Strategic Integrated Research in Timber

Scots Pine Timber Quality in North Scotland.

Report on the Investigation of Mechanical Properties of Structural Timber from Three Stands

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Executive Summary

Selected wood properties were determined for 321 pieces of Scots pine (*Pinus sylvestris*) structural timber cut from three stands located in the north of Scotland that were approximately 80 years old at the time of felling. The dynamic modulus of elasticity (E_d) was determined for each piece of timber from measurements of stress wave velocity, made with a portable acoustic instrument, and bulk density. Four-point bending tests were conducted on the same samples of timber to determine global static modulus of elasticity (MOE_G) and modulus of rupture (MOR). Basic density was determined gravimetrically from smaller samples cut from each piece of timber. Each piece of timber was uniquely coded so that it could be linked back to a specific log, tree and stand.

Values of MOE_G ranged from 3.88 kN/mm^2 up to 16.65 kN/mm^2, with a mean of 9.31 kN/mm^2 and were strongly and positively related to values of E_d (R^2=0.88). Basic density of the wood ranged from 338 kg/m^3 up to 542 kg/m^3, with a mean of 418 kg/m^3, and there was also a relatively strong positive relationship between MOE_G and basic density (R^2=0.64). Modulus of rupture ranged from 12.7 N/mm^2 up to 86.2 N/mm^2, and there was also a strong relationship between MOE_G and MOR (R^2=0.68). The vast majority of the variation in these wood properties intra-tree, with timber cut from the outer part of a log having significantly higher values of MOE_G, MOR and basic density than timber cut from the inner part of a log. Likewise, these wood properties were better in timber cut from the butt log of a tree compared with timber cut from the second log. Almost none of the variation in the wood properties was due to differences between the three sites.

The characteristic values of bending strength and stiffness, and basic density were sufficient for the timber to meet the requirements for the C20 strength class. The strength class that the timber could achieve was limited by its strength and stiffness rather than by wood density. By segregating out those logs which had low stress wave velocities, it was possible to achieve the requirement for the C22 and C24 strength classes. Only a small number of logs (12.5%) were segregated out to meet the requirement for the C22 strength class, but 65% of the population of logs had to be segregated out in order to meet the requirements for the C24 strength class. It was also possible to segregate material based on standing tree velocity measurements, but this was less efficient.

1. Introduction

Scots pine (*Pinus sylvestris*) is a native species to Great Britain, and is the second most abundant conifer species after Sitka spruce. The total area of Scots pine stands in Great Britain is approximately 227,000 ha, of which 140,000 ha are in Scotland (Forestry Commission, 2007). Approximately 80% of the area of Scots pine forest in Scotland is found in the Highland and Grampian conservancies. Much of this was planted in the 1950s and 1960s and a large proportion of the total area is in private ownership. Scots pine is a commercially important species to the timber industry and has wood properties which make it suitable for a number of uses including construction, joinery, fencing, animal bedding, and pulp and paper. However, the quality of the material can vary considerably within a stand. In particular, bark encased (i.e., dead) knots are a problem. In order to address these quality issues, Forest Research have commenced a project to develop and test methods for assessing the quality of Scots pine timber using data collected on standing trees and logs.

As part of this research project, the mechanical properties of Scots pine structural timber will be measured and the results compared with stress wave velocity measurements made on standing trees and freshly-felled logs. The purpose of this project is to understand the extent and sources of variation in the mechanical properties of Scots pine timber and to test the potential of various non-destructive assessment approaches. Napier University’s Centre for Timber Engineering was commissioned to undertake these mechanical tests. In this report, the results from these tests are presented and some preliminary analyses of the data are undertaken.

2. Material and methods

2.1. Stand characteristics

The timber was obtained from three stands that were selected from a broader pool of candidate sites in order to provide contrasting stem form (Table 1). This was based on an informal visual inspection. The stem form at Harriets Plantation in Dornoch Forest District was generally poor with quite heavy branching. The stand at Cawdor Estate was selected as having the highest quality, however it is not known how much better quality this stand is compared to the stand at Munlochy. There is some indication that it is more uniform in quality.

Table 1. Characteristics of the three sampled stands.

