RELATIONSHIP BETWEEN TIMBER GRADE, STATIC AND DYNAMIC MODULUS OF ELASTICITY, AND SILVISCAN PROPERTIES FOR *PINUS RADIATA* IN NEW SOUTH WALES

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ABSTRACT

Wood stiffness, or modulus of elasticity, can be measured or predicted using a variety of methods including standard bending tests, machine stress-grading, stress wave methods, or analysis of X-ray diffraction data from SilviScan. Each of these methods was applied to the same wood samples and the inter-relationships were determined.

Dynamic modulus of elasticity (MOE) values from stress wave and SilviScan methods produced very similar results but both these methods produced higher values than the static modulus of elasticity from the traditional bending test. Results from all methods were highly correlated and simple regression equations were developed for converting results between methods. Machine stress-grade was more strongly related to SilviScan modulus of elasticity than to either density or microfibril angle.

Keywords: modulus of elasticity; SilviScan; density; microfibril angle; machine stress-grade; *Pinus radiata*

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INTRODUCTION

Stiffness is a fundamental wood property and an essential requirement for structural timber. The traditional method of measuring stiffness involves a bending test in which a section of timber of fixed dimensions and moisture content is subjected to a known load and the resultant deflection of the section is measured (Mack 1979). The static modulus of elasticity is calculated from the linear portion of the load-deflection curve. If the load test is continued to sample failure, bending strength or the modulus of rupture (MOR) is determined.

A modified version of this test is used for routine machine stress-grading in sawmills where dry boards are run through under a known load and graded according to the resulting deflection. Coloured paint is sprayed on the board to reflect the grade at each point along its length. The resulting machine stress-grade (MGP) level, which is based on the lowest stiffness point, determines the potential end uses for each piece of timber and thus is the key factor in determining the pricing structure. Each machine stress-grade has a modulus of elasticity threshold. As an example, for 90 × 35-mm *Pinus radiata* D. Don boards, the threshold values may be F4 = 4.1 GPa, MGP10 = 5.5 GPa, MGP12 = 8.3 GPa, and MGP15 = 11.6 GPa. Therefore, each paint colour represents a range of modulus of elasticity values; for example, the MGP10 colour represents sections of board with modulus of elasticity values greater than 5.5 and less than 8.3 GPa.

Traditional bending tests on short clear samples in the laboratory are labour-intensive and time-consuming as they require the removal, drying, and machining of the samples prior to testing. Alternative methods are now available for assessing modulus of elasticity using either stress wave velocity or X-ray diffraction data (Evans 2006). The modulus of elasticity from stress wave methods is referred to as dynamic modulus of elasticity to distinguish it from the static modulus of elasticity from bending tests. The greater opportunity for stress relaxation during static testing results in lower modulus of elasticity values than those measured in dynamic tests.

Dynamic modulus of elasticity can be measured using either bending vibration or longitudinal stress waves (Divos & Tanaka 2005). The longitudinal method used in the current study relies on the velocity of stress waves along the grain of a known length of timber. This velocity is used to calculate dynamic modulus of elasticity ($MOE_{Dynamic}$ in GPa) according to:

$$MOE_{Dynamic} = density * velocity^2$$

If used on air-dry specimens, the actual air-dry density is required. If used on green wood then green density is assumed to be a constant at 1000 kg/m^3 for *P. radiata* (Lindstrom *et al.* 2004). A range of different tools are available for assessing longitudinal dynamic modulus of elasticity on standing trees, logs, or air-dried wood samples using either resonance or time of travel of the stress waves. One of these tools, WoodSpec (Dickson *et al.* 2004), was used in this study for determining dynamic modulus of elasticity of air-dry short clear samples. Static modulus of elasticity was subsequently measured on the same samples. The acoustic velocity measured by WoodSpec is calculated from longitudinal resonance frequency. This instrument generates a reading from many hundreds of reverberations of an acoustic signal within wood, providing a highly accurate measurement of the plane wave acoustic velocity. The relationship between the fundamental frequency of vibration for the short clear samples and acoustic velocity (Dickson *et al.* 2004; Kollman & Krech 1960) is:

$$\text{WoodSpec velocity} = 2 \times \text{short clear length} \times \text{fundamental frequency}$$

