MECHANICAL STABILITY OF *PINUS RADIATA* TREES AT EYREWELL FOREST INVESTIGATED USING STATIC TESTS

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ABSTRACT

Overturning bending moments were analysed for *Pinus radiata* D. Don trees which had been winched over at Eyrewell Forest, Canterbury, between 1967 and 1971. Trees were sampled from four different age-classes in three forest compartments. The bending moment applied by the winch and cable system increased rapidly and linearly to a maximum value before decreasing until the trees toppled under their own weight. The bending moment due to the mass of the offset stem plus crown contributed an average of 9% to the total overturning moment at the point of maximum applied moment. Significant positive relationships were found between the maximum resistive bending moment (M_c) offered by the tree and its total height, diameter at breast height (dbh), and stem volume. The greatest proportion of the variance in M_c was explained by a linear relationship involving dbh. The angle of stem deflection at both the maximum resistive bending moment and the point at which the tree toppled under its own weight was significantly and negatively related to tree height. Analyses of covariance found that root plate diameter had a significant effect on M_c while root plate depth did not. The effect of taper was uncertain.

Keywords: wind damage; tree winching; stability; maximum resistive bending moment; Eyrewell Forest.

INTRODUCTION

Strong winds are the principal climatic risk to plantation forestry on the Canterbury Plains (Ministry of Forestry 1994). The most common winds causing forest damage are from the north-west (approximately perpendicular to the main axis of the Southern Alps). Under certain conditions, atmospheric lee waves form on the eastern side of the Alps (Cherry 1972). These waves result in zones of increased windspeed over the lower-lying plains downwind. Eyrewell Forest sustained severe damage from north-west winds in 1945, 1964, and 1975. A south-west wind in 1968 also caused considerable damage.

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At Eyrewell Forest, shallow soils overlying compacted gravels prevent deep root penetration and on unripped sites rooting depth ranges between 0.5 and 1.0 m (Wendelken 1966). Wind damage has usually been in the form of uprooting, with an intact root plate being lifted out of the ground (Somerville 1979). Some trees have failed by stem fracture and after the 1975 storm Wilson (1976) observed that the incidence of stem breakage was higher where soils were deeper and root development greater. Strength of the root anchorage exceeded that of the stem, resulting in the latter failing under an excessive applied load (Coutts 1986). On sites which had been deep ripped to 1.2 m, Somerville (1979) found that when a force was applied to young *P. radiata* trees with a winch and cable system, failure took the form of stem breakage rather than uprooting, although the measured maximum resistive bending moment* did not increase significantly.

A tree subject to a wind load can be considered as either a static or dynamic system (Coutts 1986). In a static system the overturning moment has two components (Fig. 1). The first relates to lateral force from the wind applied to the centre of pressure of the tree. This causes the tree to lean. The second relates to the displaced weight of the stem and crown. The overturning moment is resisted by the strength of both the root anchorage and the tree stem. If the overturning moment exceeds the resistive bending moment of the tree at a particular angle of deflection, the tree will deflect further. The tree will fail if the overturning moment exceeds the maximum resistive bending moment of the tree, the mode of failure being determined by the relative strengths of the stem and roots (Petty & Worrell 1981). In a dynamic system, tree movement is driven by impulses as trees respond to intermittent gusts

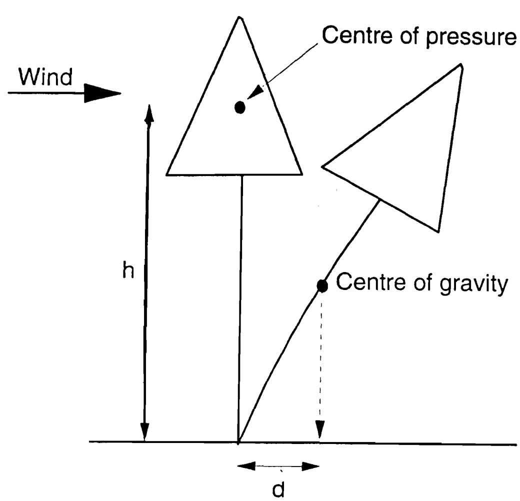


FIG. 1–The two components of the overturning moment acting on a tree. The first component is due to the wind acting at the centre of pressure of the tree crown at height *h*. Once the tree has deflected, the weight of the offset stem plus crown, acting over the lever arm *d*, provides the second component (from Quine *et al.* 1995).

* A bending moment, which may be thought of as a "turning agent", is defined as M = r F, where r is the perpendicular distance of the line of action of the applied force, F, from the base of the tree (Halliday & Resnick 1988).

sweeping into the canopy (Gardiner 1995). The response depends on the frequency of the force applied to the tree by the wind gusts (Wood 1995). At very low frequencies, the tree will respond to the instantaneous wind force whereas at high frequencies it will respond to the force due to the mean windspeed. When gust frequency coincides with the natural sway frequency of the tree, resonance occurs. If damping is inadequate, the amplitude of the tree's oscillations can increase to the point where failure occurs. Oscillations cause the root plate to rock. Hütte (1968) observed that on wet soils, rocking of the root plate draws water into and forces it out of the cavity under the root plate, in a pumping action. As the water is forced out, soil particles are removed. Eventually windward vertical roots are separated from the soil, and the root anchoring ability of the tree is reduced. In very strong winds, tree oscillations may be so heavily damped that resonance cannot occur and the tree may fail as a result of direct wind loading (Wood 1995). In this situation the wind load required to cause a tree to fail can be determined by measuring the maximum static force that the tree can withstand.