Stand	OS Grid	Quality	Age (years)	DBH (cm)	Height (m)
Cawdor	NH 886 489	Good	79	33.6	19.5
Munlochy	NH 624 535	Medium	81	34.7	21.6
Harriets	NH 776 926	Poor	77	32.0	18.9

2.2. Tree selection and processing

At each stand, ten circular 0.05-ha plots were randomly installed by Forest Research with each plot containing between 10 and 20 trees. The diameter at breast height (1.3 m, DBH) and stem straightness score were recorded for each tree. Total height was measured for the five largest trees per plot based on DBH (i.e., the 100 largest trees per hectare). In 2007, three trees were felled from each plot. Prior to felling, the stress wave velocity of the outermost wood was measured on the standing tree using the ST-300 instrument (Fibre-gen, Auckland, New Zealand). After the trees were felled, two 3.7-m logs were cut from each tree with a minimum top diameter requirement of 17 cm over bark. Each log was identified with a unique paint and stamp combination, and stress wave velocity measurements were made using the HM-200 instrument (Fibre-gen, Auckland, New Zealand). The logs were then processed into structural timber at John Gordon and Son's sawmill in Nairn. Two sizes of structural timber were produced: 100 x 47 mm and 200 x 47 mm, along with non-structural sideboard material which had smaller dimensions. Each piece of timber was uniquely coded so that it could be related back to the log, tree and site that it came from. All timber was kiln dried before being transported to Forest Research's Northern Research Station (NRS) for further measurements.

At NRS, a random sample of the structural timber was selected. This random sample contained material from all logs; in general, two pieces of timber were selected from each log. One piece was selected from the inner part of the log (i.e., composed of core wood) and the other was selected from the outer part of the log. Both 47x100 mm and 47 x 200 mm material were selected. The characteristics of the sampled timber are given in Table 2.

Table 2. Characteristics of the sub-sample of structural timber.

Stand	Number of samples		
	100x47 mm	200x47 mm	Total
Cawdor	83	26	109
Munlochy	57	54	111
Harriets	75	26	101
Total	215	106	321

2.3. Measurement of mechanical properties

Each piece of timber was appearance graded to EN 1611-1:2000 and its dynamic modulus of elasticity calculated from measurements of stress wave velocity and density using the following relationship:

$$E_d = \rho V^2 \qquad [1]$$

where: E_d is dynamic modulus of elasticity (kN/mm^2), ρ is the bulk density of the timber (kg/m^3) and V is the stress wave velocity (m/s). During this process, the moisture content of the pieces was measured using a capacitance moisture meter which revealed a large variation in moisture content between individual pieces and also between sites. While capacitance moisture meters are not accurate above the fibre saturation point, the large range of moisture content values suggested that there may have been problems with the kiln drying process. Therefore, the timber was moved to Napier University and placed in a controlled-environment laboratory at 21ºC and 65% relative humidity so that it would reach an equilibrium moisture content of approximately 12 per cent. Prior to this occurring, the 200x47 mm timber was cut in half using a WoodMizer portable sawmill to yield two pieces with dimensions of approximately 100x47 mm. Only one of these pieces was selected for further testing. The timber was stored in the laboratory at Napier University for approximately six months before being tested. During this time, the stack of timber was re-positioned several times to aid the drying process.

After six months, each piece of timber was re-weighed and had its dimensions re-measured. The dynamic modulus of elasticity of each piece of timber was predicted using Equation [1]. The stress wave velocity was measured using the HM-200 instrument, while the density was calculated from measurements of the batten dimensions and mass. Battens were then destructively tested in four-point bending using a universal testing machine (Zwick Z050, Zwick-Roell, Germany) to determine their modulus of elasticity (MOE_G) and modulus of rupture (MOR) in bending (Figure 1).

Figure 1. Four-point bending test conducted using the Zwick Z050 universal testing machine.

Tests were conducted in accordance with EN408 (CEN, 2003a), except that no attempt was made to estimate the location of the maximum strength reducing defect and to place this in the centre of the test span. Following testing, a 40-mm-long sub-sample spanning the full cross-section of the batten was cut and its density and moisture content were determined in accordance with EN 13183-1 (CEN, 2002) and EN408 (CEN, 2003a). The mass and the dimensions of the sub-sample were recorded straight away, and the sub-sample was then dried in an oven at 103ºC until it reached constant mass (approximately 48 hours). It was then reweighed and the specific gravity (G_M) at the equilibrium moisture content (MC) calculated using the following equations:

$$MC = \frac{M_M - M_d}{M_d} \qquad [2]$$

$$G_M = \frac{M_d}{V_M \rho_w} \qquad [3]$$

where M_M [g] and V_M [cm^3] are the mass and volume, respectively, at moisture content M, M_d is the oven-dry mass [g], and ρ_w is the density of water (1.0 g/cm^3). The basic specific gravity (G_b) was calculated from G_M by adjusting the volume of the sample for the shrinkage which occurred between 30% moisture content (fibre saturation point) and equilibrium moisture content (Simpson, 1993).

$$G_b = \frac{G_M}{1 + 0.265\alpha G_M} \qquad [4]$$

where α =(30–MC)/30. Basic density [ρ_b; kg/cm^3] was calculated from basic specific gravity by multiplying by the density of water.