Modulus of elasticity may also be predicted by X-ray densitometry and diffraction analysis using SilviScan (Downes *et al.* 1997; Evans *et al.* 2000; Evans 2006). Modulus of elasticity is controlled to a large extent by wood density, microfibril angle of the S2 layer of the cell wall, and the proportion of aligned microfibrillar material in the cell wall. Evans (2006) noted that the X-ray diffraction patterns contained information on both microfibril orientation and the proportion of aligned microfibrils in the cell wall. An increased background scattering indicated an increase in the proportion of relatively low modulus of elasticity material in the wood. The following semi-empirical equation was developed for estimating SilviScan modulus of elasticity (MOE_{SS}):

$$MOE_{SS} = A(I_{CV}D)^B$$

where D is air-dry density determined by X-ray densitometry,

I_{CV} is the coefficient of variation of the amplitude of the azimuthal X-ray diffraction intensity profile,

A is a scaling factor, and

B is an exponent to allow for curvature.

This is only one of many possible models based on X-ray diffractometric parameters and density that could be used. The modulus of elasticity used for development of this equation is the longitudinal sonic resonance method of Kollman & Krech (1960; Ilic 2001) based on analysis of fundamental resonance frequencies in the fibre direction. The constants A and B have been found to be insensitive to wood species but dependent on the X-ray diffractometer instrument and the method of modulus of elasticity calibration. For SilviScan calibrated using dynamic modulus of elasticity, A~0.165 and B~0.85.

Each of these measures of modulus of elasticity produces a slightly different result. Dynamic modulus of elasticity values have been found to be 10% to 20% higher than static modulus of elasticity values on the same samples (Gerhards 1982; Divos & Tanaka 2005). The difference between the methods also varies with species even if the same testing methods are used (Haines *et al*. 1996). This study provided the opportunity to determine the relationships between the different measures of modulus of elasticity and with air-dry density and microfibril angle for the same samples, and how these factors relate to grade.

MATERIALS AND METHODS

Samples were collected from boards being processed during a sawing study on 35-year-old mature clearfelled *P. radiata* from Buccleuch State Forest (Cpt 526, latitude 35°14´, longitude 148°31´, 1010 m a.s.l.) in the Tumut region of NSW. The stand had been thinned at ages 14, 22, and 28 years. Thirty trees were harvested and three logs, 5 m long, were cut from each tree. All logs were transported to a local sawmill and processed into the following dimensions: 90 × 35 mm, 90 × 45 mm, 70 × 45 mm, and 70 × 35 mm. They were kiln dried and then machine stress-graded into three grades:

- F4 or reject for low stiffness
- MGP10
- MGP12, the highest stiffness grade identified

The grade marked on the board represents the minimum grade or lowest stiffness point for the whole board. Thus a board with some sections that are MGP10 and some MGP12, will still be marked as a MGP10 board. As there was no grade above MGP12, some of the boards graded to MGP12 may in fact be of higher grade.

As the 5-m boards came out of the stress grader, boards with specific grades were put aside with the aim of getting 25 boards for each grade, with most of the board falling within a single grade. Sections (350 mm long) were cut from each board to represent each stress grade, ensuring that the section was clear of knots, sloping grain, resin pockets, etc. where possible. For ease of sampling most sections were cut from areas towards the end of a board. However, as approximately 600 mm at either end of each board is normally not graded by the stress grader, care was taken to avoid the ends of the board.

From each board section, a short clear sample (300 mm long × 20 mm × 20 mm) was prepared. During the sample preparation, a 15-mm section was cut from the ends of each short clear specimen for SilviScan analysis. All short clear specimens were placed in a temperature- and humidity-controlled room to equilibrate to around 12% moisture content prior to being measured for dynamic modulus of elasticity using WoodSpec (MOE_{WS}) and then static modulus of elasticity (MOE_{ST}) and modulus of rupture in a three-point bending test according to the Australian Standard described by Mack (1979). The 15-mm-thick sections from each short clear sample were run through SilviScan (Evans *et al*. 2000; Evans 2005) to determine average air-dry density, microfibril angle (MFA), and calculated dynamic modulus of elasticity (MOE_{SS}).

