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Differences in maximum resistive bending moments of *Pinus radiata* trees grown on a range of soil types

John R. Moore[*,1]

New Zealand Forest Research Institute Limited, Private Bag 3020, Rotorua, New Zealand

Abstract

The maximum resistive bending moments (M_b) were measured for 164 Radiata pine (*Pinus radiata* D. Don) trees spanning a range of sizes and growing on six different New Zealand soil types. M_b was significantly and positively correlated with tree height, diameter at 1.4 m (DBH) and stem volume with the latter explaining the greatest proportion of the variation in M_b (R^2=0.854). Trees with higher taper (lower ratio of tree height to DBH) had higher maximum resistive bending moments than trees with low taper. Both root plate diameter and root plate depth were significantly and positively associated with M_b. For trees which failed by uprooting, stem volume, height:DBH ratio and root plate width explain over 91% of the variation in M_b. Differences in M_b were also found between soil types. Trees growing on northern yellow-brown earths and southern yellow-grey earths had significantly greater values of M_b than those growing on yellow-brown pumice soils. A higher incidence of stem failure was also recorded on yellow-grey and yellow-brown earths. This type of failure could not be successfully modelled using elementary beam theory because of the breakdown of the uniform stress assumption and the presence of stem defects. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Wind damage; Tree winching; Stability; Maximum resistive bending moment; Abiotic risk

1. Introduction

The plantation forestry estate in New Zealand covers a total area of ≈1.63 million hectares (Ministry of Forestry, 1997) and is distributed over a wide range of soil types. Radiata pine (*Pinus radiata* D. Don) is the predominant species occupying ≈91% of this area. Since records began, wind damage in the form of stem breakage and uprooting has occurred throughout much of the country (Wendelken, 1955, 1966; Prior, 1959; Chandler, 1968; Irvine, 1970; Wilson, 1976; Somerville et al., 1989; Somerville, 1995).

Keeping in mind the threat posed by wind, a model which uses a combination of fundamental physics and empirical data is being developed to predict the risk of damage (Moore and Somerville, 1998). The model predicts the threshold wind speed necessary to damage the mean tree within a stand of given diameter at breast height (DBH), height and spacing, and which is growing at a particular location. Within the model a tree is assumed to fail if the applied overturning moment exceeds the maximum resistive bending moment (M_b) of the tree. M_b is defined as the maximum resistance of the tree stem to failure or the root system to overturning, with the relative strengths of these determining the mode of failure (Petty and Worrell, 1981).

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[*] Tel.: +64-7-347-5899; fax: +64-7-347-5332.
E-mail addresses: john.moore@forestresearch.co.nz, moorejo@ccmail.orst.edu (J.R. Moore)

[1] Present address: Department of Forest Resources, Oregon State University, Corvallis, OR 97331, USA.

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In order to determine M_b for trees with certain characteristics and growing conditions, a number of authors have used winch and cable systems to apply artificial wind loads to trees. One of the first such studies was carried out by Fraser (1962) who found that a linear relationship existed between M_b and stem weight for Sitka spruce (*Picea sitchensis* Bong Carr.). Other authors (Fraser and Gardiner, 1967; Smith et al., 1987; Frederickson et al., 1993) have obtained similar results.

In New Zealand two previous tree winching studies have been performed (Somerville, 1979; Papesch et al., 1997). The latter found that strong linear relationships existed between M_b and both stem volume and DBH for the range (DBH=18.2–63.9 cm) of Radiata pine trees measured at Eyrewell Forest, Canterbury. In the same forest, Somerville (1979) investigated the effect of different site preparation techniques on M_b. He found that there was a tendency for trees growing in deep rips to fail by stem fracture rather than by uprooting but that this was not accompanied by a significant increase in M_b. This indicates that root architecture has an influence on the failure mode of a tree. Further observational evidence was provided by Wilson (1976) who observed that the incidence of stem breakage during the 1975 storm in Eyrewell Forest was higher where soils were deeper.