The values of static global modulus of elasticity obtained from the four-point bending tests were adjusted to a 12 per cent moisture content basis in accordance with EN384 (CEN, 1995). Similarly, values of bending strength were adjusted to a 150 mm sample depth using the method described in EN384.

2.4. Data analysis

Data were analysed using the open source statistical package R (www.r-project.org). Values of dynamic modulus of elasticity were compared to those obtained from static bending tests. Linear regression was used to investigate the relationships between modulus of rupture, modulus of elasticity and density. The average modulus of elasticity of the battens tested from each log was calculated and linear regression analysis used to compare these average values with the dynamic modulus of elasticity predicted from stress wave velocity measurements made on logs. A linear random-effects model (Pinhero and Bates, 2000) was used to examine the sources of variation in specific gravity, MOE_G and MOR. A nested structure was assumed for the random effects of log, tree, plot and site in accordance with the experimental design. The following model was fitted to data from the measurements on the structural timber:

$$y_{ijklm} = \mu + S_i + P_{j(i)} + T_{k(ij)} + L_{l(ijk)} + e_{m(ijkl)} \qquad [5]$$

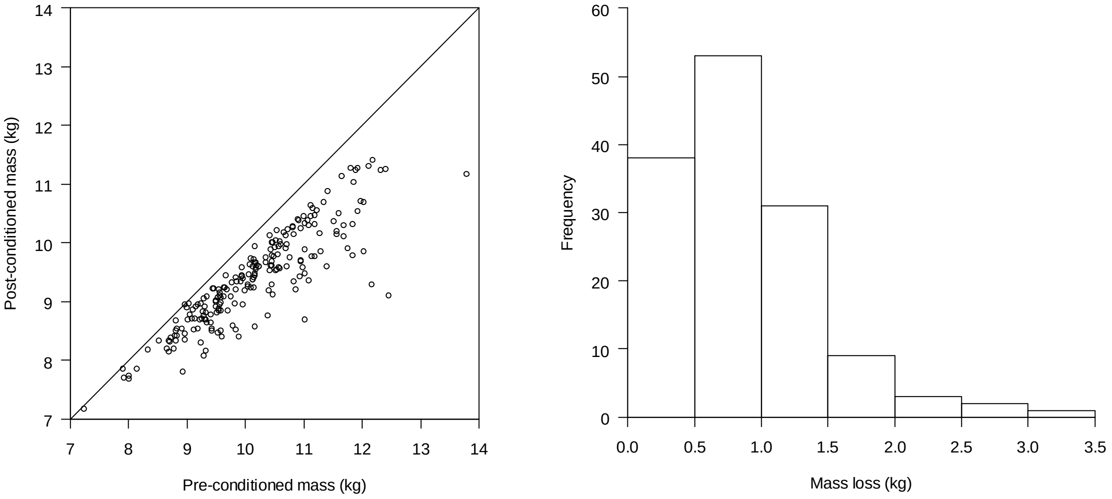
where y_{ijklm} is the measurement of specific gravity, MOE_G or MOR on an individual specimen, μ is the overall mean, S_i is the random effect of block i (~N(0, σ_S^2)), $P_{j(i)}$ is the random effect of the j^{th} plot within the ith site (~N(0, σ_P^2)), $T_{k(ij)}$ is the random effect of the

k^{th} tree within the j^{th} plot (~N$(0, \sigma_T^2)$), $L_{l(ijk)}$ is the random effect of the l^{th} log within the k^{th} tree(~N$(0, \sigma_L^2)$, and $e_{m(ijkl)}$ is the random effect of the m^{th} piece of timber from the l^{th} log (~N$(0, \sigma_e^2)$. Because only one site of each type was sampled, it was not possible to investigate the impact of site type on timber mechanical properties. However, by comparing the relative magnitudes of between site and within-site variation, it was possible to gain some insight into whether differences between sites were likely to exist or whether these will be small relative to the differences that exist within a site.

