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Effects of Length and Grade on In-grade Tensile Strength and Stiffness Properties of Radiata Pine Timber*1

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ABSTRACT

This paper examines the effects of specimen length and grade on the strength and stiffness properties of structural timber of radiata pine. The tensile strength and modulus of elasticity of 1,902 machine-graded boards with 3.15- and 1.62-m clear span lengths, were determined using a horizontal tension test machine. The mean failure and characteristic stress values for tensile strength show an extremely high dependency on test specimen length. The mean and characteristic values of both modulus of elasticity and tensile strength show significant dependency on machine stress grades.

Keywords : *Radiata pine*, tensile strength, modulus of elasticity, structural timber, length effect, grade effect.

1. INTRODUCTION

Radiata pine (*Pinus radiata*, D. Don) is the most important plantation species in New Zealand. Of the 1.3million hectares of plantation forest in the country, 90% is radiate pine (New Zealand Forest Owners' Association, 1994). This paper addresses one of the fundamental issues in timber engineering: the effect of specimen length and grade on the strength and stiffness properties of structural timber from this species. The paper also examines relative strength and stiffness values relative to design code values.

2. MATERIALS & METHODS

2.1 Dimensional effects on strength properties

2.1.1 Size effect theory

It is well-known that timber is subject to "size effects" whereby large members tend to fail at lower stresses than do smaller members. This is because the larger the member, the greater the probability of the presence of a significant defect in the member. To some extent, these effects can be explained by the brittle fracture theory developed by Weibull (1939), which applies to "perfectly brittle" materials. The brittle fracture theory is based on the concept of a material consisting of a large number of brittle elements in series, so that the failure of any one element will cause failure of the member. The theory can be developed mathematically by assuming that the distribution of element strengths follows an extreme value distribution such as the Weibull distribution, as described by Madsen and Buchanan (1986). If it is

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assumed that the strength tends to be zero for infinite size, then the brittle fracture theory can be described by a two-parameter Weibull model, giving a simple relationship between size and strength.

For members of varying length, the theory gives:

$$x_1 / x_2 = (L_2/L_1)^{1/k} \quad \cdots\cdots\cdots \quad (1)$$

where x_1 and x_2 are strength of members of lengths L_2 and L_1, respectively, and k is the length effect parameter (or the shape factor of the two-parameter Weibull distribution of element strength). This can be used to make a straight-line log-log plot of strength vs. length given by:

$$\log(x_1 / x_2) = 1/k \, [\log(L_2 / L_1)] \quad \cdots\cdots\cdots \quad (2)$$

According to this theory, the variability of strength between members would be described by the same distribution as that of element strength, so that the parameter k could be determined from the variability in test results from a population of members of the same size. The coefficient of variation of the two-parameter Weibull distribution is given by

$$c.v.= \{ \Gamma(1+2/k)/\Gamma^2(1+1/k)- 1 \}^{1/2} \quad \cdots\cdots\cdots \quad (3)$$

where Γ represents the gamma function (Bury, 1975). An often-used approximation is $k = c.v.^{-1.22}$, so that the parameter k can be found from the coefficient of variation of member strengths.

However, it can be shown that there is very little error in using $k = c.v.^{-1}$, allowing an even simpler estimation of the size effect parameter from test results and quantification of length effects using

$$x_1 / x_2 = (L_2/L_1)^{c.v.} \quad \cdots\cdots\cdots \quad (4)$$

2.1.2 Size effects applied to timber

If timber was "perfectly brittle," the size effects described in the previous text would apply to members of different lengths, widths, and depths, and to members of the same length with different load configurations in bending, with the same value of k for all variations in size.

Madsen and Buchanan (1986) showed that timber is not perfectly brittle because it exhibits different size effects for different grades and in different directions. Hence, there are different size-effect parameters for different changes in dimension and different loadings. Madsen and Buchanan(1986) used the term k_1 for the length effect parameter and other k factors for other related effects. The term k_1 will be used as the length effect parameter in this paper.

The largest discrepancy from brittle fracture theory in wood is shown when length and depth are kept constant, in which case increasing the width of a bending member tends to cause an increase in strength, not a decrease as predicted by the theory. The reason for this increase is that defects that occupy the whole width of narrow boards are less likely to occupy the whole width of wider boards.