All modulus of elasticity data were collated into a single file, together with the SilviScan data. The two sets of SilviScan data from the ends of each short clear sample were averaged to give single values for density, microfibril angle, and MOE_{SS}. Correlations were determined between the measures of modulus of elasticity (MOE_{ST}, MOE_{WS}, and MOE_{SS}), air-dry wood density, and microfibril angle. Regression equations were developed for prediction of MOE_{ST} from the MOE_{WS} and MOE_{SS}. Histograms of the SilviScan and modulus of rupture data were produced to describe the distributions of density, microfibril angle, modulus of elasticity, and modulus of rupture within each stress grade.

RESULTS

Mean moduli of elasticity from both WoodSpec and SilviScan were higher than static modulus of elasticity for each stress grade (Table 1). Plots of MOE_{WS} and MOE_{SS} against static modulus of elasticity (Fig. 1) indicated that the data did not match the line of equivalence, which represents a 1 to 1 agreement in values (45° line). However, when MOE_{WS} and MOE_{SS} were plotted against each other, the data matched well to the line of equivalence, indicating that these methods were giving similar results.

Correlations between the different measures of modulus of elasticity and modulus of rupture, density, and microfibril angle (Table 2) indicated excellent agreement of static modulus of elasticity with MOE_{WS} and MOE_{SS}, with correlation coefficients

TABLE 1–Means for each measure of modulus of elasticity (MOE) plus modulus of rupture (MOR), density, and microfibril angle (MFA) by stress grade for *Pinus radiata*.

	Units	F4	MGP10	MGP12
MOE_{ST}	GPa	7.0	8.9	12.8
MOE_{WS}	GPa	7.8	9.8	14.4
MOE_{SS}	GPa	7.7	10.0	14.1
MOR	MPa	62.7	72.0	87.4
MFA	Degrees	22.7	19.2	14.5
Density	kg/m^3	465	488	543

TABLE 2–Correlations between the different measures of modulus of elasticity (MOE) with modulus of rupture (MOR), airdry density, and microfibril angle (MFA) for *Pinus radiata*.

	MOE_{ST}	MOE_{WS}	MOE_{SS}	MOR	MFA
MOE_{WS} (GPa)	0.99				
MOE_{SS} (GPa)	0.97	0.97			
MOR (MPa)	0.87	0.86	0.82		
MFA (degrees)	–0.82	–0.81	–0.83	–0.55	
Density (kg/m^3)	0.70	0.71	0.75	0.79	–0.30