Several studies (Fraser 1962; Fraser & Gardiner 1967; Somerville 1979; Smith *et al.* 1987; Frederickson *et al.* 1993) have used a cable and winch system to investigate the response of the roots and stem of a tree to a simulated static wind load. Significant relationships have been found between the maximum resistive bending moment of a tree and various measures of its size. Fraser (1962) and Fraser & Gardiner (1967) found a linear relationship between maximum resistive bending moment and stem weight and Frederickson *et al.* (1993) found relationships between maximum resistive bending moment and total tree weight, stem volume, dbh, and tree height.

This paper presents the results of analyses performed on data collected from winching experiments carried out on *P. radiata* trees at Eyrewell Forest. The aim of these analyses was to determine whether relationships exist between the maximum resistive bending moment of a tree, which quantifies the capability of a tree to resist an applied load, and various measures of its size. The effects that factors such as rooting depth and tree taper have on maximum resistive bending moment were also investigated.

METHOD

Site and Sample Selection

Eyrewell Forest covers approximately 6200 ha and is located 40 km west of Christchurch on a sloping plain rising east to west from 66 m to 210 m a.s.l. The soils belong to the Lismore series of Brown Soils (Hewitt 1993). They are shallow and derived from old, waterlaid, greywacke gravels. The amount of gravel in the top 1 m often exceeds 65% by weight and is sometimes in excess of 85% (Wendelken 1966). At a depth of 25 to 40 cm the gravels are generally so compacted that vertical penetration of roots is restricted or prevented. The average annual rainfall at Eyrewell is approximately 750 mm.

Between 1967 and 1971, 63 trees were winched over until they failed. The trees were randomly selected from four age-classes: 10, 19, 28, and 39 years in compartments 2, 50, and 54 (now compartments 5, 39, and a firebreak respectively). The range of tree diameters at breast height 1.4 m (dbh) and heights of the trees selected in each age-class are shown in Table 1. The 10- and 39-year-old trees had been planted, but the 19- and 28-year-old trees had grown from natural forest regeneration. Somerville (1979) observed no significant

TABLE 1–Minimum, maximum, and mean values of the tree height and dbh measurements for each age-class.

Age-class (years)	Number of trees	Dbh (cm)			Height (m)		
		min.	max.	mean	min.	max.	mean
10	16	18.2	29.1	22.8	8.5	13.1	10.6
19	20	31.5	46.6	37.2	17.6	22.5	19.3
28	9	42.9	63.9	50.2	21.1	30.4	25.6
39	17	42.0	61.4	52.1	22.2	33.5	27.9

difference between *P. radiata* natural regeneration and planted stock in terms of the maximum resistive bending moments of 11-year-old trees. It was assumed there would be no differences in this respect between older trees considered in this study.

Measurements and Observations

The trees were winched over using a cable and pulley system, as shown in Fig. 2. The system was similar to that used by Fraser (1962) except that a D9 crawler tractor was used instead of a hand winch. The winch cable was attached with a strop to the tree stem at a point between one-quarter and one-third of tree height. The pull was applied through a snatch block fixed to an anchor tree at the same height as the strop.

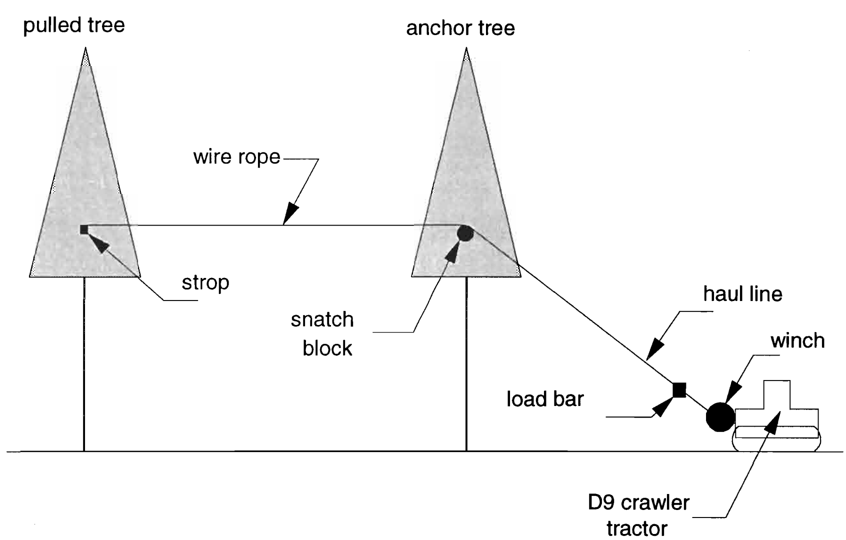


FIG. 2–Schematic diagram of the tree winching system.

A full bridge of strain gauges cemented to an aluminium strain bar (Fig. 3) was calibrated, and used to measure the winch loads with the aid of an electrical resistance strain indicator. Tree deflection under load was measured by marking off the wire rope at a series of fixed intervals. As the crawler tractor winched in the haul line, the load applied to the tree was measured at each mark. Since the height of the rope was known, the applied bending moment and angle of deflection could be computed.

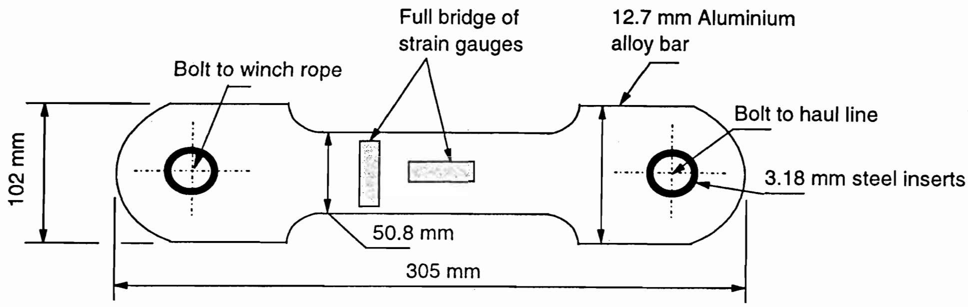


FIG. 3–Dimensions of the strain bar used to measure load on the winch rope.