Length effects are included in AS/NZS 4063 (SAA, 1992) by specifying a length effect parameter equal to the inverse of the coefficient of variation (using the approximation described above). This is based on the assumption that between-board variability(as measured by the coefficient of variation) is the same as within-board variability leading to length effects. This assumption is not necessarily true, but it may be reasonably used in many cases, given the difficulty of measuring within-board variability.

2.2 Material

Eighty unpruned radiate trees were felled from a 25-year-old stand in the Southern Pigeon Valley, Nelson Region, South Island, New Zealand. The trees were cross-cut into four logs each. These logs were milled to yield 1,902 90- by 35mm dressed, dried (12% moisture content), machine-stress-graded boards, 4.2m long.

The boards were machine graded using normal commercial settings to mark each board with intermittent coloured paint marks. Each board was allocated the machine stress grade corresponding to the lowest grade mark along its length. Of the 80 trees, 60 were randomly allocated to tension testing, at a clear length of 3.15m, which is a standard length according to SAA specifications (1992). The remaining 20 trees were allocated to tension testing of a nonstandard clear length of 1.62m. A total of 1,902 boards were available for testing; 1,333 of these boards were 3.15m and 569 boards were 1.62m.

Just prior to destructive testing in tension, the expected failure point(i.e., usually the largest knot) on each board was identified and marked on the basis of visual grade inspection according to the specifications in the New Zealand Timber Grading Rules (NZS 3631, 1988).

2.3 Method

For each board, the modulus of elasticity and tensile strength were measured by testing in tension to failure. The tensile strength of each board was determined using a horizontal tension test machine; length between the 450-mm-long grips was 3.15 or 1.62m. The hydraulically operated grips applied sufficient gripping force to prevent specimens from slipping at the grips while low enough force to avoid crushing the wood. The tensile force was applied by a 200-kN capacity hydraulic ram connected at one end of the test machine. At the other end, a load cell measured the applied force, which was continuously recorded. The failure load ranged from 25 to 150-kN.

The modulus of elasticity in axial tension was determined by measuring the elongation of the boards at low load levels (up to 35 kN) over a length of 3.15m for the long-span specimens and 1.62m for the short-span specimens. In all except the weakest boards, the recording transducers were removed before failure to avoid the risk of damage.

2.3.1 Fifth percentile values

For structural use, the issue is not how strong a piece of timber is but how weak it might be. That is a question of probability and reliability theory. The design stress in most modern codes is the "characteristic" stress, which is the lower 5th percentile value for the population determined with a specified confidence (Addis *et al.*, 1991). The 5th percentile values of tensile strength were calculated by the method described in SAA (1992), where the individual values are ranked in ascending order and each is assigned a rank value, R_i as described by the following equation:

$$R_i = (i - 0.5)/(n) \quad \cdots\cdots \quad (5)$$

Where i = 1, 2, 3, ... for the first, second, third, ... ranked values,
n = total sample size, and
the 5th percentile corresponds to $R_i = 0.05$.

2.3.2 Characteristic stress

According to the New Zealand standard (NZS, 1993), the characteristic stress or strength (R_k) for strength properties is defined as an estimate of the lower 5th percentile value determined with 75% confidence from tests on a representative sample of full-size test specimens. For stiffness, the characteristic value (E_k) is the mean value.

The characteristic stress(R_k) values for tensile strength for this study were estimated from the lower 5th percentile values in accordance with SAA (1992). The lower 5th percentile is reduced by a factor(F) as follows:

$$F = (1 - 2.7V_R/\sqrt{n}) \quad \cdots\cdots \quad (6)$$

where V_R is coefficient of variation of the measured data and n is sample size.

This adjustment reflect the confidence with which the lower 6th percentile value of a population can be estimated when using a small sample. The normalized characteristic value, for use in the design code, is a normalized value given by:

$$R_{k,\,norm} = [1.35 / \phi] \times [R_k/(1.3+0.7V_R)] \quad \cdots\cdots \quad (7)$$

where ϕ is the capacity factor specified in the limit state design code(0.8 for timber properties) in NZS 3603(SNZ, 1993).