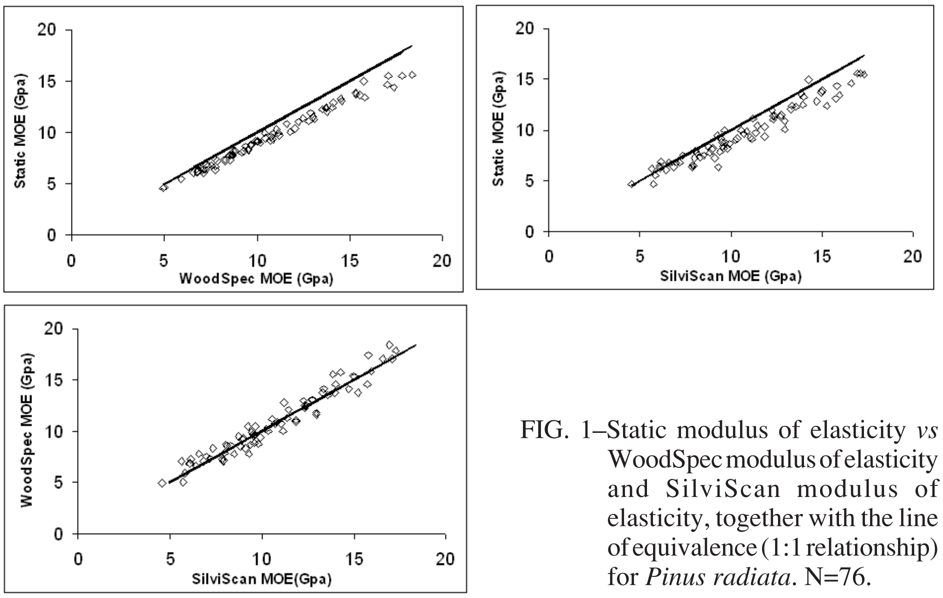

FIG. 1–Static modulus of elasticity *vs* WoodSpec modulus of elasticity and SilviScan modulus of elasticity, together with the line of equivalence (1:1 relationship) for *Pinus radiata*. N=76.

(r) being 0.99 and 0.97 respectively. Fitted regression equations (Table 3) indicated that both WoodSpec and SilviScan moduli of elasticity could explain most of the variation in static modulus of elasticity (R^2 of 98% and 93% respectively) but that the slope of the regression was less than 1, as expected. The standard errors of prediction were 0.34 GPa for WoodSpec (done on exactly the same piece of wood) and 0.73 GPa for SilviScan (done on samples removed from ends of static modulus of elasticity sample). For converting from WoodSpec to SilviScan modulus of elasticity, the slope of the curve was 1.01 with an R^2 of 94%, indicating good agreement between these methods. This is to be expected, as the constants in the SilviScan model were determined using the same sonic resonance technique employed by WoodSpec.

TABLE 3–Regression equations for converting dynamic modulus of elasticity (MOE) into static modulus of elasticity, for converting MOE_{SS} into MOE_{WS}, or predicting static modulus of elasticity from density, together with percentage of variance accounted for (R^2) and standard error of prediction (SEP) for *Pinus radiata*. N=76.

Equation	Units	R^2 (%)	SEP
$MOE_{ST} = 0.891 * MOE_{WS}$	GPa	98	0.34
$MOE_{ST} = 0.899 * MOE_{SS}$	GPa	93	0.73
$MOE_{WS} = 1.008 * MOE_{SS}$	GPa	94	0.77
$MOE_{ST} = -7.37 + 0.0340 * Density$	GPa, kg/m^3	48	2.05

Correlations between the different measures of modulus of elasticity and density and microfibril angle (Table 2) indicated that microfibril angle had a slightly stronger influence on modulus of elasticity than did density. For modulus of rupture, the reverse appeared to be true; the correlation with density was stronger than that with microfibril angle. Density alone explained less than 50% of the variation in static modulus of elasticity (Table 3).

Frequency distributions of microfibril angle, density, and MOE_{SS} within each grade (Fig. 2) indicate that MOE_{SS} was considerably better than either microfibril angle or density for discriminating the three stress-grades. Each grade was associated with a reasonably symmetric MOE_{SS} distribution and, although the distributions overlapped, the peaks were distinct. In addition, there was minimal overlap of the distributions for the top and bottom grades, indicating a clear distinction between the MGP12 and F4 grades. In contrast, for both microfibril angle and density, the MGP10 and F4 grade distributions overlapped significantly and neither grade had a clear peak. The microfibril angle and density distributions for the MGP12 grade were clearly distinct from those of the MGP10 and F4 grades. Interestingly, some of the MGP10 and F4 samples had high density, well into the range of the MGP12 samples (Fig. 2 and Table 4).

As each machine stress-grade is determined by a threshold value, it would be expected that the modulus of elasticity values within each grade would be variable, and the range in the MOE_{ST} and modulus of rupture for each stress grade was quite large (Fig. 3). Although the minimum values within each grade differed (Table 4), the maximum values indicated considerable overlap of the grades. Of interest is the