Once the tree had been winched over, its total height and dbh, the width and length of the crown, and the depth and diameter of the root plate were all measured. Over-bark stem volume was calculated using *P. radiata* tree volume functions T78 and T89 in the forestry calculation package FFCalc (Pavarno 1993).

Slight variation in soil moisture content was observed over the period of the tests. Non-cohesive soils such as those of the Lismore series anchor the tree through frictional forces, which are known to be less dependent on soil moisture content than cohesive forces (Craig 1990). It was assumed that minor variations in soil moisture content did not affect the tests.

Calculation of the Maximum Resistive Bending Moment.

Because the strain bar records only the bending moment applied to the tree, the component of the overturning force due to the weight of the displaced stem and crown has to be added in order for the maximum resistive bending moment of each tree to be determined. This second component was calculated from Eq. 1:

$$M_{off} = m\, g\, \mathrm{CoM} \sin\theta \qquad \ldots[1]$$

where m is the mass of the stem plus crown (kg), g is the acceleration due to gravity (9.81 m/s^2), CoM is the height to the centre of mass (m), and θ is the angle of deflection of the tree stem from vertical (degrees). CoM was determined by calculating the centre of mass for the stem and the crown and deriving a weighted average based on relative mass. The centre of mass of the stem was found by dividing it into a series of 1-m-long sections and calculating the weight of each section from volume estimates. The green density of the wood was assumed to be constant throughout the stem. The volume in each section was determined by combining the appropriate volume function with an integrated taper equation (Goulding & Murray 1976). Taper equation 182, which is applicable to *P. radiata* throughout New Zealand (A. Gordon pers. comm.) was used in this calculation. Each section was assumed to be approximately cylindrical, having its centre of mass at the midpoint. The centre of mass of the stem was calculated from Eq. 2:

$$Cm_s = \frac{\sum_{i=1}^{n} Vs_i y_i}{V} \qquad \ldots[2]$$

where Cm_s is the centre of mass, Vs_i is the volume of the ith section with distance y_i to its centre of mass, and V is the total stem volume. Total live crown weight was determined by calculating the oven-dry weight of needles and branch material from Eq. 3 and 4 developed by Madgwick (1983):

$$\ln(\text{needle dry weight}) = 2.193\ln d_c - 3.952 \quad ...[3]$$

$$\ln(\text{branch dry weight}) = 2.448\ln d_c - 4.189 \quad ...[4]$$

where d_c is the diameter at the base of the crown (m), estimated from taper equation 182. The values of both needle weight and branch weight were consistently over-estimated due to the antilogarithmic conversion required to solve the above equations (Madgwick 1983). These are relatively small components of the bending moment due to the weight of the offset stem and crown which in turn constitutes only a small component of the total overturning moment. No attempt was therefore made to correct for this bias. The *in situ* live crown weight was determined from the oven-dry mass using a conversion factor of 2.5 (P. Beets pers. comm.).

The crown was assumed to be triangular in shape, with a centre of mass at a point one-third of crown height from the base. The centre of mass of the whole tree was calculated from a weighted average of the centres of mass of the stem and crown using Eq. 5.

$$Cm_t = \frac{\rho V Cm_s + Tcm Cm_c}{\rho V + Tcm} \quad ...[5]$$

where Cm_t is the centre of mass of the whole tree, Cm_c is the centre of mass of the crown, and Tcm is the total crown weight.

Statistical Analysis

Data were analysed using the SAS System (SAS Institute (Inc.) 1994). Regression equations were developed to relate the maximum resistive bending moment (M_c), the angle of stem deflection at maximum load, and the angle at which the stem toppled to tree height, dbh, and stem volume. Analysis of covariance was used to investigate the effects of tree age, root plate diameter, root plate depth, and stem taper on M_c. In each analysis stem volume and dbh were used as covariates.

RESULTS

Once tree winching commenced, the bending moment due to the applied load increased rapidly and linearly with increasing stem deflection to a maximum (Fig. 4). Loud popping sounds associated with root failure were observed at or near this point. With further winching, the applied bending moment decreased until either the trees toppled under their own weight or the stem fractured. The cable attachment on the 10-year-old trees was too low to allow accurate measurements of stem deflection. For other age-classes, the angle of stem deflection at the maximum applied bending moment ranged from 1.8° up to 15.6° while the angle of deflection at which the tree toppled under its own weight ranged from 9.8° up to 42.3°. At the point of maximum applied moment, the bending moment due to the displaced weight of stem and crown contributed an average 9% of the total overturning moment. Beyond this point the contribution increased because of a decrease in the applied moment. The stem deflection angle at the maximum applied bending moment and the angle of deflection at which the tree toppled were both weakly but significantly related to measures of tree size (Table 2). Tree height was the best predictor of stem deflection at both maximum applied bending moment and tree topple, with taller trees failing at smaller angles of deflection (Fig. 5a, b).

TABLE 2–Relationships between tree size variables (diameter; height; volume) and (1) maximum resistive bending moment, (2) angle of stem deflection at maximum applied load, and (3) angle of stem deflection at tree topple. Data for 10-year-old trees were excluded from analysis of Eq. 16–21.