3. RESULTS & DISCUSSION

3.1 Grade distribution

The structural grade values used in this paper follow the Australian grading rules (SAA, 1988), A summary of the Australian characteristic stresses for radiata pine structural grades in tension and for stiffness are presented in Table 1.

Although all boards were machine stress graded by bending, the stiffness values measured from the tension tests were used to allocate timber to a grade. In tensile testing the machine was checked at intervals with a standard reference load cell and any drift was corrected. The grade boundaries were set on the basis of the measured modulus of elasticity, using the code values (SAA, 1994) as shown in Table 1, as cut-off values.

Table 1. Characteristic stresses for radiata pine structural grades in tension and modulus of elasticity (SAA, 1994).

Stress Grade	Tensile strength parallel to the grain (MPa)	Modulus of elasticity (GPa)
F2	4.0	4.5
F3	5.0	5.2
F4	6.5	6.1
F5	8.2	6.9
F8	13.0	9.1
F11	16.6	10.5
F14	21.1	12.0

A summary of the grade out-turn for all the boards according to the 1.62m and 3.16m clear spans is summarized in Table 2. A high proportion (>85%) of the tested material satisfied the equivalent code values for the Australian F5 and better grades in stiffness. This outcome indicates that high performance structural timber can be obtained from the Nelson Region in the South Island of New Zealand.

3.2 Characteristic actresses for tensile strength and mean modulus of elasticity

A summary of characteristic stresses for tensile strength and mean modulus of elasticity of the tested timber on the basis of specimen length and machine stress grades is presented in Table 3. Fig. 1 shows cumulative frequency distribution curves for tensile strength is a function of length. Comparison of the characteristic stresses of the tested timber in Table 3 with the respective code values in Table 1 shows that all the assigned stress grades on the basis of the test stiffness values exceed their respective code values for the Australian grade in tensile strength. Even when all lengths and grades are combined, the material satisfies the equivalent code value for the Australian F5 grade. This is a favourable outcome since structural timber with F5 grade from radiata pine is acceptable in the international market.

Table 3 also shown that the mean modulus of elasticity does not change with changes in the length of specimens. The mean failure and the characteristic stresses for tensile strength decrease with increasing length (Fig. 1). According to the principle of the weakest link (Madsen & Buchanan, 1986), this span length variation will have a large

Table 2. A summary of the grade outturn of all the boards according to the 1.62 m and 3.15 m clear spans.

Specimen Length	Grade							
	F2	F3	F4	F5	F8	F11	F14	Total
1.62m	21 (4%)	29 (5%)	39 (7%)	126 (22%)	108 (19%)	95 (17%)	151 (26%)	569 (100%)
3.15m	36 (3%)	65 (5%)	88 (7%)	397 (29%)	235 (18%)	198 (15%)	314 (23%)	1333 (100%)
All	57 (3%)	94 (5%)	127 (7%)	523 (28%)	343 (18%)	293 (15%)	465 (24%)	1902 (100%)

Table 3. Mean and characteristic stresses for tensile strength and modulus of elasticity (MOE) as function of specimen length and grade.

Specimen length	Grade	Tensile strength (MPa)			MOE (GPa)		
		Mean	c.v.	5%-ile	$R_{k,\,norm}$	Mean	c.v.
1.62m	F2 & below	9.9	37.7	4.6	3.9	4.0	15.0
	F3	13.1	37.5	6.0	5.3	5.7	5.3
	F4	15.1	35.6	7.5	6.9	6.5	3.1
	F5	18.5	37.2	9.8	9.6	8.0	7.5
	F8	23.7	34.2	10.9	10.9	9.8	4.1
	F11	27.5	37.6	13.3	12.9	11.2	3.6
	F14	32.5	35.2	17.3	17.4	14.0	4.3
	All grades	23.9	47.0	9.7	9.5	10.1	29.9
3.15m	F2 & below	9.2	36.5	4.5	4.1	4.4	13.6
	F3	11.5	34.1	5.1	5.0	5.7	5.3
	F4	11.6	32.0	5.8	5.8	6.5	3.1
	F5	13.7	28.8	8.3.	9.0	8.0	7.5
	F8	16.9	31.7	9.8	10.3	9.8	4.1
	F11	20.5	34.4	14.9	11.8	11.2	3.6
	F14	27.9	35.8	15.0	15.4	14.2	5.6
	All grades	18.3	47.0	8.3	8.3	9.9	32.0
All lengths & grades		20.6	47.8	8.5	8.5	10.0	32.9