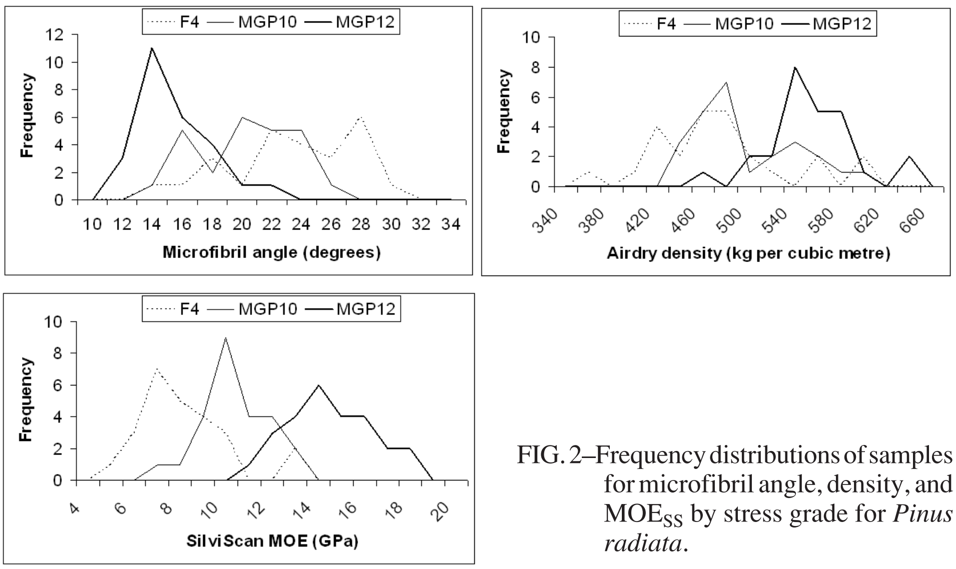

FIG. 2–Frequency distributions of samples for microfibril angle, density, and MOE_{SS} by stress grade for *Pinus radiata*.

TABLE 4–Range in values for each stress grade for *Pinus radiata*

	F4		MGP10		MGP12	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
MOE_{ST} (GPa)	4.6	11.9	6.9	10.9	9.7	15.6
MOR (MPa)	41	101	56	86	60	113
MFA (degrees)	13.2	29.8	13.6	24.6	10.25	21.1
Density (kg/m^3)	348	592	426	585	457	639

fact that the minimum values for modulus of elasticity and modulus of rupture for the MGP10 grade occurred below the peak of the distribution for F4, the lower grade. Similar results were apparent for the MGP12 data, with the minimum being below the peak of the MGP10 distribution.

In terms of MOE_{SS}, the F4 and MGP12 grades appeared largely distinct, with the exception of two samples that were graded to F4 but had a relatively higher MOE_{ST}. As all samples were taken from clear sections of board, the reason for the low grading of these two samples is unclear. The MOE_{SS} distribution for the MGP10 grade considerably overlapped those of the F4 and MGP12 grades.

The modulus of rupture distributions were very wide, allowing considerable overlap of the F4 and MGP12 grades. It appears that all of the MGP10 boards could easily have been classified into one of the other two classes (*see* Fig. 3).

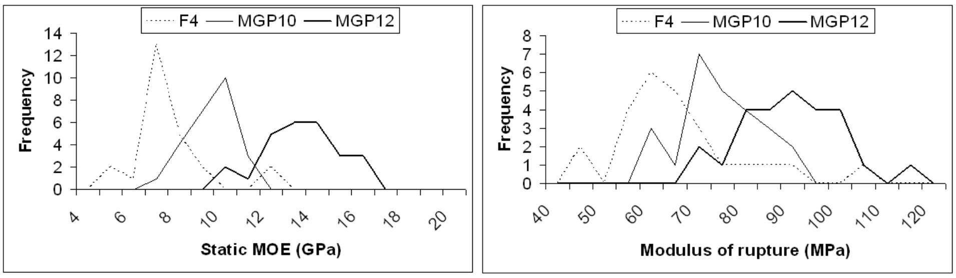

FIG. 3–Frequency distributions of samples for static modulus of elasticity and modulus of rupture by stress grade for *Pinus radiata*.

DISCUSSION

The three different methods for measuring modulus of elasticity examined in this study produced results that were strongly correlated with each other. The average longitudinal dynamic modulus of elasticity values from WoodSpec and SilviScan were 11% larger than those from the static bending tests. However, this study confirmed that an accurate prediction of stiffness for *P. radiata* can be obtained using the X-ray diffraction pattern from SilviScan.