Model	Parameter estimates	Standard error	r^2	RMSE	PRESS statistic
(1) Bending moment					
[6] $M_c = a_6$ dbh $+ b_6$	a_6 = 5.4846	0.38	0.778	37.44	88 975
	b_6 = –99.553	15.66			
[7] $M_c = a_7$ h $+ b_7$	a_7 = 8.8133	0.90	0.614	49.39	155 845
	b_7 = –62.497	19.41			
[8] $M_c = a_8$ vol $+ b_8$	a_8 = 90.392	7.59	0.690	43.42	119 940
	b_8 = 26.622	9.35			
[9] Mc = a_9 ln(h) +b_9	a_9 = 162.261	15.55	0.645	47.37	142 604
	b_9 = –360.937	46.18			
[10] ln(M_c) = a_{10} ln(dbh) +b_{10}	a_{10} = 2.8591	0.16	0.835	0.45	139 366
	b_{10} = –5.9923	0.60			
[11] ln(M_c) = a_{11} ln(h) + b_{11}	a_{11} = 2.5578	0.16	0.817	0.48	250 381
	b_{11} = –3.18	0.46			
[12] ln(M_c) = a_{12} ln(vol) + b_{12}	a_{12} = 1.0419	0.05	0.844	0.43	146 331
	b_{12} = –4.7417	0.06			
[13] $M_c = a_{13}\, \mathrm{dbh}^{b_{13}} + c_{13}$	a_{13} = 5.376	11.10		37.75	
	b_{13} = 1.00	0.45			
	c_{13} = –98.708	87.88			
[14] $M_c = a_{14}\, \mathrm{h}^{b_{14}} + c_{14}$	a_{14} = 48.573	126.30		48.69	
	b_{14} = 0.592	0.59			
	c_{14} =–168.697	255.78			
[15] $M_c = a_{15}\, \mathrm{dbh}^{b_{15}}\, \mathrm{h}^{c_{15}} + d_{15}$	a_{15} = 5.758	12.56		37.99	
	b_{15} = 1.051	0.47			
	c_{15} = –0.072	0.15			
	d_{15} =–103.385	97.81			
(2) Angle of stem deflection at maximum applied bending moment					
[16] $\theta_{Mc} = b_{16}$ dbh $+ c_{16}$	b_{16} = –0.2163	0.05	0.323	2.86	390.45
	c_{16} = 18.037	2.18			
[17] $\theta_{Mc} = b_{17}$ h $+ c_{17}$	b_{17} = –0.5416	0.08	0.519	2.41	278.11
	c_{17} = 21.099	1.90			
[18] $\theta_{Mc} = b_{18}$ vol $+ c_{18}$	b_{18} = –3.4574	0.64	0.399	2.69	345.91
	c_{18} = 12.691	0.91			
(3) Angle of stem deflection when tree uprooted or stem fractured					
[19] $\theta_t = b_{19}$ dbh $+ c_{19}$	b_{19} = –0.4259	0.12	0.238	6.96	2298.40
	c_{19} = 43.105	5.30			
[20] $\theta_t = b_{20}$ h $+ c_{20}$	b_{20} = –1.2636	0.18	0.537	5.43	1413.84
	c_{20} = 53.818	4.28			
[21] $\theta_t = b_{21}$ vol $+ c_{21}$	b_{21} = –7.2614	1.54	0.335	6.50	2019.76
	c_{21} = 33.164	2.20			

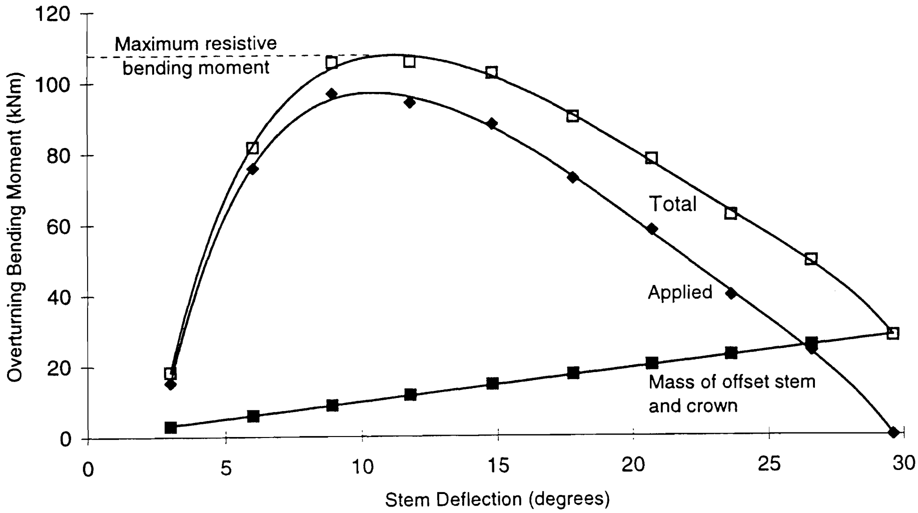
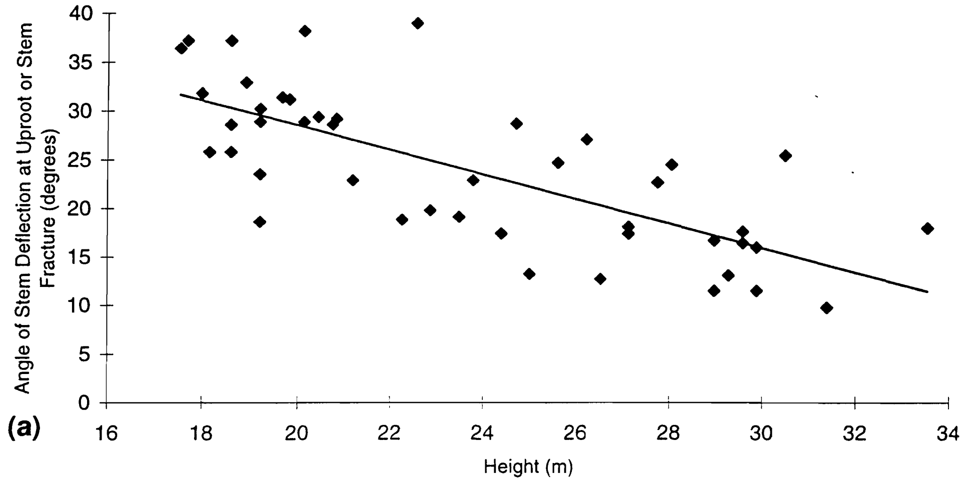


FIG. 4—The relative contribution of the applied bending moment and the bending moment due to the offset mass of the tree to the total overturning bending moment at various angles of stem deflection.