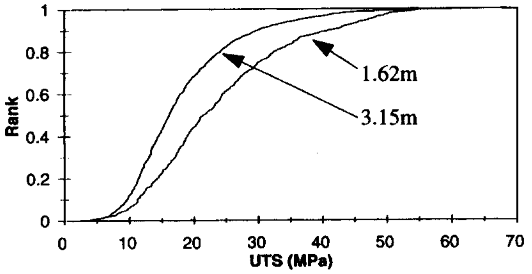

Fig. 1. Cumulative frequency distribution curves for tensile strength on the basis of test length.

effect on the results, with larger spans giving lower strength values. Hence, in order to make a fair comparison, the data in Table 3 need to be standardized to a 3.16m span length by applying a length effect parameter, k_l, as shown by Equation (4). A summary of the adjusted mean failure and the characteristic stresses for tensile is presented in Table 4. The coefficient of variation for both long and short boards was 47%, giving a length effect factor of $k_l = 1/0.47 = 2.13$ in both cases. The adjustment factor then becomes

$$(x_1/x_2) = (L_2/L_1)^{c.v.} = (1.62/3.16)^{0.47} = 0.73$$

This gives a prediction reduction of 100 - 73 = 27% for the strength value, when moving from a teat length of 1.62m to 3.16m.

Fig. 2 shows cumulative frequency distribution curves for tensile strength as a function of grade for the 3.16m specimen length, and Fig. 3 shows the relationship between tensile strength and modulus of elasticity. As can be seen from Fig. 2, tensile strength depends on grade. However, a linear regression analysis between the modulus of elasticity and tensile strength values showed an R^2 value of 0.46 for the entire set of 1,333 boards tested in the 3.16m test length. This value indicates a poor correlation between modulus of elasticity and tensile strength; this correlation is a little higher than, but comparable to, the results of Addis Taehaye *et al.* (1995), who obtained an R^2 value of 0.32 between modulus of elasticity and tensile strength in their study of 90- by 36-mm timber sawn from a 25-year-old stand of radiate pine trees

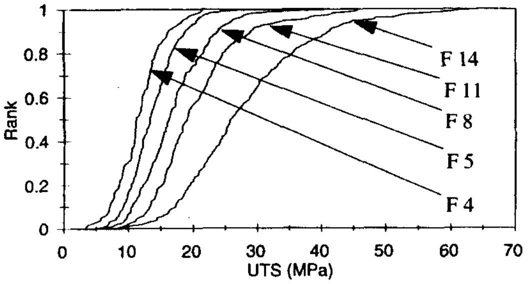

Fig. 2. Cumulative frequency distribution curves of tensile strength for boards segregated into machine stress grades.

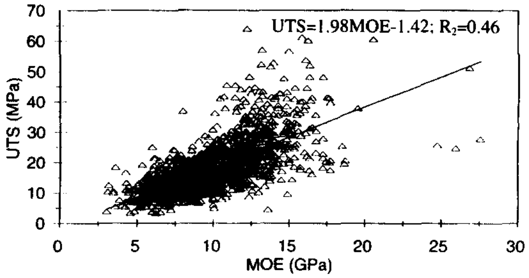

Fig. 3. Ultimate tensile strength (UTS) vs modulus of elasticity (MOE), for all the 1333 boars tested in 3.15 m specimen length.

from the Canterbury Plains. Addis Tsehaye *et al.* (1995) reported that such poor correlation coefficients reflect the limited range of modulus of elasticity and tensile strength values in these sample populations, in part as a result of the immaturity of the timber.

Table 4 demonstrates the way in which the original data in Table 3 change as the span length is increased or reduced. The original tensile strength values over the shorter 1.62m length are reduced by 27% when adjusted to the longer 3.16-m span, giving slightly lower values than found in the test results. The difference between mean values of 18.3 and 23.9 would give a length effect factor of $k_l = 2.50$, which would have been obtained from a coefficient of variation of $2.50^{-1} = 40\%$.