The wind forces acting on tree stems have been the subject of several studies (Petty and Swain, 1985; Milne, 1995; Wood, 1995) while Coutts (1983, 1986) performed some of the first work investigating the mechanics of tree root anchorage. He used static tree pulling tests to identify the four main components of the root anchorage of shallowly rooted Sitka spruce. These were (1) tensile strength of windward roots, (2) weight of the root–soil plate, (3) resistance of leeward roots to bending at the hinge region and (4) the resistance to failure of the soil underneath the root–soil plate. The shallow rooting of the trees in these studies was due to the presence of a high water table; a condition relatively uncommon in New Zealand. However, for hybrid larch (*Larix europea*×*japonica*) growing on a free draining soil, Crook and Ennos (1996) found that ≈75% of the anchorage strength was provided by the windward sinkers and tap root. Because the root–soil plate is a compound structure the material properties of the soil are also very important in determining overall root anchorage strength (Mattheck et al., 1997).

The physical properties of forest soil types in New Zealand vary widely and it is therefore possible that the relationship between M_b and tree size will also differ between soil types. More than one function for M_b may therefore be necessary in the model to predict the risk of wind damage to forest stands. This paper investigates the relationship between M_b and tree size by performing a series of tree winching experiments on trees of different sizes growing on a range of New Zealand forest soils types. The effects of tree taper, root plate size and differences in M_b between modes of failure are also investigated.

2. Method

2.1. Site and resource descriptions

Data were collected from seven sites in New Zealand which contained soils with widely varying physical properties (Table 1). Limited data were available on the physical properties of the soils at the seven sites. (DSIR Soil Bureau, 1954, 1968a, and unpublished data). No information was available on rooting depth in soils at Maramarua Forest; however the maximum penetration resistance of the nearby Naike clay soil is 2.54 MPa (DSIR Soil Bureau, 1968b). Radiata pine root penetration is severely restricted above a critical penetration resistance of 3.0 MPa (Sands et al., 1979). Chaney's plantation has been established on a sand dune complex and the close proximity to the coast means that rooting depth may be limited by a saline water table. The presence of an ignimbrite layer under Kaingaroa Forest can restrict vertical root development. In this study, the trees were winched over in the northern part of the forest where Radiata pine roots have been found at depths of 3–4 m (Will, 1966).

2.2. Winching tests

At least 13 trees per site were measured with a maximum number of 62 trees measured at Eyrewell Forest (Table 2). Trees were selected across a range of size classes with tree age varying between 9 and 39 years. The selected trees were pulled over with a

Table 1
Descriptions of tree winching sites

Forest	Area (ha)	Elevation range (m)	Mean annual rainfall (mm)	Soil type[a]	Soil descriptions	
					Parent material	Estimated rooting depth (cm)
Berwick	11,000	100–684	700–1000	Southern yellow-brown earths	Schist and schist loess	45+
Chaney's	1,000	Sea level	600	Yellow-brown sands	Greywacke sands	–
Eyrewell[b]	6,200	66–210	750	Yellow-brown stony soils	Greywacke gravels with a thin layer of loess	<50
Kaingaroa	148,000	250–850	1500	Yellow-brown pumice soils	Taupo ash	300–400
Kinleith	120,000	250–850	1600	Yellow-brown pumice soils	Taupo ash	300–400
Maramarua	4,900	280	1200	northern yellow-brown earths	Greywacke; Hamilton and Mairoa volcanic tephra	–
Otago Coast	9,400	0–440	600–700	Yellow-brown– yellow-grey earths	Greywacke and sub-schist conglomerate gravels	50+

[a] New Zealand Generic Soil Classification (DSIR Soil Bureau, 1954, 1968a).

