The Use of Acoustic-Based NDT to Predict the Wood Properties of UK-Grown Sitka Spruce at Different Stages in the Wood Supply Chain

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Abstract

This paper is concerned with the extent to which portable stress-wave-based instruments can be used to segregate Sitka spruce trees and logs; in particular the relationship between acoustic velocity and the properties of sawn timber. Measurements were made at 64 sites which were selected to span a range of conditions. At each site a portable stress wave timer (IML Hammer) was used to estimate the dynamic modulus of elasticity (E_d) on a sample of ten standing trees. Differences between sites accounted for 36 percent of the total variation in E_d, while differences between trees within a site and sides of the tree account for 55 and 9 percent of the variation respectively. Trees were felled from a representative sub-sample of 12 sites and the E_d of logs estimated using the HM-200 resonance instrument. At an individual tree level, a strong relationship was observed between measurements made on standing trees and those made on the butt log. The mean bending stiffness (E_s) of timber cut from an individual site was strongly related to the mean stress wave velocity of both trees and logs from that site showing that it is possible to directly manipulate the characteristic stiffness of a population of sawn timber by segregating logs based on stress-wave velocity values. Taken together, these results demonstrate how non-destructive measurements made on standing trees and logs can assist the forest products industry to improve timber properties and that such approaches work for Sitka spruce grown under UK conditions. The average E_d of logs at a site was also found to be negatively associated with the average live crown ratio of trees at the site offering the possibility of partial sorting, even without acoustic tools.

Introduction

Sitka spruce (*Picea sitchensis*) is the most widely planted coniferous tree species in the United Kingdom. Historically, the wood has been used for utility purposes such as fencing, pallets and packaging, but is increasingly being processed into structural timber. For this relatively large and high value market bending stiffness is a key property of interest. Aside from being the fundamental property for serviceability in design, it is often as the indicating parameter for strength prediction in timber grading. Both strength and stiffness directly affect the strength class that timber can attain.

To date the segregation of trees and logs prior to processing has been on the basis of external characteristics such as diameter, straightness and branch size. While these characteristics are important determinants of sawn timber quality, the advent of portable stress-wave-based instruments has afforded a new way to predict wood stiffness from measurements made on standing trees and logs (e.g., Wang et al., 2007). These measurements not only offer the potential to

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segregate material prior to processing, but also to map the variation in wood stiffness of the standing forest resource and investigate the site and stand factors that affect this.

While the use of stress-wave-based non-destructive testing is relatively common in the forest-to-mill wood supply chain in Australasia (e.g., Tseheye et al 2000) and North America (e.g., Wang et al., 2000; 2004), up until very recently it has been much less common in Europe. In the UK, this was partly due to concerns, by some in the forest industry, about the uncertain effectiveness of these stress-wave tools in Sitka spruce, with its high frequency of knots and compression wood. A comprehensive study has been carried out in order to evaluate the potential of these tools as a means of segregating Sitka spruce trees and logs, and to determine the relationship between stress wave velocity and the properties of sawn timber. An overview of the study is given in this paper and the key results obtained to date are presented.

Materials and Methods

The study was undertaken in three stages. In the first stage, 64 stands were selected on the basis of the following attributes: (1) site productivity (as quantified by yield class), (2) elevation, (3) latitude, (4) longitude, (5) initial planting spacing, and (6) thinning history. This was to enable the likely range of variation in wood properties to be captured, and the influence of silvicultural and site factors to be examined. In order to reduce any confounding influences of tree age on wood properties, stands were selected in the 35 to 45 year age range. A full description of the study design, along with the criteria for each of these factors, is given in Moore et al. (2009). All measurements in this first phase were made on standing trees. In the second phase of the study, 12 sites were selected that spanned the full range of variation encountered in the initial 64 sites, and a sample of trees from these sites were felled. Measurements were made on the felled trees which were then processed into logs. In the third phase, these logs were processed into sawn timber which was then mechanically tested for the determination of bending strength and stiffness.

Standing tree measurements

For each of the 64 selected sites, a fixed area plot was installed and within each plot the stress wave velocity was measured on ten randomly selected trees from the population of live trees with DBH greater than 17 cm. The measurement was made using a modified version of the IML Hammer (Instrumenta Mechanic Labor GmbH, Germany). The two probes from this time-of-flight instrument were inserted into the tree with one metre separation in the vertical direction centred about breast height. Two sets of measurements were made on each tree: one on the north side and one on the south. The longitudinal dynamic modulus of elasticity (E_d) of the outermost wood of each standing tree was calculated from the mean of the stress wave velocity measurements made on the two sides of the tree (V) using the following equation:

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

The density of green sapwood (ρ) was assumed to be 1000 kg/m^3 for all trees. All measurements were made over a two-month time window to reduce the impacts of any seasonal variation in sapwood moisture content and hence bulk density. This assumption about the density of green sapwood is currently being investigated.

Felled log measurements

Twelve sites were selected based on the standing tree measurements so that four sites had a mean value of E_d from standing tree measurements greater than 9 kN/mm^2, four had a value less than 7 kN/mm^2 and the remaining four values between 7 and 9 kN/mm^2. These values corresponded to the upper and lower quartiles of the distribution of E_d obtained from standing tree measurements made on the wider population of 64 sites. At each of these 12 sites, the ten trees that had been assessed for stress-wave velocity were felled and their total height, height to lowest live branch and height to lowest live whorl was measured. Up to three 3-m-long sawlogs were cut from each tree starting at breast height. The dimensions of these logs were recorded and a longitudinal stress-wave velocity measurement was made on each of them using the HM-200 tool (Fibre-gen, Auckland, New Zealand). The value of E_d for these logs was calculated using Eq. [1]. Logs were then processed into structural timber (100 mm by 47 mm cross section). Each piece of timber was uniquely identified so that it could be attributed to a specific log, tree and site.