At the 5th percentile level, the length effect is not as strong. The difference between values of 8.3 and 9.7 would imply a length effect factor of $k_l = 4.2$, which would have been obtained from a coefficient of variation of $4.3^{-1} = 23\%$.

3.3 Pre-assumption of failure point

As explained earlier, just prior to destructive testing in tension the expected failure point on each board was marked on the basis of visual inspection of the worst defect (i.e., the largest knot) on any one of the four sides of the board. The object of marking of these worst defects was to test the accuracy of assumption of the failure point when compared with the actual failure point during destructive testing of the board in tension.

Table 5 summarizes this comparison on the basis of visual grades, for the longer 3.16-m and the shorter 1.62m span specimens separately. Note that in Table 5, "true" indicates a situation where the expected failure point coincides with the actual failure point, and "false" indicates where the two failure points are different.

Table 5 demonatrates that a failure point for timber cannot be predetermined prior to testing. Of the 1,902 test specimens, our expectation was true for only 1,118 (68.8%) specimens; the remaining

Table 4. Mean and characteristic stress values for tensile strength adjusted for length using Equation (2), and the length effect parameter, k_l.

Specimen length	Original/adjusted values	Tensile strength (MPa)				
		Mean	c.v. (%)	5%-ile	k_l	$R_{k,\text{norm}}$
1.62 m	(a) original value	23.9	47.0	9.7	2.13	9.5
	(b) adjusted to 3.15 m	17.5		7.1		7.0
3.15 m	Original value	18.3	47.0	8.3	2.13	8.3

Table 5. A summary of the proportion of the pre assumed failure points (%) for all the tested specimens on the basis of specimen length and visual grade.

	Grade	'True' (%)	'False' (%)	Total # of specimens
1.62 m	Box	68.7	31.3	115
	No.2F	66.2	33.8	201
	No.1F	55.3	44.7	253
	All grades	61.9	38.1	569
3.15 m	Box	68.4	31.6	493
	No.2F	57.9	42.1	378
	No.1F	53.7	46.3	493
	All grades	57.5	42.5	1333
All lengths & grades		58.8	41.2	1902

784 (41.2%) specimens failed at different points. Note that the percentage of our expectation ("true") decreased from Box to No.1 Framing grades. This trend suggests that the defects causing failure in the lower grade boards are much more obvious than those in the higher grade boards.

The poor ability of anticipating the point of failure raises questions about the technical validity of sampling procedures where short specimens with predetermined failure points are cut and tested as if representing the original longer material without due consideration of errors due to the length effect. The sampling technique used by Smith *et al.* (1993), which was revisited recently by Addis *et al.* (1997), could be cited as an example of this difficulty.

Smith *et al.* (1993) examined the tensile strength and stiffness of 95 by 45, 145 by 45, and 195 by 45 mm radiata pine timber from normal mill runs collected from different regions of Chile. The researchers used 855mm span length in accordance with the specifications in ISO 8375(ISO, 1985). These short specimens were cut from 3 or 4m lengths of timber in such a way that the grade-determining feature (as detected by visual inspection) was included in the 855mm test span. Thus, the results were seemed to apply to the original 3- to 4-m length (Addis *et al.*, 1997). Our data suggest that Smith *et al.* (1993) overestimated the strength of their 3 to 4m lengths of timber about 40% of the time, although the error in their procedure will be somewhat less for the lowest grades.

4. CONCLUSION

1. Our observations in this study showed the high dependence of characteristic tensile strength on test specimen length and support the following recommendations:
    - It is important that in-grade tensile testing be conducted using a consistent specimen length representative of real world applications.
    - It would be desirable for the very large difference between test specimen lengths in different codes (such as AS/NZ and ISO) be rationalized.
    - Most importantly for designers, a length-effect correction factor should be introduced into NZS 3603 and other timber design codes, following research to obtain the correct numbers.
2. The experiment on the visual assessment of failure points demonstrates that it is not possible to predetermine a failure point for timber prior to testing;
3. As expected, the mean and the characteristic stresses for both tensile strength and modulus of elasticity decrease with lower grades.
4. There is a poor correlation between modulus of elasticity and tensile strength.

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