One of the winched trees failed by stem fracture and the rest by uprooting. A fault with the electrical resistance strain indicator meant the peak load was not recorded for one tree. The final data set was therefore derived from 62 trees. Height, dbh, and stem volume were used as predictors of the maximum resistive bending moment, M_c (Fig. 6). Linear relationships (significant at $p<0.01$) were observed in each case (*see* Eq. 6, 7, and 8 in Table 2). The greatest proportion of the variance in M_c was explained by dbh ($r^2 = 0.78$). Although volume data from the 10-year-old trees suggested that the value of the intercept in Eq. 8 could be zero (Fig. 6c), analysis of variance showed that the intercept term was significant ($p<0.01$) and it was therefore retained in the model. Analysis of residuals showed that for relationships between either stem volume or dbh and M_c the variance was normally distributed and relatively constant. The relationship between tree height and M_c had a normally distributed but non-constant residual variance. The error term generated when predicting M_c could therefore be expected to increase with tree height. Logarithmic transformations (Eq. 9 and 11 in Table 2) were used in an attempt to correct for this. From comparisons of the prediction sums of squares (PRESS statistic) it was found that the relationship between tree height and M_c was best represented by a log-linear model (Eq. 4, Table 2), although this transformation did not correct for non-constant variance. Logarithmic transformations were also performed for the models involving dbh (10) and stem volume (12). No improvement was noted in either case. Non-linear relationships between M_c and dbh, height and dbh×height were investigated (Eq. 13, 14, and 15 in Table 2), with values for the power terms in these models being determined by the non-linear modelling procedure, NLIN, in the SAS system (SAS Institute (Inc.) 1994). For Eq. 13, the power term was found to be unity, indicating that the relationship between Mc and dbh was linear. The non-linear relationship between M_c and height (Eq. 14) had an RMS error that was lower than that of the linear relationship (Eq. 7), but higher than the log-linear relationship (Eq. 9). When both height and diameter were incorporated, the



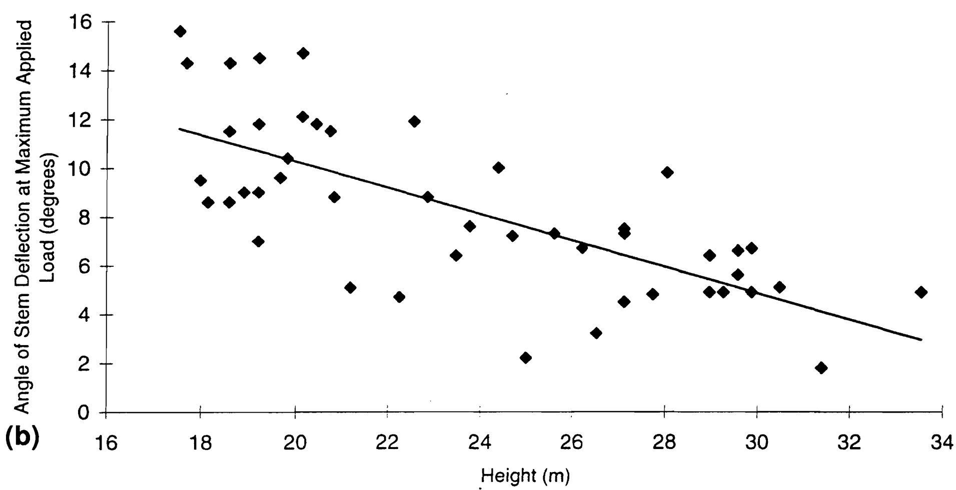


FIG. 5–Relationships between tree height and (a) the angle of stem deflection at uproot or stem fracture, and (b) the angle at the point of maximum applied moment.

non-linear relationship (Eq. 15) had a lower RMS error than the linear equation based on stem volume (Eq. 8). Overall, the linear equation involving dbh (Eq. 6) was the best predictor of M_c.

Age/site Effects

The 19-year-old trees had greater maximum resistive bending moments than might normally be expected for trees of their size (Fig. 6a, c). Since trees of different age-classes were sampled at different locations, site differences may be confounded with age. In order to investigate the effect of site and age, a dummy variable representing the location and age

