure point (data from 1589 boards).

Board stiffness gives a better indication of tensile strength than KAR, as can be seen from the stronger coefficient of determination (Fig. 5, 6, and 7). Local failure stiffness gave the best estimation of tensile strength ($R^2 = 0.54$) (Fig. 7). The lowest local bending stiffness ($R^2 = 0.47$) was less relevant to tensile strength at the weakest point than local failure stiffness (Fig. 6 and 7), because the lowest local bending stiffness did not always coincide with the failure zone. However, the lowest local bending stiffness gave a somewhat better coefficient of determination than the average stiffness of the board in tension (Fig. 5 and 6).

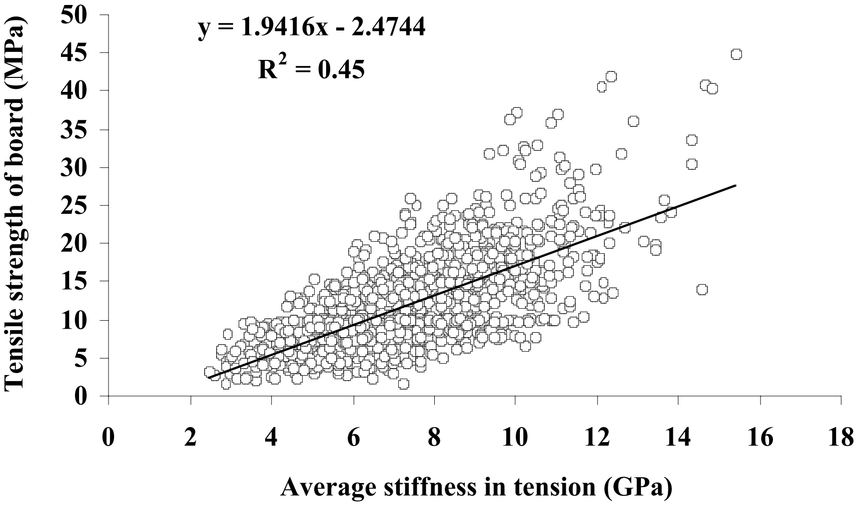

FIG. 5–The correlation between tensile strength and average stiffness in tension (E_T) (data from 1589 boards).

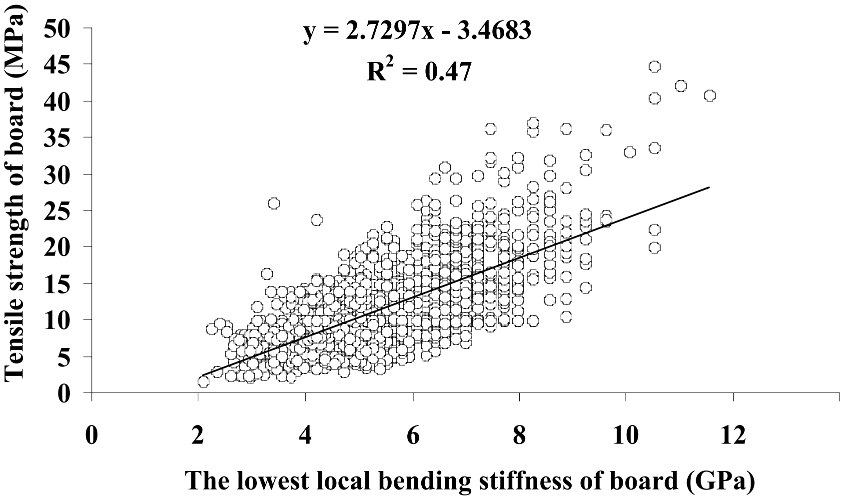

FIG. 6–The correlation between tensile strength and lowest local bending stiffness ($E_{P,min}$) (data from 1589 boards).

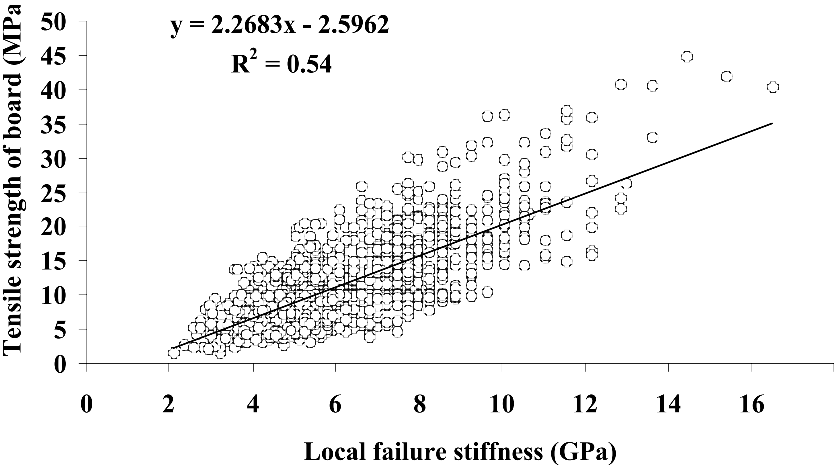

FIG. 7–The correlation between tensile strength and local failure stiffness ($E_{P,fail}$) (data from 1589 boards).