The characteristic values of modulus of elasticity, modulus of rupture and density were calculated using the procedures described in EN384 and the timber assigned to appropriate strength class based on the requirements given in EN338 (CEN, 2003b). For timber to be assigned to a particular strength class, the characteristic values for its bending strength (5th percentile value) and density (12 percent moisture content basis) must equal or exceed the values required for that class, while the characteristic modulus of elasticity (mean value) must be at least 95 percent of the required value for that class.

3. Results and Discussion

On average, the mass of each piece of timber decreased by 0.85 kg as a result of the conditioning process, however in some cases the loss in mass exceeded 2.0 kg (Figure 2). As a percentage of the non-conditioned mass, the decrease in mass ranged from 0.7% up to 27.0%, with a mean of 8.4%. The stress wave velocity measured with the HM-200 instrument increased following conditioning by an average of 0.27 km/s. In the most extreme case, the stress wave velocity increased by 0.83 km/s. The increase in stress wave velocity following conditioning was strongly and positively related to the moisture content of the timber prior to conditioning (R^2=0.60; Figure 3). As the moisture content following conditioning was relatively constant (mean of 13.0%, range 12.0-14.5%), the pre-conditioning moisture content was effectively a surrogate for the change in moisture content that occurred during the conditioning process.



(a) (b)

Figure 2. (a) Comparison of the pre- and post-conditioned mass of the timber, and (b) a histogram showing the distribution of the loss in mass between the pre- and post-conditioned states.

Values for dynamic modulus of elasticity of the conditioned timber ranged from 4.82 kN/mm^2 up to 18.42 kN/mm^2, with a mean of 10.72 kN/mm^2. On average, values of E_d determined after the timber had been conditioned were approximately 9 per cent higher than those measured prior to the conditioning process. In some cases this difference was as great as 25 per cent and one extreme case it was 55 per cent (Figure 4), but overall there was a strong relationship between the pre- and post-conditioning estimates of E_d (R^2=0.69). In the analyses that follow, the values of dynamic modulus of elasticity that are used are those from the post-conditioned samples.

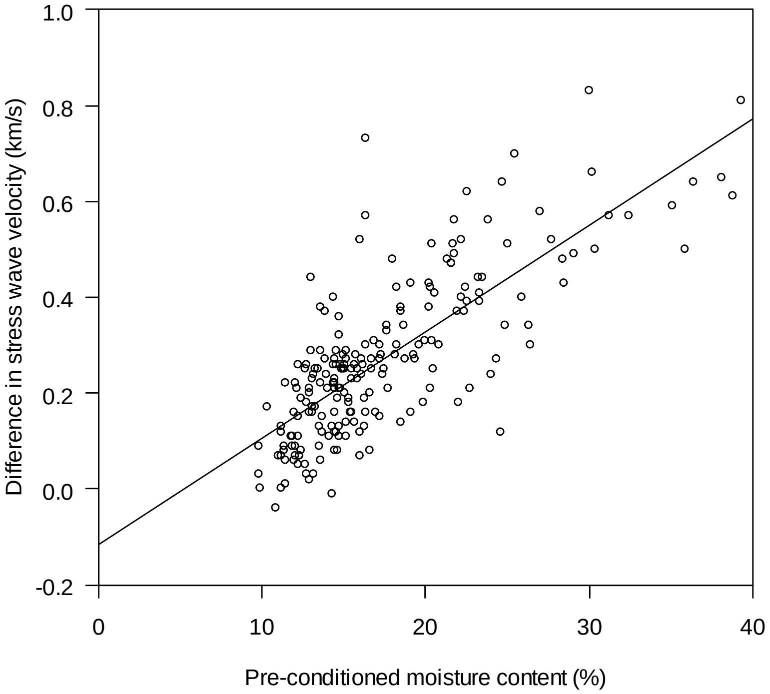
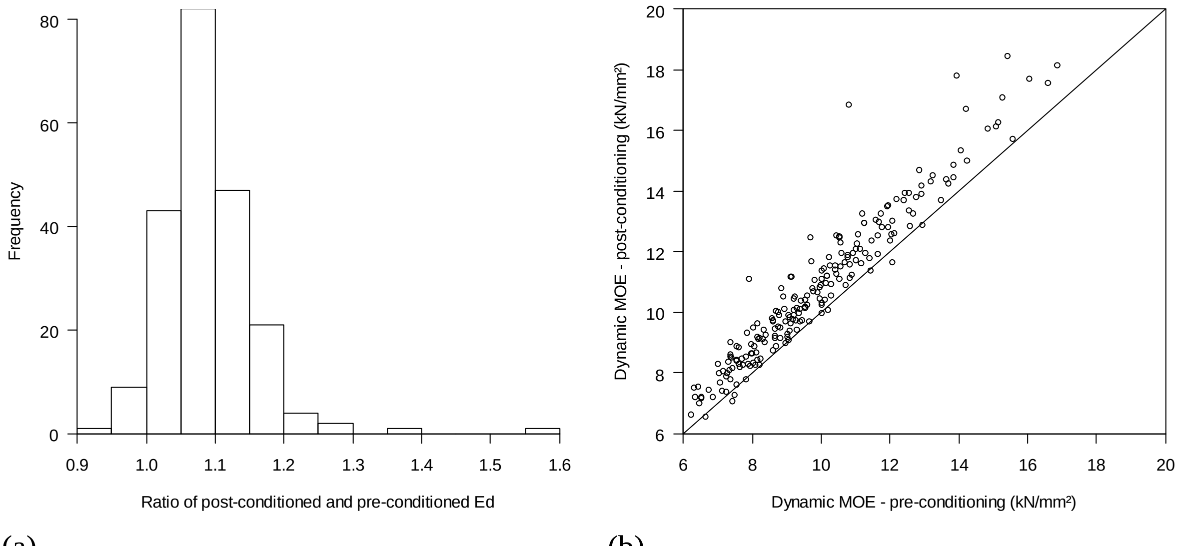


