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Radial modulus of rupture in radiata pine measured by individual rings

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Abstract New equipment was developed to measure the strength of individual annual rings in green wood under predominantly tensile stress. This equipment was then used to assess the variation of the radial modulus of rupture (rMOR) in thirty-six 25-year-old radiata pine trees taken from three sites in New Zealand. The rMOR for individual rings ranged from 4.2 to 12.7 MPa and was calculated on the assumption that during bending of the specimens fracture was caused by the tensile force in the radial direction (i.e., perpendicular to the tangential-longitudinal plane). No consistent trends were observed in rMOR from pith to bark; nor was there any evidence of differences between the three sites. However, there was substantial between-tree variability that manifested mainly in different average rMOR values for the trees rather than in variations from pith to bark. These results indicate that there are no concerns with respect to splitting resistance for the juvenile wood of radiata pine. It will be of interest to investigate whether splitting resistance is under genetic control.

Key words Radiata pine · Modulus of rupture · Within-tree and between-tree variation

Introduction

Patterns of within-tree and between-tree variation in wood properties such as density, spiral grain, microfibril angle, and tracheid length are well known for many softwood species.[1] These trends, particularly the pith-to-bark trends, are of key importance for some species, including radiata pine. This is because they lead to variation in performance characteristics such as the modulus of rupture (MOR) and bending elasticity, or modulus of elasticity (MOE), which in turn affect utilization in structural applications.[2–6] The common method of testing MOR and MOE is with the wood grain parallel to the length of the product, as this is the typical way for wood to be utilized and the one that best exploits the natural anisotropy.

A lesser known characteristic of wood is the MOR measured in the radial orientation (rMOR).[7–9] Our purpose for studying this characteristic is that low rMOR might increase the potential for within-ring internal checking. These checks form occasionally in radiata pine sapwood during kiln drying,[10] as they do in various hardwood and softwood species.[11]

We report here the development of an instrument for quickly measuring rMOR on an individual ring basis using wood samples sawn from large increment cores. Our approach to measuring rMOR was one where the breaking force is predominantly tensile in nature rather than shear, such as the force (albeit tangential) that causes internal checking. We also describe variation in rMOR in plantation-grown radiata pine: (1) from pith to bark; (2) between trees (genotypes); and (3) among three sites.

Materials and methods

Wood materials

Twelve trees were selected in each of three 25-year-old forests of radiata pine (*Pinus radiata* D. Don). These forests were all located in the central north island of New Zealand at Kaingaroa, Broadlands, and Omanawa. From each of the 36 trees, a 10 cm long disk was obtained, at 5 m height, from the small end of the pruned butt log. Three pith-to-bark strips were then sawn from each disk (10 × 10 mm × stem radius) which were longitudinally end-matched. All these wood materials were wrapped in plastic and stored at 4°C throughout the experiment to prevent desiccation.

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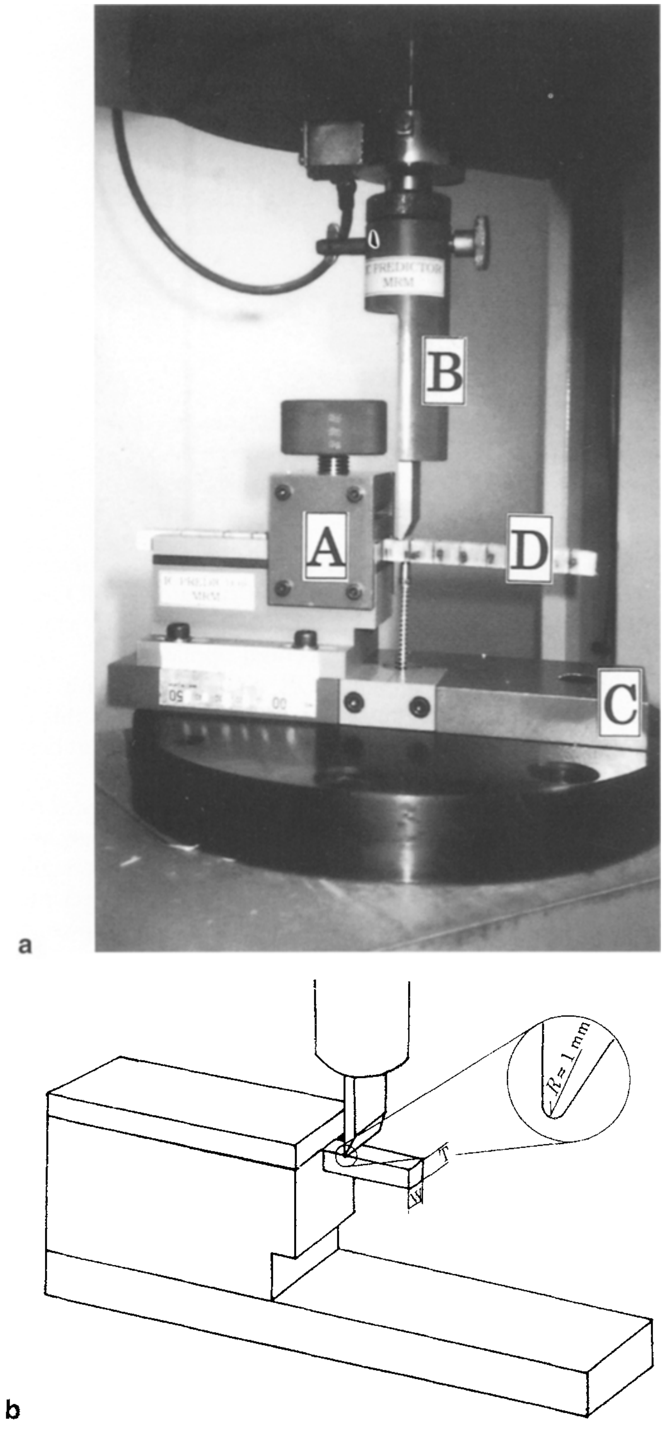