Comparison of the Characteristic Tensile Strength, Calculated from Test Data, with the Currently Assigned Values in Machine Stress-grading Systems

F-grades

Firstly, the cut-off limits for $E_{P,\ min}$ were calculated using the yellow program card (Forestry Commission of New South Wales 1974). Then 1862 machine stress-graded boards were sorted into several F-grade groups according to the calculated cut-off limits (Appendix, Table A1). This step determined the tested sample size in each F-grade. The characteristic tensile strength for each group was calculated according to Equation (1) using the coefficient of variation, sample size, and 5% percentile value from the measured data in the group. Then the results were compared with the code values of characteristic tensile strength presented in the Standard (AS 1720.1: 1997) for these F-grade groups. The results showed that the characteristic tensile strength calculated from the test data was slightly lower than the currently assigned characteristic tensile strength in F-grades (Table 1).

MGP-grades

MGP-grade groups in this study were sorted by $E_{P,\ min}$ in the same way as for F-grades. MGP 15 is considered equivalent to F11, MGP 12 equivalent to F8, and MGP 10 equivalent to F5 (Walford 2001). Then the characteristic tensile strengths calculated from the test data were compared with the code values of characteristic tensile strengths presented in the Standard (AS 1720.1: 1997) for these three MGP-grades (Table 2).

There are two notable features in Table 2. Firstly, only 44% of the tested boards satisfied the requirements for MGP-grades. This means that the currently assigned MGP-grades in the Standard (AS 1720.1: 1997) do not cover the full range of strength properties found in New Zealand *P. radiata*, which agrees with a statement by Gaunt *et al.* (1999): “New Zealand radiata pine resource falls below MGP 12 with majority being around MGP 8”. Secondly,

TABLE 1–Comparison of the characteristic tensile strength (R_K) calculated from the test data (1862 boards) with the currently assigned characteristic tensile strength for F-grades (AS 1720.1: 1997).

	Stress grade				
	F11	F8	F5	F4	Rejected
Sample size (n)	1	67	744	724	326
Mean of measured tensile strength (MPa)		24.25	14.36	9.61	7.46
Coefficient of variation of the measured data (V_R)		0.338	0.419	0.349	0.449
5th percentile of the measured tensile strength (MPa)		12.90	7.02	4.64	3.01
Characteristic tensile strength calculated from test data (MPa)		11.47	6.73	4.48	2.81
Code value: Characteristic tensile strength (MPa)	17.0	13.0	8.20	6.50	n/a
Discrepancy (%)		–12	–18	–31	

TABLE 2–Comparison of the characteristic tensile strength (R_K) calculated from the test data (1862 boards) with the currently assigned characteristic tensile strength for MGP-grades (AS 1720.1: 1997).

	MGP grades				
	MGP 15	MGP 12	MGP 10	n/a	n/a
Equivalent F-grades	F11	F8	F5	n/a	n/a
Sample size (n)	1	67	744	724	326
Mean of measured tensile strength (MPa)		24.25	14.36	9.61	7.46
Coefficient of variation of the measured data (V_R)		0.338	0.419	0.349	0.449
5th percentile of the measured tensile strength (MPa)		12.90	7.02	4.64	3.01
Characteristic tensile strength calculated from test data (MPa)		11.47	6.73	4.48	2.81
Code value: Characteristic tensile strength (MPa)	23.0	15.0	8.9	n/a	n/a
Discrepancy (%)		–24	–24		

the code values for characteristic tensile strength in MGP-grades are higher than the code values for the characteristic tensile strengths in the equivalent F-grades (Table 1). More critically, the characteristic tensile strengths calculated from the test data lie below both code values, which cannot ensure safe design. Therefore, it is necessary to explore ways for improving the MGP-grade system. In the first instance, Forest Research (Walford 2001; Gaunt *et al.* 1999) has proposed two lower MGP-grades (MGP 8 and MGP 6) as an equivalent to No.1 Framing and as a replacement for No.2 Framing, and this is discussed in the next section.

Comparison of Characteristic Tensile Strength, Calculated from Test Data, with the Currently Assigned Values in the Visual Stress-grading System

The two visual stress-grading standards, Australian Standard (AS 2858: 1986) and New Zealand Standard (NZS 3603: 1993), were the main interest of this study. The Australian Standard (AS 2858: 1986) considers the influence of three different knot types on the grades, whereas the New Zealand Standard considers only KAR for No.1 and No.2 Framing grades. Engineering grade was not included, because it is practically unobtainable.