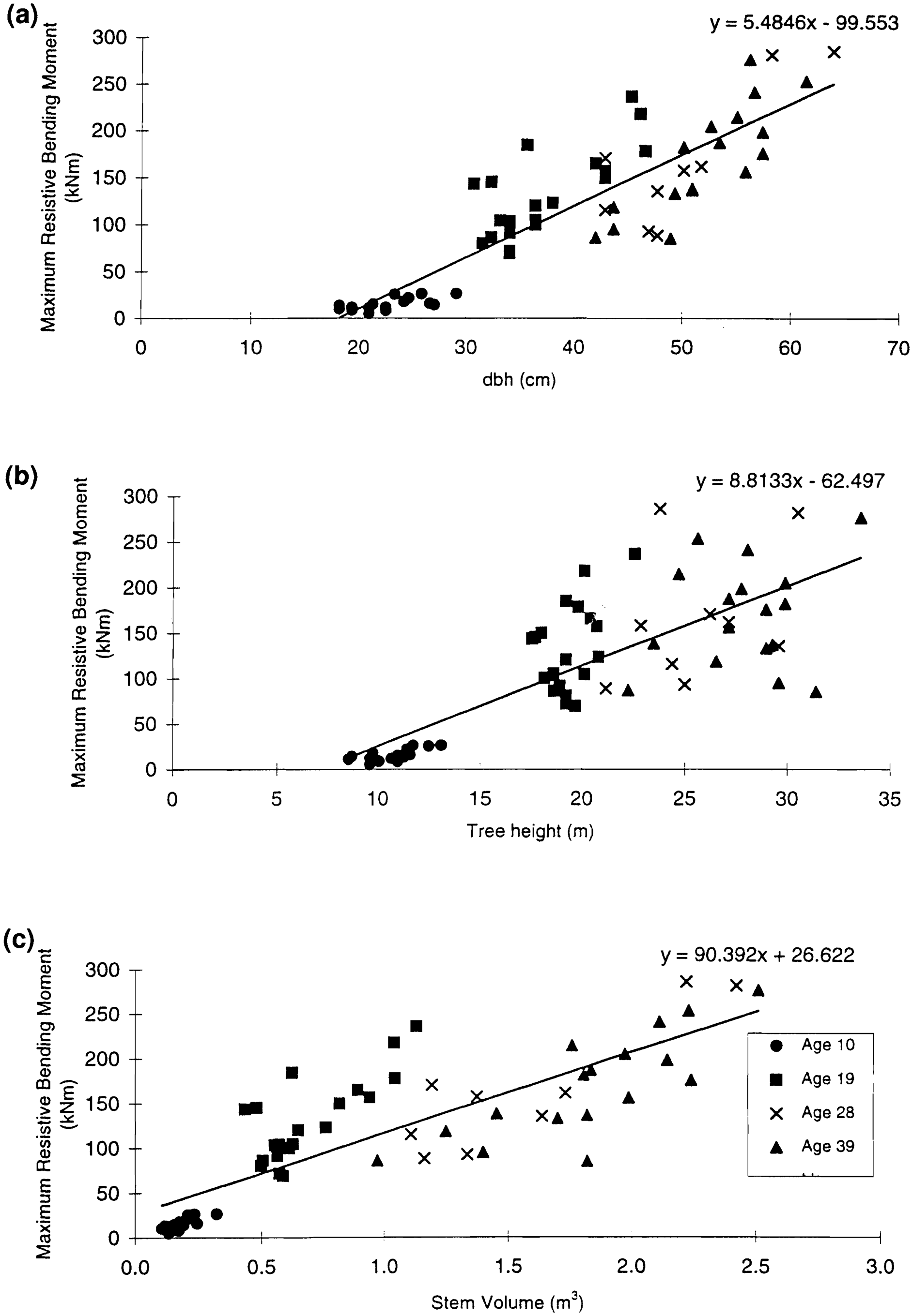


FIG. 6–Relationships between maximum resistive bending moment and (a) diameter at breast height, (b) tree height, and (c) stem volume.

of a sampled tree, was included. This had a significant effect on M_c ($p<0.01$) when incorporated into the relationships defined by Eq. 6 and 8. Covariance analysis of mean maximum resistive bending moments, adjusted for either dbh or stem volume, found that trees in the 19-year age group had higher ($p<0.01$) maximum resistive bending moments than trees from the 10-, 28-, and 39-year age groups (Table 3). The interaction between site/age and dbh was also significant ($p<0.01$) which indicates that the effect of dbh on M_c differs for different sites or ages. When means were adjusted for stem volume, trees from the 39-year age group had significantly lower maximum resistive bending moments than trees from the 10- and 28-year age groups.

TABLE 3–Mean maximum resistive bending moments derived from covariance analysis for each age-class.

Age-class	Mean M_c (adjusted for stem volume)	Mean M_c (adjusted for dbh)
10	127.07 a	37.55 a
19	171.89 b	147.10 b
28	87.43 a	69.92 a
39	58.21 c	58.17 a

Means followed by the same letter are not significantly different ($p>0.05$) from each other.

Root Plate Size

The rooting depth of the uprooted trees ranged between 0.3 m and 1.2 m. Diameters of the root plates varied between 1.2 m and 6.7 m. The effects of root plate size on M_c were examined by analysis of covariance. The maximum resistive bending moment was not affected by root depth (Eq. 22 and 23 in Table 4), but was higher ($p<0.01$) where the root plate was wider (Eq. 24 and 25).

Stem Taper

When based on the 62 tree dataset, stem taper calculated as the ratio of tree height to dbh ranged between 32 (more tapered) and 68 (less tapered) (*see* Fig. 7). Analysis of covariance indicated greater stability of the more tapered trees ($p=0.05$), but only when stem volume was used as the covariate (Eq. 26 and 27 in Table 4). Exclusion of the 10-year-old trees resulted in a closer relationship between taper and M_c ($p<0.01$ with stem volume as the covariate; $p=0.05$ when dbh was the covariate—*see* Eq. 28 and 29 in Table 4).

DISCUSSION

The maximum resistive bending moment of a tree, M_c, was significantly and positively related to tree height, dbh, and stem volume. Correlation between stem volume and M_c was weaker than that calculated for loblolly pine (*Pinus taeda* L.) growing in Hobcaw Forest, South Carolina, United States (Frederickson *et al.* 1993), although tree height and M_c were strongly related in both studies. The stronger relationship between stem volume, calculated as $dbh^2 \times$ height, and M_c at Hobcaw ($r^2=0.94$) was probably a consequence of the close

TABLE 4—Results of covariate analyses performed to investigate the effect of taper and root plate depth and diameter on maximum resistive bending moment.