Fig. 1. **a** New equipment used for radial modulus of rupture (MOR) testing. *A*, Strip holder; *B*, wedge to apply the force; *C*, base plate; *D*, specimen. **b** New equipment

Measurement of radial MOR of individual rings

New equipment was developed to measure the MOR in the tangential-longitudinal plane on an individual ring basis. For convenience this is called the rMOR, as the wood specimen extends in the radial direction and is perpendicular to the direction of the applied force. The equipment (Fig. 1) consisted of three parts: a specimen holder with movable clamp, and base plate, and a wedge to apply force, all of which were installed in a Zwick 1445 universal testing machine. The specimen was inserted into the holder with the grain direction vertical and was firmly held by a small steel plate that was pressed down by means of a knurled knob. The distance between the wedge and the specimen holder was 10 mm.

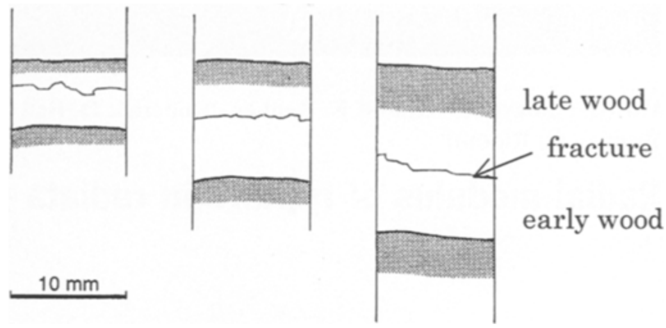

Fig. 2. Typical tangential longitudinal fracturing at the transverse surface

Each specimen was placed in the holder so that the middle of the earlywood of an annual ring was between the specimen holder and the wedge. Therefore, the break would occur in the middle of the earlywood of the annual ring being tested. In radiata pine the distinction between earlywood and latewood is usually clear (Fig. 2). To achieve good contact between the wedge and the specimen, a preload of 5 N was applied, which was less than 5% of the mean maximum load. The speed of the wedge was 25 mm/min. The rMOR (MPa) was calculated as:

$$\mathrm{rMOR} = \frac{6 \times L \times F_{\max}}{W \times T^2} \tag{1}$$

where $F_{\max}$ is the maximum force of rupture (N); L is the distance between the wedge and the specimen holder (i.e., 10 mm); and W and T are the width and thickness of the specimen, respectively, in millimeters. W and T were measured on an individual ring basis using sliding calipers.

The rMOR was measured in 16 annual rings from the bark side toward the pith. The outer ring was not tested. When successive annual rings were narrower than 10 mm, measurements were made on alternate rings using more than one of the longitudinally matched specimens. Therefore, it was possible to obtain a continuous record of the rMOR versus the ring number for each tree.

Statistical analyses were then used to study within-tree and between-tree patterns of variation. A linear mixed effects model was fitted:

$$\mathrm{rMOR} = a + b \times \text{ring number} \tag{2}$$

The coefficients a and b were modeled as an overall effect plus a site effect plus random tree effects. The ring number ranged from 1 at the bark to 16 adjacent to the pith.