Figure 3. Relationship between the change in stress wave velocity of timber between the pre- and post-conditioned states and the initial moisture content of the timber in the pre-conditioned state.



(a) (b)

Figure 4. (a) Histogram showing the distribution of the ratio of post-conditioning and pre-conditioning dynamic MOE, and (b) relationship between pre- and post-conditioning estimates of dynamic MOE.

Modulus of elasticity determined from static bending tests ranged from 3.88 kN/mm^2 up to 16.65 kN/mm^2, with a mean of 9.31 kN/mm^2. Batten 582 had a cluster of knots which opened up with the application of very little external force. This resulted in large deflections under very little applied load (maximum force applied before test was stopped was 0.75 kN) and as a result it was not possible to calculate modulus of elasticity. This sample was not included in any of the analyses. In addition, a number of pieces of timber were under-dimensioned as their widths were less than 42 mm (nominal width was 47 mm). Problems were encountered when testing some of these specimens due to the increased flexibility about their minor axis, however this did not appear to affect the results obtained and they were retained in the analyses. Overall, there was a strong relationship between MOE_G and E_d (R^2= 0.88). On average, values of E_d were approximately 15 per cent higher than values of MOE_G. Values of MOR ranged from 12.7 N/mm^2 up to 86.2 N/mm^2, with a mean of 44.5 N/mm^2. There was a relatively strong relationship between MOE_G and MOR (R^2=0.68; Figure 5). Basic density of the wood ranged from 338 kg/m^3 up to 542 kg/m^3, with a mean of 418 kg/m^3. There were moderately strong relationships between basic density and both MOE_G and MOR (R^2=0.64 and 0.47, respectively).