[b] Data from Papesch et al. (1997).

winch, cable and pulley system. Winching was carried out during the summer months (December–March) when the soil moisture content was lowest. A hand winch ('Tirfor block') was used for winching and the tension in the cable required to cause tree failure (defined as the point when the maximum applied load was reached) was measured using a Reliance SSM5000 loadcell which was graduated in 1 kg increments. Loadcell data were processed using an RM4-SG process module and recorded using a portable data logger. The nominal height of cable attachment was 30–50% of total tree height. This was <80% calculated by Wood (1995) that is necessary to achieve a uniform stress profile in the outer fibres; however, it is similar to the attachment heights used in previous studies (Fraser, 1962; Fraser and Gardiner, 1967; Smith et al., 1987; Frederickson et al., 1993). In addition, at 80% of the height for tall trees, an extremely long cable length would be required in order to maintain a small angle between the attachment point and the base of the anchor trees.

The actual height of the cable attachment, along with the distance between the cable anchor points and the tree to be winched over were both measured and used to calculate the horizontal force acting on the tree. M_b was calculated using the following equation:

$$M_b = F_{max} g h \cos\theta \qquad (1)$$

where F_{max} is the maximum force measured in the cable, g the acceleration due to gravity (9.81 m s^{-2}), h

Table 2
Characteristics of sampled trees

Forest	No. of trees	Age range	DBH (cm)			Height (m)		
			Min.	Mean	Max.	Min.	Mean	Max.
Berwick	12	9–30	23.3	40.1	59.0	9.4	21.6	31.1
Chaneys	18	17	17.3	34.2	52.1	15.4	24.1	30.5
Eyrewell	62	10–39	18.2	39.5	63.9	8.5	20.3	33.5
Kaingaroa	20	9–17	20.7	34.5	51.6	14.0	20.5	29.9
Kinleith	18	11–23	17.4	37.4	65.9	12.3	25.6	34.5
Maramarua	20	10–21	22.3	40.2	56.0	13.9	25.0	35.8
Otago Coast	13	10–27	23.5	36.9	52.6	11.3	20.3	28.9

the height of cable attachment, and θ the angle of the cable from the horizontal in degrees. The bending moment due to the self-weight of the offset stem and crown was not calculated in this study.

At all sites except Eyrewell Forest, total stem volume was calculated from measurements of stem diameters made at 0.15 m, breast height (1.4 m), 3 m above ground, and at 3 m intervals above this point. Stem volume for trees at Eyrewell Forest was calculated as a function of height (H) and DBH (Papesch et al., 1997). Total tree height was measured and the ratio of height to DBH (H/DBH) calculated. Discs were cut from each tree at 5 m intervals from the base and measurements of specific gravity of green wood and basic density were made. Fracture height was measured for trees which failed due to stem fracture. Four basic root plate dimensions were measured if the tree failed by uprooting. Three root plate width measurements were made, two parallel to the ground and one perpendicular to it. In each case root plate width was recorded as the distance from the centre of the tree stem to the edge of the central mass of roots and soil. Root plate diameter was calculated as twice the average of these three measurements. The root plate depth was also measured.

2.3. Modelling stem fracture

The theoretical maximum resistive bending moment required to rupture the outer fibres in the stem and result in stem fracture was calculated using Eq. (2) (Petty and Worrell, 1981).

$$M_b = \frac{\pi \times \mathrm{MOR} \times \mathrm{DBH}^3}{32} \tag{2}$$

where MOR is the modulus of rupture (MPa). For trees which failed by stem fracture, this was calculated from basic density using a relationship developed by Walford (1993). As Eq. (2) calculates the bending moment at breast height (1.4 m), the length of the lever arm (cable attachment height) used in the calculation of M_b was reduced by 1.4 m to compensate.