When comparing static and longitudinal dynamic modulus of elasticity values, similar high correlations have been reported in a wide range of species by Gerhards (1982), Smulski (1991), Larsson *et al*. (1998), Ilic (2001), and Lindstrom *et al.* (2002, 2004). The 11% difference between static and dynamic modulus of elasticity is at the lower end of the range reported by Gerhards (1982) and similar to the 10% reported by Larsson *et al*. (1998) for Norway spruce (*Picea abies* (L.) H. Karst.) and 11% reported by Haines *et al.* (1996) for silver fir (*Abies alba* Mill.), but higher than the 6% these authors reported for Norway spruce. Lindstrom *et al*. (2002) reported a 7% difference between dynamic and static modulus of elasticity for 4-year-old *P. radiata* in New Zealand. Larger differences have been reported in hardwoods, with Smulski (1991) reporting differences of 22% to 32% for a range of North American hardwoods and Ilic (2001) reporting a difference of 29% for *Eucalyptus delegatensis* R. T. Baker. In contrast, Lindstrom *et al.* (2004) found the static and dynamic modulus of elasticity values to be very similar in 3-year-old *P. radiata*.

These observed differences may be due in part to different experimental techniques for measuring dynamic modulus of elasticity (Smulski 1991). A good example of this effect can be seen in the results for Norway spruce by Larsson *et al.* (1998) and Haines *et al.* (1996) who reported differences between static and dynamic modulus of elasticity data of 10% and 6% respectively. Differences between species are also apparent, as indicated by the results of Smulski (1991) and Haines *et al.* (1996) who found that different species did not produce identical results under the same test conditions. Similarly, differences in hardwoods would appear to be greater than those found for softwoods. All of these results indicate that it is important to determine the relationships for each species and specific test method.

It should also be noted that the static test used in the current study actually determines the apparent modulus of elasticity, which may be up to 16% less than the true modulus of elasticity because of the inclusion of deflection due to shear (Mack 1979). This would partly explain why the static value is around 11% lower than the dynamic modulus of elasticity.

The current study found that both microfibril angle and density were significantly correlated with all measures of modulus of elasticity and with modulus of rupture. Wood density alone explained only 48% of the variation in static modulus of elasticity; this agrees with the results of Larsson *et al*. (1998) who found that density explained 50% of the variation in modulus of elasticity in Norway spruce. This is in conflict with the results of Lindstrom *et al.* (2002, 2004) who found strong significant relationships between microfibril angle and both static and dynamic modulus of elasticity but only a weak relationship between modulus of elasticity and density for very young (3- or 4-year-old) *P. radiata* in New Zealand. These results may indicate age effects or differences between species.

Our results indicated that machine stress-grade of *P. radiata* is related to modulus of elasticity, but that the range of modulus of elasticity values within each grade is broad enough to overlap adjacent grades. When collecting the samples used in this study, great care was taken to ensure that all samples came from boards with low variability in grade, and that the clearwood samples were taken from sections of board that did not include knots or grain deviation. Given these precautions, the degree of overlap of the modulus of elasticity distributions was surprising, and appears to indicate considerable imprecision in the machine grading.

How these results relate to routine sawmill output and machine stress-grading raises important issues. The results presented here are all for clearwood; the impact of knots and associated grain deviation has not been considered. The size and location of defects generally determine the grade limiting point (lowest modulus of elasticity point) for a board. One obvious consideration is that localised measurements (such as those from SilviScan) cannot directly predict a minimum somewhere else in a board. One way to alleviate this problem may be to take into account the expected probability distribution of stiffness within boards of various sizes. In addition, the precision and accuracy of machine grading need to be considered. The prediction of machine stress-grade from clearwood properties by SilviScan provides a best case scenario on grade recovery. The use of samples taken from short clears allowed the evaluation of the accuracy and precision of SilviScan as a tool for predicting dynamic modulus of elasticity. In practice, SilviScan assessment of forest resources is done on increment cores taken from standing trees at breast height. In that situation the prediction of board machine stress-grade recovery can take into account the radial (pith-to-bark) variation in modulus of elasticity.

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