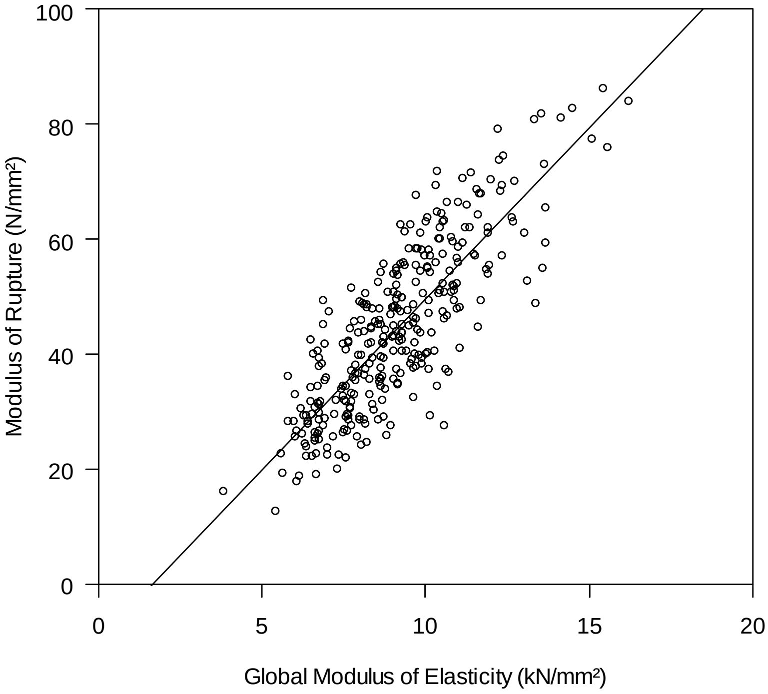


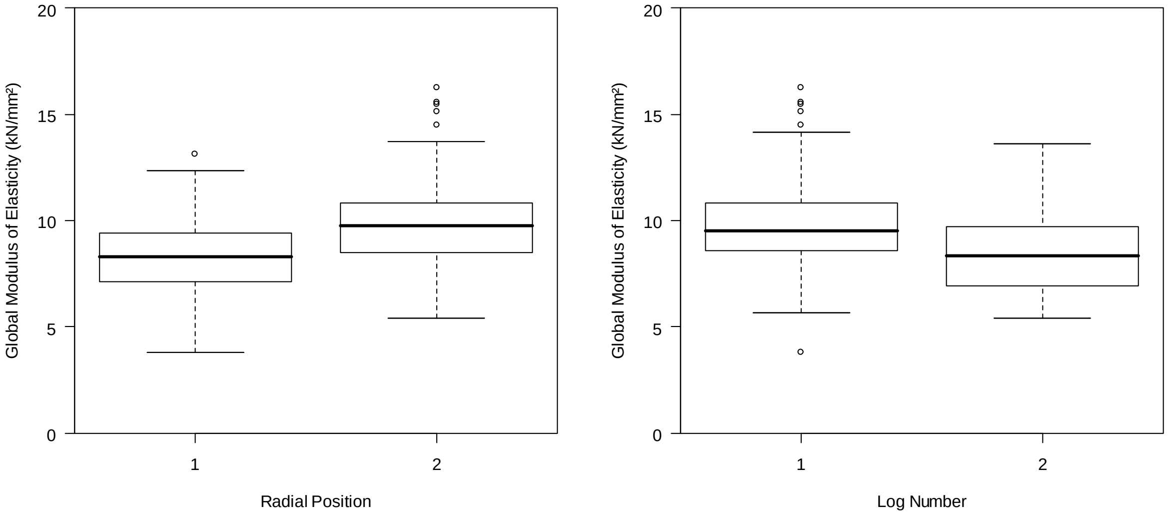
Figure 5. Relationship between global modulus of elasticity and modulus of rupture. The solid line was fitted using ordinary least squares regression.

Over 50 per cent of the variation in MOE_G was due to variation between individual pieces of timber within a log, with a further 25 per cent due to variation between individual trees within a site (Table 3). Less than six per cent of the variation was due to differences between sites. There was a significant difference in MOE_G between timber cut from nearer the pith of the tree (position 1) and that cut from nearer to the bark (position 2) ($F_{1,155}=164$; $p<0.001$). Similarly, there was a significant difference in MOE_G between timber cut from the butt log and timber cut from the second log ($F_{1,70}=66$; $p<0.001$). On average, timber cut from position two had a value of MOE_G that was 1.41 kN/mm^2 greater than that for timber from position one, while timber from the second log had an average value of MOE_G that was 1.24 kN/mm^2 lower than timber from the butt log (Figure 6).

The majority of the variation that was observed in MOR was due to differences between battens from within a log (Table 3). Approximately, 30 per cent of the variation in MOR was due to differences between logs from within the same tree, with less than 10 per cent of the variation due to differences between trees. On average, the MOR of battens from the outer part of the logs was 8.3 N/mm^2 higher than for battens from closer to the pith. There was also an average decrease in MOR of 10.9 N/mm2 between battens from the second log compared with those from the first log. Similarly, nearly 90 per cent of the variation in basic density that was observed was due to differences within a tree. The remaining 10 per cent was due to differences between trees, with almost none of the variation associated with differences between plots or between sites (Table 3). Again, battens from the outer part of a log were 26 kg/m^3 denser than battens from the inner part of the log. Battens from the butt log were also 38 kg/m^3 denser than battens from the second log.