Model	Parameter estimates	p value	RMSE	Comments
Root plate depth				
[22] $M_c = a_{22}$ dbh + b_{22} depth + c_{22}	a_{22} = 5.356	0.0001	37.71	Depth not significant.
	b_{22} = 14.625	0.6027		
	c_{22} = −104.594	0.0001		
[23] $M_c = a_{23}$ vol + b_{23} depth + c_{23}	a_{23} = 85.938	0.0001	43.61	Depth and intercept not significant.
	b_{23} = 29.051	0.3703		
	c_{23} = 11.845	0.5378		
Root plate diameter				
[24] $M_c = a_{24}$ dbh + $b_{24}\,\phi + c_{24}$	a_{24} = 4.561	0.0001	32.30	Diameter significant at 1% level.
	b_{24} = 17.354	0.0001		
	c_{24} = −121.649	0.0001		
[25] $M_c = a_{25}$ vol + $b_{25}\,\phi + c_{25}$	a_{25} = 73.142	0.0001	32.72	Diameter significant at 1% level.
	b_{25} = 24.129	0.0001		
	c_{25} = −37.050	0.0025		
Taper				
[26] $M_c = a_{26}$ dbh + b_{26} taper + c_{26}	a_{26} = 5.484	0.0001	37.75	Taper not significant.
	b_{26} = 0.038	0.9560		
	c_{26} = −101.467	0.0097		
[27] $M_c = a_{27}$ vol + b_{27} taper	a_{27} = 92.039	0.0001	44.11	Intercept term not significant.
	b_{27} = 0.465	0.0144		
[28] $M_c = a_{28}$ dbh + b_{28} taper	a_{28} = 4.561	0.0001	40.44	10-year-old data excluded. Intercept not significant.
	b_{28} = −1.030	0.0181		
[29] $M_c = a_{29}$ vol + b_{29} taper + c_{29}	a_{29} = 57.778	0.0001	38.88	10-year-old data excluded.
	b_{29} = −3.172	0.0008		
	c_{29} = 246.010	0.0001		

correlation between dbh^3 and M_c (r^2=0.93)*. In the South Carolina study, all except one of the 40 trees failed by stem fracture. If the stem is considered as a cantilever beam, the maximum resistive bending moment against stem fracture would be proportional to the modulus of rupture of the wood multiplied by dbh^3. Because most Eyrewell Forest trees failed by uprooting, the cantilever analogy does not apply. The relationship between dbh^3 and M_c (Eq. 13) was much weaker (r^2=0.73) than in the South Carolina study where tree behaviour more closely resembled that of a true cantilever. Because stem volume was strongly correlated with dbh^3 at both Hobcaw and Eyrewell Forests (r^2=0.98 and 0.93, respectively), the degree of the relationship between stem volume and M_c was similar to that between dbh^3 and M_c in both cases.

* Frederickson *et al.* (1993) developed a linear regression between dbh^3 and M_c (r^2=0.93)and a non-linear regression (second order polynomial) between height and M_c. The relationship between dbh^3 and M_c at Eyrewell Forest was much weaker (r^2=0.73).

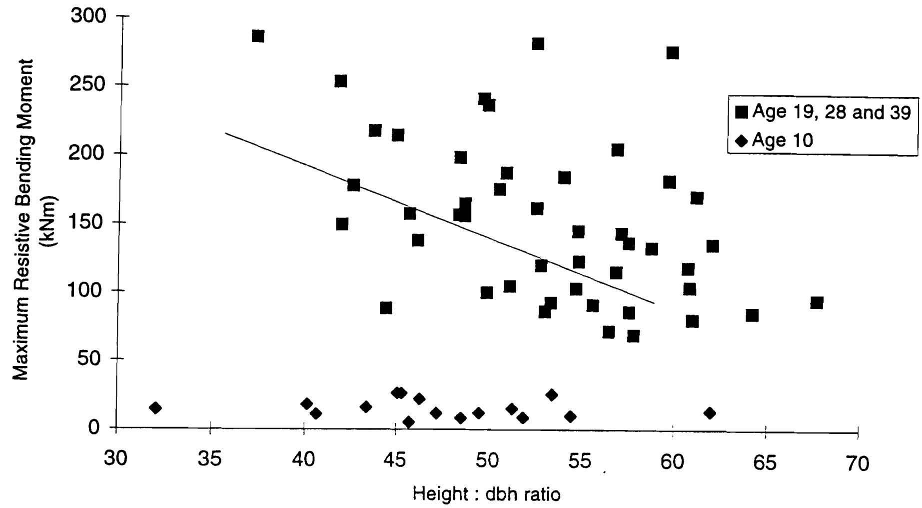


FIG. 7–Relationship between stem taper (height : dbh ratio) and maximum resistive bending moment.

The relationship between total overturning moment and stem deflection in *P. radiata* at Eyrewell differed from that found for *Picea sitchensis* (Bong.) Carr. at Kershope Forest by Coutts (1986). At an equivalent stem volume index, the contribution of the bending moment due to the mass of the offset stem and crown to the total overturning moment at the maximum applied bending moment was approximately 30% in *P. sitchensis*, because of greater stem deflection. The total overturning moment in *P. sitchensis* increased after the maximum applied bending moment had been reached. In *Pinus radiata*, the total overturning moment decreased once the maximum applied bending moment had been reached. It is therefore possible that a bending moment applied by wind could cause a *P. radiata* root system to fail but does not result in the tree toppling. A subsequent smaller applied bending moment could then deflect the stem to the point where the tree would topple under its own weight. This could result from the next gust, or it could occur after a period of days or months. In 1964 a series of strong winds on 13–14, 20–21, and 24–26 March, with a maximum gust of 102 km/h recorded on March 13–14, caused extensive damage at Eyrewell Forest (Wendelken 1966). The winds on the 13–14 March may have predisposed trees to damage from the later wind events.