2.4. Data analysis

Linear models were fitted to the data using the SAS System (SAS Institute Inc., 1989). In addition, both adjusted R^2 and stepwise model selection techniques (Rawlings et al., 1998) were used to determine which tree characteristics were most significantly associated with M_b. For models that were statistically significant ($p<0.05$), the validity of the assumptions of linearity, constant variance and normality of residuals were evaluated. Analysis of covariance was then used to investigate if differences in M_b existed between different soil types and for the different modes of failure. Values of M_b for trees that failed by stem fracture were compared with those obtained from Eq. (2).

3. Results

3.1. Prediction of M_b from tree characteristics

Since the variance of M_b increased with increasing predicted values, a logarithmic transformation was performed to stabilise this. In order to maintain linear relationships between M_b and each of the potential explanatory variables, logarithmic transformations were also applied to height, DBH and stem volume. Significant linear relationships ($p<0.001$) existed between M_b, and tree height, DBH and stem volume (Table 3, relations (1)–(3)). The H/DBH ratio of sampled trees ranged between 32 for the most tapered tree and 113 for the least tapered. Both the stepwise and adjusted R^2 selection methods found that M_b was best predicted as a function of stem volume and H/DBH (relation (4), $R^2=0.865$, $p<0.001$).

3.2. Mode of failure

Three distinct modes of failure were observed: stem failure; root failure and uprooting. Stem failures were visible as either a break, failure under tension and compression or splits usually from the root system up. Uprooting failures were characterised by the lifting of the intact root plate with the tree falling under its own weight. In cases of root failure, trees were pulled over without lifting of the root plate and without stem failure. 29 of the 164 trees winched over exhibited stem failure, 19 root failure and the remaining 116 failed by uprooting (Table 3). Uprooting was most prevalent in the trees winched over in Kinleith, Kaingaroa, Eyrewell and Chaney's forests. Stem and root failure were most common in Berwick, Otago Coast and Maramarua forests (Table 4). The two trees which

Table 3
Relationships between M_b and tree size variables[a]

	Model	Parameter estimates	Standard error	R^2	p-Value
(1)	$\ln(M_b)=a_1+b_1\ln(\mathrm{DBH})$	$a_1=1.740$	0.353	0.821	<0.001
		$b_1=2.655$	0.098		
(2)	$\ln(M_b)=a_2+b_2\ln(H)$	$a_2=4.695$	0.334	0.700	<0.001
		$b_2=2.166$	0.112		
(3)	$\ln(M_b)=a_3+b_3$ vol.	$a_3=11.502$	0.029	0.854	<0.001
		$b_3=0.963$	0.031		
(4)	$\ln(M_b)=a_4+b_4\ln(\text{vol.})+c_4 H/\mathrm{DBH}$	$a_4=11.831$	0.128	0.860	<0.001
		$b_4=0.971$	0.031		
		$c_4=-0.006$	0.002		

[a] Height (H), DBH, stem volume and H/DBH and maximum resistive bending moment (M_b).

Table 4
Number of trees exhibiting each failure mode

Forest	Mode of failure		
	Stem failure	Uprooting	Root failure
Berwick	3	4	5
Chaney's	1	17	1
Eyrewell	1	61	0
Kaingaroa	1	18	1
Kinleith	2	14	2
Maramarua	16	0	4
Otago coast	5	2	6
Total	29	116	19

failed by uprooting in Otago Coast Forest were located on a ridge top where the soil was shallow. Due to the marked difference in the soil type at this point, these two trees were excluded from the Otago Coast data set for inter-site comparisons.

The ratio of stem failure height to cable attachment height ranged between 0.09 and 0.66 with a mean of 0.23 (Fig. 1). Many of the failures were associated with stem defects such as branches, however the visual appearance of stem fractures varied considerably. Younger trees at Maramarua Forest tended to exhibit relatively 'clean' breaks while the older trees tended to fail with the stem on either side of the failure point still partially joined. Evidence of failure in compression on the 'winchward' side of the trees was also observed. The trees at Otago Coast and Berwick forests tended to exhibit 'clean' breaks.