Table 3. Components of variation in MOE_G, MOR and G_b.

Stratum	Percentage of Variation Attributable to a Stratum		
	MOE_G	MOR	G_b
Site	5.59	3.39	<0.01
Plot	0.99	<0.01	0.50
Tree	24.88	7.95	9.75
Log	14.65	30.18	43.24
Batten	53.89	58.48	46.51
Total	100.00	100.00	100.00



(a) (b)

Figure 6. Comparison of global modulus of elasticity between (a) radial positions within a log and (b) between logs within a tree.

The characteristic bending strength of the entire population of timber was calculated using the approach described in EN384 (CEN, 1995). The 5th percentile value of MOR was 24.21 N/mm^2. This was multiplied by factors which accounted for the size of the timber (k_h=1.08), the number of samples (k_s=0.85) and the method of grading (k_v=1.12) to give an overall characteristic bending strength of 21.0 N/mm^2. Combining this value with the mean density at 12 percent moisture content (504 kg/m^3), the timber was assigned to the C20 strength class according to EN 338 (2003). The mean value of MOE$_G$ (9.31 kN/mm^2) exceeded 95% of the mean requirement for the C20 strength class which was 9.5 kN/mm^2. Therefore, the timber satisfied the strength, density and stiffness requirements of the C20 strength class. In order for Scots pine timber to achieve the requirements of higher strength classes, both strength and stiffness need to improve as these are the principal limiting factors. One option is to use acoustic tools to segregate the current population of material. At the log level, there was a significant positive relationship between stress-wave velocity and the average modulus of elasticity of timber cut from the log (R^2=0.43), but this relationship was not quite as strong at the individual board level (R^2=0.32). However, it could still be adequate for identifying those logs which, on average, will yield timber with inferior mechanical properties.

The utility of portable acoustic tools to improve the grade out-turn of sawn timber, was examined by setting various velocity thresholds and calculating the characteristic values for bending strength, stiffness and density of the timber sawn from those logs which had a velocity greater than this threshold value. For example, if those logs which had a stress wave velocity of less than 3.1 m/s were removed from the population, then the characteristic values of strength and stiffness increased to 22.0 N/mm^2 and 9.55 kN/mm^2, respectively. These values were sufficient for the timber to meet the requirements for the C22 strength class. Only 20 logs (12.5% of the population) were removed using this criteria, but this resulted in an improvement of one strength class. In order to achieve the requirements of the C24 strength class, this threshold velocity needed to be set at 3.45 km/s (Figure 7). The resulting characteristic values of strength and stiffness were then 24.4 N/mm^2 and 10.47 kN/mm^2, respectively. However, approximately 65 per cent of the logs were rejected in order for the timber to meet these requirements.

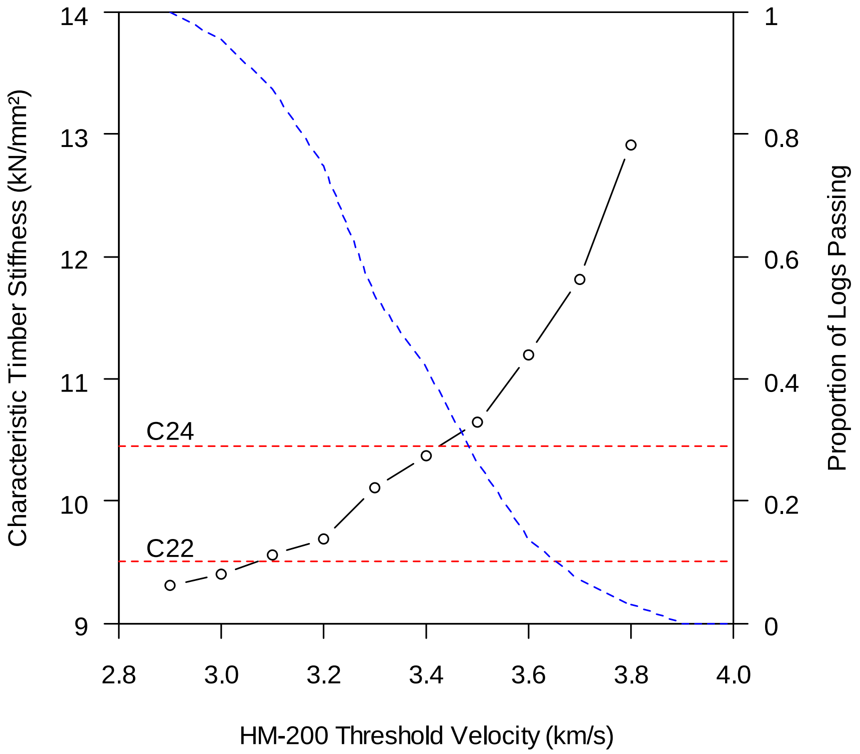


Figure 7. Effect of log segregation using the HM-200 on the characteristic stiffness of sawn timber. The dashed blue line indicates the proportion of logs meeting this threshold.