Australian structural-grades

Based on the permissible maximum KAR for face, edge, and other knots, the Australian Standard (AS 2858:1986) denotes five structural-grades for softwood. These grades apply to both Australian and New Zealand *P. radiata* (Appendix C in AS 2858: 1986).

AS 2858: 1986 suggests that the characteristic tensile strength in each structural-grade can fit the code value of an equivalent F-grade presented in AS 1720.1: 1997. The relationships between the permissible maximum KAR, structural-grades, and the corresponding F-grades are listed in the Appendix (Table A2). For example, if the KARs for face knots, edge knots, and other knots are 25%, 50%, and 15% respectively, then the structural-grade and the equivalent F-grade of this board would match No.3 and F8 respectively, according to AS2858 (Appendix, Table A2).

The 1862 machine stress-graded boards were sorted into several structural-grade groups according to the permissible maximum KAR in the board, and then the characteristic tensile strengths were calculated for these groups and compared with the code values of characteristic tensile strength presented in the standard (AS 1720.1: 1997). The experimental results (Table3) indicated that the characteristic tensile strength from the test data in each structural grade group was significantly lower than the code value of characteristic tensile strength of

TABLE 3–Comparison of the characteristic tensile strength (R_K) calculated from the test data (1862 boards) with the currently assigned characteristic tensile strength for Australian structural-grades (AS 2858: 1986).

	Australian structural-grades				
	No.1	No.2	No.3	No.4	No.5
Equivalent F-grades	F14	F11	F8	F7	F5
Sample size (n)	117	183	361	394	807
Mean of measured tensile strength (MPa)	17.64	15.57	14.09	11.36	8.96
c.o.v	0.557	0.480	0.414	0.401	0.416
5th percentile of the measured tensile strength (MPa)	7.13	6.85	6.27	5.54	3.77
Characteristic tensile strength calculated from test data (MPa)	6.14	6.19	5.90	5.28	3.62
Code value: Characteristic tensile strength (MPa)	21.0	17.0	13.0	10.0	8.2
Discrepancy (%)	–71	–64	–55	–47	–56

F-grade that is suggested by AS 2858: 1986 to fit the structural-grade group. This clearly demonstrates that the assumed relationship between the structural-grades and the corresponding F-grades in AS 2858: 1986 does not match the wood resource used in this study well.

New Zealand Framing grades

New Zealand Standard (NZS 3603: 1993) segregates No.1 Framing and No.2 Framing grades according to the maximum KAR in the board — the maximum KAR is less than 33% in No.1 Framing, and more than 33% but less than 50% in No.2 Framing. NZS 3603: 1993 only gives the code value for the characteristic tensile strength of No.1 Framing; a code value for No.2 Framing is not available. Therefore, this study considered the suggested code value of characteristic tensile strength for No.2 Framing as proposed by Walford (2001).

Characteristic tensile strengths calculated from test data, and the code values for No.1 and No.2 Framing, are shown in Table 4a. Compared with the Australian structural-grades, the calculated R_K values from the test better approach the code values for No.1 and No.2 Framing. However, the calculated characteristic tensile strengths are still lower than the code values for both No.1 and No.2 Framing (Table 4a). One reason for this is that Framing grades assign tensile strength on the basis of a single parameter, i.e., the maximum KAR in the board, and there is only a poor correlation between tensile strength and maximum KAR (Fig.3). In practice, the influence of knots on tensile strength should take into account the effect of KAR together with other parameters such as knot types, knot positions, growth angle of knot (Xu 2000, in press).

Walford (2001) suggested a correspondence between MGP-grades and New Zealand visual structural-grades:

- MGP 8 as equivalent to the current No.1 Framing, and MGP 6 as a replacement for No.2 Framing;
- Code values for tensile strength of 6.3 MPa in MGP 8, and 4.0 MPa in MGP 6.

The study reported here study examined this proposal — 1862 boards were sorted into No.1 Framing and No.2 Framing groups according to the rules for New Zealand visual stress-grading. Then the characteristic tensile strengths were calculated for these groups and compared with the code values for the characteristic tensile strength of MGP 8 and MGP6, as suggested by Walford (2001). This approach achieved the desired outcomes: the characteristic tensile strengths obtained from test data were higher than the suggested code values in both No.1 and No.2 Framing groups, which ensures safe design (Table 4b).

CONCLUSIONS

Nearly 99% of the tensile tested boards broke at a knot zone and tensile strength reduced with an increase of knot area ratio. This re-emphasised that knots are an important factor affecting tensile strength of timber. However, a single parameter, i.e., KAR alone, does not reliably indicate tensile strength, since there was no strong correlation between tensile strength and the maximum KAR ($R^2 = 0.21$), or tensile strength and the KAR at the actual failure point of the board ($R^2 = 0.19$).