Design aspects of the technique

The equipment was developed to measure rapidly the radial variation in rMOR of standing trees. A standard three-point bending test requires a single specimen for each measurement, so to measure the rMOR of 16 annual rings 16 individual specimens must be sawn and broken. In contrast, the technique described here requires, at most, two radial specimens to measure the rMOR for all annual rings. The disadvantage is that the distance between the wedge and the support is only 10 mm, so that there is a shear component present as well. As already discussed, the aim was to cause each annual ring to break by bending rather than shearing. The shear component has been omitted in the derivation of Eq. (1). However, because the conditions are the same for all specimens, the values obtained for the various annual rings and trees are directly comparable. It was observed that splitting of the wood started from the upper surface of the specimens, and rupture by shearing was not observed.

A faster than usual wedge speed was used for mechanical testing. The main reason for this was to prevent drying of the green specimens during the test. It also enabled the large number of annual rings to be tested within the time constraints of the project.

Results and discussion

In contrast to the strong pith-to-bark patterns of variation found in radiata pine for some basic wood properties, we found no such trend between the pith and the bark for rMOR (Fig. 3). There was, however, a considerable degree of scatter, with individual rings having values of 4.2 to 12.7 MPa. The overall fitted population equation, which would be used to predict the relation for an unknown new tree was:

$$\text{rMOR} = 7.66(\text{standard error(SE)} = 0.19) - 0.027(\text{SE} = 0.015) \times \text{ring number} \quad (3)$$

There was no evidence of a trend of rMOR with ring number ($P < 0.05$) and any effect is likely to be small (95% confidence interval, -0.027 ± 0.030 MPa per ring).

Although the above relation holds in general, for some trees the rMOR increased with distance from the pith, whereas for others it decreased. The estimated variance components are given in Table 1, which shows that slightly more than half of the variability in rMOR occurs between trees (standard deviation for coefficient a is 0.83). The between-tree variation in ring effect (coefficient b) had a standard deviation of 0.09, which is greater than the estimated overall population effect of b. This is consistent with the fact that there was no consistent pattern or trend observed in the pith-to-bark measurements of rMOR. For the three forest stands sampled there was no evidence of a difference in rMOR for $P < 0.05$ (Table 2).

In summary, we found that for 25-year-old radiata pine the greatest variation in rMOR was between individual trees. Significant systematic pith-to-bark variation was absent, and there were no differences across the three sample sites. The trees used in this study came from production forests that originated from seedlings. As such, each tree studied was a distinctly different genotype. Donaldson[12,13] studied tangential longitudinal fracturing in different genetic materials of radiata pine and reported a variation in fracture properties (i.e., transwall, middle lamellae/S_1, and S_1/S_2). Differences in cell coarseness and the distribution of lignin across the cell wall were shown to explain some of this variation in fracturing between genetic materials and could

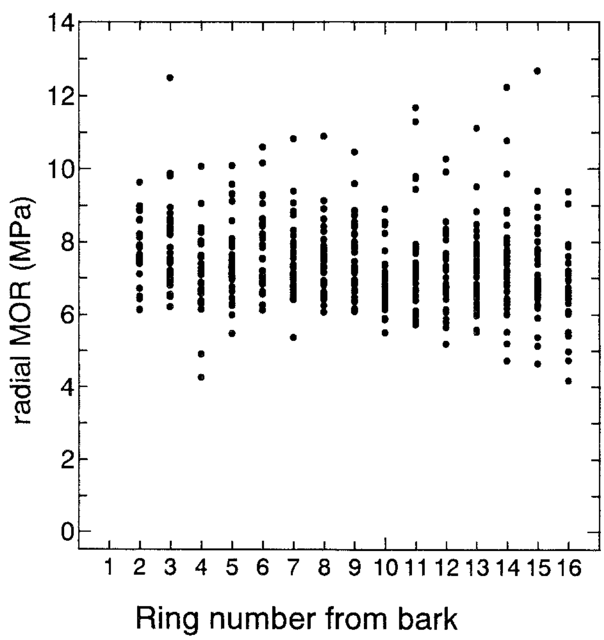

Fig. 3. Pith-to-bark trend in radial MOR for thirty-six 25-year-old radiata pine trees at 5 m height

Table 1. Estimated variance components for radial MOR for radiata pine

Variance component	Estimate
Between-tree (coefficient a)	0.6800
Between-tree (coefficient b)	0.0083
Within-tree	0.5000

A linear mixed effects model was fitted to the form rMOR $= a + b \times$ ring number
rMOR radial modulus of rupture

Table 2. Radial modulus of rupture for 25-year-old radiata pine from three sites

Stand	rMOR (MPa)
Kaingaroa	7.3
Broadlands	7.3
Omanawa	7.8

Standard error of the difference was 0.3

also possibly explain the variation in rMOR between trees identified in this study.

The fact that there was no trend in rMOR with ring number means that on average the wood of young trees is as resistant to breaking along the grain direction as that of older trees. This means that there are no concerns about juvenile wood in radiata pine with respect to this property.

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