A similar analysis was undertaken using the ST-300 readings made on the standing trees. However, there was not the same monotonic increase in characteristic timber stiffness within increasing velocity threshold as was observed for the HM-200 (Figure 8). However, it was still possible to meet the requirement for the C22 strength class by removing those trees with an ST-300 velocity less than 4.5 km/s from the population. This resulted in an increase in the characteristic values of strength and stiffness to 22.1 N/mm^2 and 9.71 kN/mm^2, respectively. A total of 30 trees (33% of the population) failed to meet this velocity threshold. Segregating material using the ST-300 does not appear to be as efficient as using the HM-200. In order to achieve the requirements for the C22 strength class, 30 per cent of the population was segregated out using the ST-300, but this figure was only 20 per cent when using the HM-200. This is presumably due to the stronger relationship between log-level measurements and timber properties.

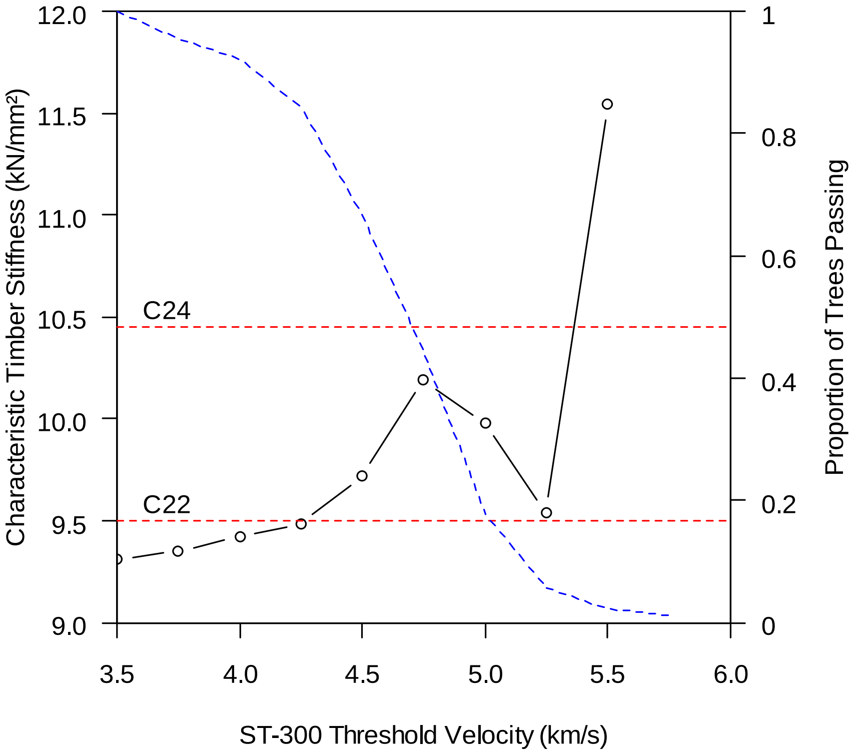


Figure 8. Effect of tree segregation using the ST-300 on the characteristic stiffness of sawn timber. The dashed blue line indicates the proportion of tree meeting this threshold.

4. Conclusions

Data obtained from the mechanical tests undertaken indicate that Scots pine timber from the three sites in this study had physical and mechanical properties that result in it achieving the requirements for the C20 strength class. Bending strength and stiffness, rather than wood density were the key factors which prevented the timber from achieving the requirements of higher strength classes. Most of the variation in density, bending strength and bending stiffness was due to differences within a tree, with significant differences in these properties found in the radial and longitudinal directions. Almost none of the variation in these properties was associated with differences between the three sites investigated in this study. If sites were chosen from a broader spread of geographic locations and/or stand structures, then it could be expected that more of the variation in wood properties would be due to differences between sites. The differences in wood properties between timber cut from different logs means that portable acoustic tools can be used to segregate out those logs which are likely to produce timber with inferior properties.

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