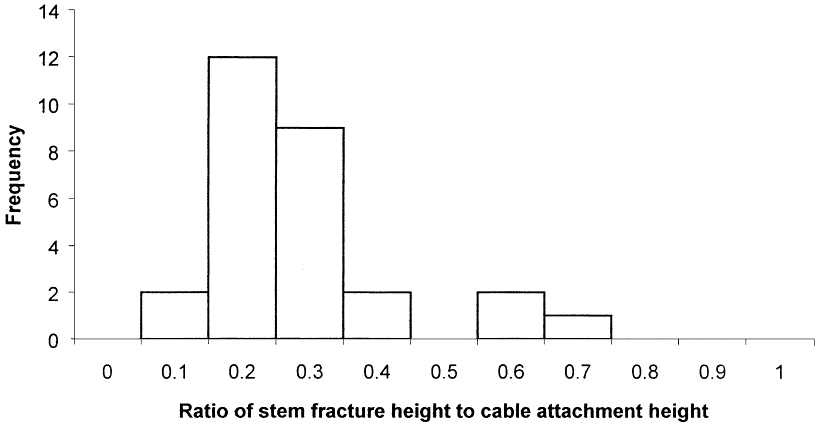

Fig. 1. Histogram of the ratio of failure height to cable attachment height for trees which failed by stem fracture. Trees were more likely to fail near the stem base for the range of cable attachment heights used in this study.

Table 5
Comparisons of M_b between failure modes[a]

Mode of failure	Mean M_b[b] (k Nm)
Stem failure	122.33 a
Root failure	93.76 ab
Uprooting	79.02 b

[a] Means have been adjusted for stem volume and taper, and corrected for logarithmic transformation bias.

[b] Means followed by a different letter are significantly different at 0.05 level.

For a given stem volume and taper, trees which exhibited stem failure had significantly (p<0.001) higher mean values of M_b than trees which uprooted (Table 5). There was suggestive but inconclusive evidence of a difference in M_b between trees which uprooted and those which exhibited root failure (p=0.066). A comparison of the measured and predicted values of M_b for trees which failed by stem fracture found that the two were significantly different (p<0.01) and that the deviation between the two lines increased with increasing stem volume (Fig. 2).

3.3. Root plate size

Data were available for 86 of the 116 trees which failed by uprooting. Root plate diameters ranged between 1.2 and 6.7 m and the rooting depth ranged between 0.2 and 2.1 m. The statistical model to examine the effect of root depth (RD) was weighted by RD^2 to correct for decreasing variance. Trees with a greater rooting depth had higher values of M_b (Table 7, relation (5)). M_b was also higher for trees with wider root plates (relation (6)). Both root plate width and root depth were significantly associated with M_b when included in the model together (relation (7)). Root plate width even still significantly associated with M_b once the effects of stem volume and taper were accounted for (p<0.001).

Table 6
Comparisons of M_b between soil types[a]

Soil type	Mean M_b[b] (k Nm)
Southern yellow-grey earth	98.42 a
Northern yellow-brown earth	94.94 a
Southern yellow-brown earth	85.56 abc
Yellow-brown sand	82.95 abc
Yellow-brown stony soil	82.70 ab
Yellow-brown pumice soil	70.40 c

[a] Means have been adjusted for stem volume and taper, and corrected for logarithmic transformation bias.

[b] Means followed by a different letter are significantly different at 0.05 level.