Age/site Effects

Covariance analysis indicated that, at a given stem volume, 19-year-old trees had significantly higher maximum resistive bending moments than 10-, 28-, or 39-year-old trees. The implications of this result are difficult to assess since it was not possible to determine the extent to which factors other than age (e.g., site effects, establishment method, and experimental method) were also involved. Future studies should investigate the behaviour of trees of a similar age at more than one site. The use of a more accurate load cell in combination with a hand-operated winch, especially for small trees, would be likely to increase the sensitivity of the measurements.

Stem Deflection

If the tree stem is considered to be a tapered cantilever beam, the curvature, R, due to an applied bending moment, M, can be determined from Eq. 30:

$$\frac{1}{R} = \frac{M}{EI} \quad \ldots[30]$$

where E is the modulus of elasticity and I the area moment of inertia. The moment of inertia is a function of diameter to the fourth power and since it has been shown that the applied bending moment is linearly related to tree diameter, stem deflection can be expected to be less in larger trees. This elementary theory applies only when the beam deflects less than 25% of its length or approximately 14° (Morgan & Cannell 1987). The stem deflection at the maximum applied load was less than 14° in most of the trees in this study (Fig. 6b). For larger deflections, Morgan & Cannell (1987) divided the stem into a series of short sections, each having only a small deflection, and used the transport matrix method of structural analysis to determine the deflection of the whole stem. The relationship between tree size and stem deflection would still be expected to hold under these conditions. The Eyrewell data indicated an inverse relationship between tree height and stem deflection, but the relationship between dbh^3 and stem deflection was much weaker ($r^2 = 0.17$) than would be expected from theoretical considerations. The most likely explanation is that the tree stem does not behave as a true cantilever due to deformation of the root plate under loading. This would reduce the modulus of elasticity, the degree of reduction depending on the characteristics of the root plate, especially the strength of the root/soil bond. This is an area which requires further research.

Stem Taper

Petty & Swain (1985) found that stem taper was the most important factor affecting susceptibility to wind breakage. A similar result was obtained by Cremer *et al.* (1982) in Australian *P. radiata* plantations where the ratio of tree height to diameter at 1.3 m in dominant trees (largest 200 trees/ha based on diameter) was found to be the most valuable index of wind-damage risk, at least with respect to stem failures. Trees with little taper were more susceptible to damage. Cremer *et al.* (1982) associated a height/diameter ratio below 60 with stability and values above 100 with 25–100% instability, noting that fewer data were available for uprooting than for stem failure. The Eyrewell study demonstrated correlation between the height/dbh ratio and M_c, with tapered stems being more stable. More of the initial variance in M_c was associated with dbh than with stem volume. Although stem taper appears to have less effect on uprooting than on stem breakage, forest managers should realise that there is some basis for expecting more stability from highly tapered stems than from trees which could yield more valuable logs.

Root Plate Size

The preponderance of uprooting in this study agreed with observations made by Somerville (1979) during actual wind-damage events at Eyrewell. Wilson (1976) observed that the incidence of stem breakage at Eyrewell was higher where soils were deeper and root development greater. Site preparation trials produced similar results, with trees at control sites having taproots that penetrated one-third of the depth of those on deep-ripped sites

(Balneaves & de la Mare 1989), and slightly weaker root anchorage (Somerville 1979). Since the strength of root anchorage influences mode of failure (Coutts 1986), a positive relationship between strength of root anchorage (quantified through M_c) and rooting (soil) depth might be expected. Analysis of covariance showed no significant relationship between M_c and rooting depth, but demonstrated that root plate diameter and M_c were related. The 61 trees examined had relatively shallow root systems (maximum recorded root depth = 1.2 m). The absence of deep-rooted trees in this study may have obscured a more normal relationship between *P. radiata* rooting depth and M_c. For shallow-rooted *Picea sitchensis*, the weight of the root/soil plate was found by Coutts (1986) to be the second-largest component of root anchorage after root tensile strength. Any increase in either root plate depth or width can be expected to increase root plate weight and thus M_c. An increase in root plate diameter increases the distance to the fulcrum about which the leaning tree pivots. This increases the mechanical advantage of the root anchorage component associated with resistance to bending of the roots at the fulcrum (Quine *et al.* 1995). In fact, forest managers can do little to increase root plate width. They should be aware that any practice which restricts lateral root spread (e.g., deep plough furrows) will reduce the strength of root anchorage. Rooting depth can be increased by ripping, which has been carried out at Eyrewell Forest since 1966 (Somerville 1979). Although inclusion of root plate dimensions in relationships between M_c and stem volume significantly reduces the RMS error, it is unrealistic to include them in a predictive model because measurement involves destructive sampling.

CONCLUSIONS

The maximum resistive bending moment of *Pinus radiata* trees growing at Eyrewell Forest was strongly correlated with tree height, dbh, and stem volume, larger trees having a greater resistance to an applied load. Larger trees also had reduced angles of stem deflection at the point of tree failure and the point of topple. Because winching resulted in uprooting rather than stem breakage, trees did not behave as true cantilever beams, and tree height rather than dbh^3 provided the closest correlation with stem deflection. Although previous studies have shown that root plate weight constitutes a large component of root anchorage, root plate diameter rather than depth affected the maximum resistive bending moment of trees at Eyrewell. The effect of stem taper on susceptibility to uprooting was not well defined.

The bulldozer and load bar arrangement used in this study may not have been sufficiently sensitive to small changes in the applied moment. A more accurate load cell and a hand-operated winch are recommended for future studies, especially if small trees are involved.

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