Of the five examined parameters, local bending stiffness at the failure point best indicated the tensile strength of the board ($R^2 = 0.54$). However, one knows the local failure stiffness

TABLE 4a–Comparison of the characteristic tensile strength (R_K) calculated from the test data (1862 boards) with the currently assigned characteristic tensile strength for New Zealand Framing grades (NZS 3603: 1993).

	Framing grades		
	No.1 Framing	No.2 Framing	Below grade*
Sample size (n)	608	817	437
Mean of measured tensile strength (MPa)	15.29	10.83	8.19
c.o.v	0.483	0.408	0.424
5th percentile of the measured tensile strength (MPa)	7.03	5.26	3.38
Characteristic strength calculated from test data (MPa)	6.66	5.06	3.19
Code value: characteristic tensile strength (MPa)	8.8	7.7†	n/a
Discrepancy (%)	–24	–34	

Characteristic tensile strength has been recalculated in NZS 3603: 1993 (*see* Amendment No.1, April 1996). The new code value for No.1 Framing is 8.8 MPa.

* Indicates that KAR > 50%;

† Value proposed for No.2 Framing by Walford (2001), but not available in the current standard.

TABLE 4b–Comparison of the characteristic tensile strength (R_K) calculated from the test data (1862 boards) with the proposed code values of characteristic tensile strength in MGP 8 and MGP 6 (Walford 2001).

	Framing grades		
	No.1 Framing	No.2 Framing	Below grade*
Sample size (n)	608	817	437
Mean of measured tensile strength (MPa)	15.29	10.83	8.19
c.o.v	0.483	0.408	0.424
5th percentile of the measured tensile strength (MPa)	7.03	5.26	3.38
Characteristic strength calculated from test data (MPa)	6.66	5.06	3.19
Code value: characteristic tensile strength for MGP 8 and MGP 6 (MPa)	6.3	4.0	n/a
Discrepancy (%)	+5.7	+27	

* Indicates that KAR > 50%.

only after destructive testing, so this can only be used in combination with an accurate prediction of the location of the weakest point in the board. Therefore, it is necessary to explore other failure features of knots, such as the frequency of different knot types, failure patterns, and the failure angles, which will give a clearer insight for estimating the weakest point in *P. radiata* structural timber.

For visually graded timber, the characteristic tensile strengths calculated from test data in this study were significantly lower than the published code values in Australian structural-grades and New Zealand Framing grades, but especially the Australian structural-grades. In contrast, when this wood was machine stress-graded according to F-grades and MGP-grades the characteristic tensile strength for each population corresponded more closely to the code values. However, the code values for F-grades and MGP-grades were still higher than the calculated values from test data, which would compromise safe design. In addition, there is an absence of lower MGP-grades in AS 1720.1: 1997, which limits the use of MGP-grades in the New Zealand *P. radiata* market.

Using the equivalence between the lower MGP-grades and the New Zealand framing grades as suggested by Walford (2001), then the experimental results showed a very acceptable match with the characteristic tensile strengths, while also being somewhat above these limits — so ensuring safe and satisfactory design.

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APPENDIX

TABLE A1–Cut-off limits for the lowest local bending stiffness $E_{P,min}$ according to the yellow program card (Forestry Commission of New South Wales 1974)

Grade	E_P range (GPa)	Mid E_P (GPa)	Cut-off limits for $E_{P,min}$ (GPa)
F11	Max. ~ 11.58	11.89	$11.89 \le E_{P,min}$
F8	12.19 ~ 8.27	8.43	$8.43 \le E_{P,min} < 11.89$
F5	8.58 ~ 5.52	5.59	$5.59 \le E_{P,min} < 8.43$
F4	5.65 ~ 4.14	4.18	$4.18 \le E_{P,min} < 5.59$
Rejected	4.21 ~ Min		$E_{P,min} < 4.18$

TABLE A2–The relationship between the permissible maximum KAR, Australian structural-grades, and the corresponding F-grades (after AS 2858: 1986)

Structural grade	Equivalent F-grades	Face knots	Edge knots	Other knots*
No.1	F14	KAR ≤ 25%	KAR ≤ 25%	KAR ≤ 15%
No.2	F11	KAR ≤ 33%	KAR ≤ 40%	KAR ≤ 25%
No.3	F8	KAR ≤ 40%	KAR ≤ 50%	KAR ≤ 30%
No.4	F7	KAR ≤ 50%	KAR ≤ 60%	KAR ≤ 40%
No.5	F5	KAR ≤ 60%	KAR ≤ 66%	KAR ≤ 45%

* Includes all knots that do not fit the definitions of face and edge knots (AS 2858: 1986)