3.4. Soil type

Differences in maximum resistive bending moments between trees growing on different soil types were examined using analysis of covariance. For a given stem volume and taper, trees growing on northern yellow-brown earths and southern yellow-grey earths had greater M_b (p<0.05) than those growing on yellow-brown pumice soils (Table 6). Similarly, trees growing on yellow brown stony soils had greater

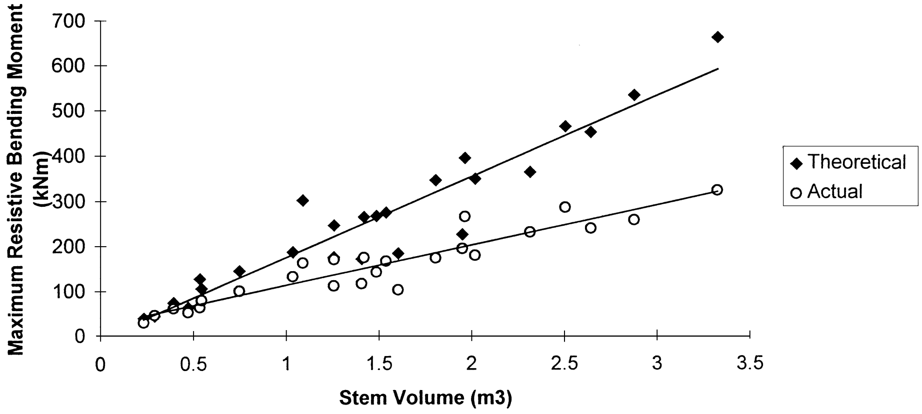

Fig. 2. Comparisons of measured M_b and that predicted using Eq. (2).

Table 7
Relationships between M_b and measures of root plate size[a]

	Model	Parameter estimates	Standard error	R^2	p-Value
(5)	$\ln(M_b)=a_5+b_5$ depth	$a_5=10.773$	0.190	0.147	<0.001
		$b_5=0.779$	0.154		
(6)	$\ln(M_b)=a_6+b_6$ width	$a_6=9.064$	0.242	0.533	<0.001
		$b_6=0.647$	0.069		
(7)	$\ln(M_b)=a_7+b_7$ width$+c_7$ depth	$a_7=9.372$	0.223	0.324	<0.001
		$b_7=0.617$	0.123		
		$c_7=0.445$	0.058		
(8)	$\ln(M_b)=a_8+b_8\ln(\text{vol.})+c_8\,H/\text{DBH}+d_8$ width	$a_8=10.863$	0.236	0.914	<0.001
		$b_8=0.831$	0.046		
		$c_8=-0.006$	0.003		
		$d_8=0.278$	0.036		

[a] Root plate width and depth are both in metres.

maximum resistive bending moments than those growing on yellow-brown pumice soils ($p<0.05$). Once the effects of soil type had been accounted for, the effect of mode of failure on M_b was not significant ($p=0.43$).

4. Discussion and conclusions

Failure mode is closely linked to soil type. Ninety-two percent trees failed by uprooting on non-cohesive soils but only 11% failed by this mode on clay soils. Mergen (1954) stated that the distribution and anchoring ability of tree roots are affected by soil texture and consistency. Stronger root anchorage prevents a tree from uprooting and the force is transferred to the tree stem resulting in stem breakage (Coutts, 1986). The factors determining consistency are cohesive and adhesive strength and the angle of internal friction. Craig (1990) describes a cohesive soil as one where the particles adhere after wetting and subsequent drying and if significant force is required to crumble the soil. No quantitative information on soil shear strength was available for the sites used in this study.

Trees winched over on yellow-brown sands were characterised by an absence of soil on the root plate and by the presence of large tap-roots. Mergen (1954) suggests that these are only of minor mechanical value, however Crook and Ennos (1996) found that the tap root and windward sinkers constitute up to 75% of the anchorage strength. Higher maximum resistive bending moments of these trees compared with those growing on yellow-brown stony soils suggests that these tap roots do increase the strength of root anchorage. The root plates of trees winched over on yellow-brown pumice soils had soil attached to them but this could be removed easily. The significant difference in M_b between trees growing on yellow-brown pumice soils and those on yellow-brown stony soils is most probably due to the larger number of trees winched over on these two soil types.

Non-cohesive soils anchor tree roots mainly through frictional forces and are most resistant when their moisture content is at or close to field capacity (Mergen, 1954). Trees winched over on yellow-grey and yellow-brown earths exhibited a greater resistive force than those on the yellow-brown sand, pumice and stony soils. These results are in direct contrast to those obtained by Fraser (1962); however, the cohesion of the clay soils is dependent on moisture content and is greatest when the soils are dry (Mergen, 1954). All the trees in the New Zealand study were winched over during the summer months when the measured moisture content of the clay soils was between 30 and 37%. Mergen (1954) found that trees growing on non-cohesive soils had deep spreading root systems with few branches, whereas in dry clay soils, root systems were shallow and less wide spreading. This suggests that root architecture may be more important than root plate size in defining the overall root anchorage strength. Root systems of trees growing on clay soils need to be excavated to test this hypothesis particularly as Stokes (1999) found that the location of the failure point on a tree differed between species and was dependent on root architecture.

The hypothesis that a tree stem can be considered as a cantilever beam, of circular cross-section, with a uniform resistance to bending was first proposed by Metzger (1893) and has more recently reassessed by Morgan and Cannell (1994). If the application of a force to the free end of this beam generated constant stresses, in the outer fibres, along the length of the beam then the likelihood of breakage should be the same for any point along it. However, 71% of the trees which failed by stem fracture had the failure point at <10% of tree height. This indicates that the stresses are greater in the bottom part of the stem. Wood (1995) found that a pull height equal to 80% of tree height was necessary to achieve a uniform stress distribution. Trees pulled from above this point have excessive stress at the top while trees pulled from below have their largest stresses at the bottom. Trees in this study were pulled from between one third and one half of tree height which has led to the largest stresses and hence failure occurring in the lower portion of the stem. While the attachment height used in this study may not accurately simulate actual wind loading, comparisons of failure modes between different soil types should still be valid as the method was consistently applied across all sites.

The different types of stem fracture observed may be a result of the ratio of tensile strength to compressive strength of the stem. Where the strength in tension just exceeds the strength in compression, some crushing will occur in compression and the stem will fail in tension. This type of fracture was common in large trees at Maramarua Forest where the tensile strength of the wood may have been reduced by the presence of small branches. Larger branches (relative to stem size) were present in trees grown in younger stands which are more open. These could reduce the strength in tension to a level where brittle fractures occur. No significant difference was observed in M_b between these fracture types. The effect of branches and other stem defects on the overall strength of the stem coupled with the violation of the assumption of uniform stress distribution has led to the differences between the actual values of M_b and those predicted using Eq. (2). Empirically derived equations should therefore be used in place of theoretical equations in the model for predicting wind damage risk.

For stem fracture, Cremer et al. (1982) found that the ratio of tree height to diameter at 1.3 m of dominant (largest 200 trees per hectare based on diameter) was the most valuable index of the risk for Australian *P. radiata* plantations. A *H*/DBH ratio of <60 was generally associated with stability and values above 100 with 25–100% instability. Few data were available for trees which failed by uprooting; however, the New Zealand study found that the distribution of stem volume has a significant effect on M_b for all three modes of failure.

McLaren et al. (1995) found that height growth of New Zealand Radiata pine was positively correlated with final-crop stocking. One possible reason they suggest for this reduction in height growth is that increased wind forces act on the crowns of trees in stands with lower stockings. Increased stem taper has been identified by a number of authors (see Telewski, 1995) as an adaptive response to wind loading. The greater root anchorage strength of highly tapered trees may also be an adaptive growth response to wind. For young Sitka spruce and European larch (*Larix europea*), Stokes et al. (1995) found evidence to suggest that wind action stimulates the growth of those roots most important for anchorage. There is also evidence that roots are able to optimise their shape to resist applied loads by concentrating material in the regions of greatest stress (Nicoll and Ray, 1996). Unfortunately, these theories cannot be tested further as much of the information on tree spacing is incomplete and root growth was not investigated in this study.

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