Sawn timber measurements

Sawn timber was stored in a conditioned room until it attained constant mass.. After conditioning, the dimensions and mass of each piece of timber were measured and the stress-wave velocity measured using the HM-200 tool. E_d was calculated from these measurements using Equation [1]. The timber was then destructively tested in four-point bending using a universal testing machine (Z050, Zwick Roell, Ulm, Germany) in accordance with EN408 (CEN, 2003a) to obtain global modulus of elasticity (E_s) and bending strength (modulus of rupture, MOR).

Linear mixed-effects models were used to quantify the extent of variation in wood properties due to the different strata in the experiment, i.e., site, tree and log. Regression analysis was used to investigate the relationships between sawn timber properties and stress-wave velocity measurements made on standing trees and logs.

Results and Discussion

A total of 640 stress wave velocity measurements were made on standing trees using the IML Hammer. Values of E_d for individual trees ranged from 3.81 kN/mm^2 up to 12.29 kN/mm^2, with a mean of 7.71 kN/mm^2. Approximately 55 percent of the variation in E_d (Figure 1) was due to differences between individual trees within a site, while 35 percent was due to differences between sites. The remaining 10 percent was due to differences between the measurements made on opposite sides of each tree. The DBH and heights of felled trees ranged from 193 mm up to 453 mm and from 16.7 up to 31.6 m respectively. A total of 301 logs were cut from the across the 12 sites, with most sites yielding at least 25 logs. The breast height age of each tree was determined from ring counts made at breast height. In almost all cases, stands were in the target age range of 35-45 years. However, site 449 only had a breast height age of 26 years. Values of E_d for individual logs ranged from 7.1 kN/mm^2 up to 15.9 kN/mm^2.

There was a strong relationship between E_d calculated from measurements made on individual standing trees using the IML hammer and E_d calculated from measurements made on the butt log from those same trees using the HM-200 (R^2=0.600). The average E_d of logs from each site ranged from 9.36 kN/mm^2 up to 13.69 kN/mm^2 and this was strongly associated with the average E_d determined from measurements made on standing trees (R^2=0.713). At the site level there was also a moderate negative relationship between live crown ratio (ratio of crown length to tree height) and E_d of both standing trees and freshly-felled logs (R^2=0.402 and 0.603, respectively; Figure 2). This indicates that stands containing trees with deep crowns will have, on average, a lower value of E_d than those stands with shorter crowns. Therefore, live crown ratio could be a useful visual assessment criteria for helping to determine the likely wood quality of a stand. There was no apparent relationship between E_d and either DBH (p=0.854) or total height (p=0.229).

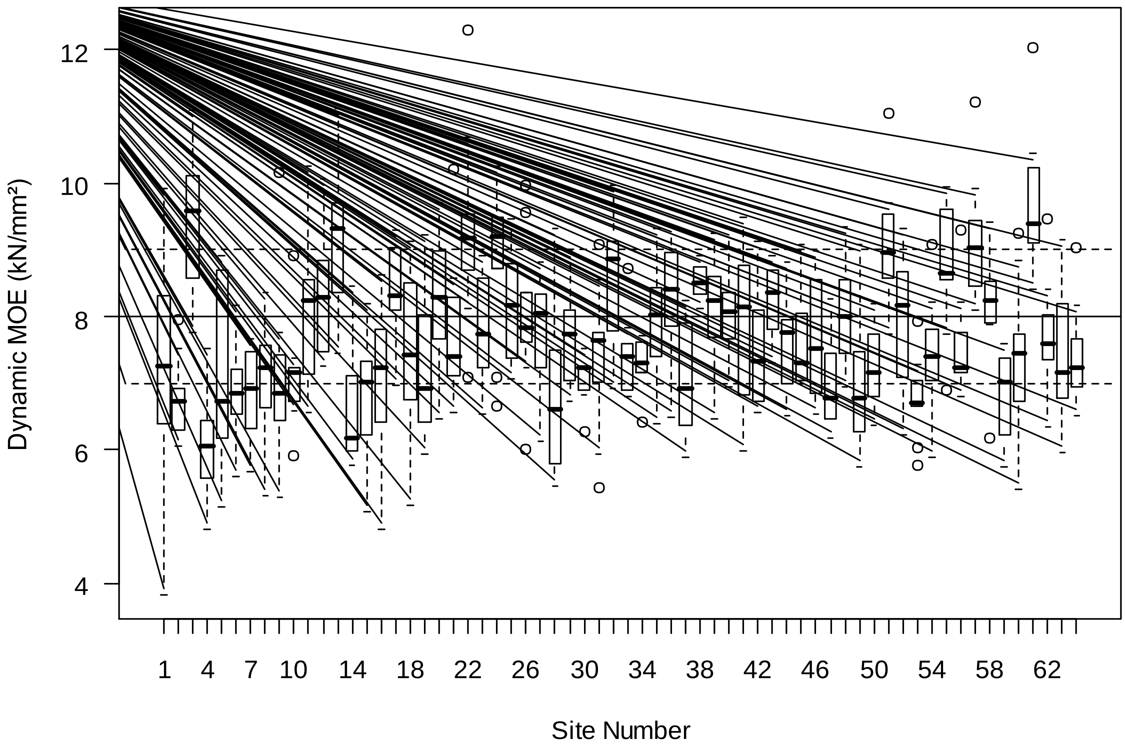

Figure 1. *Intra and inter-site variability in dynamic modulus of elasticity determined from measurements made on standing trees at 64 sites using the IML Hammer.*

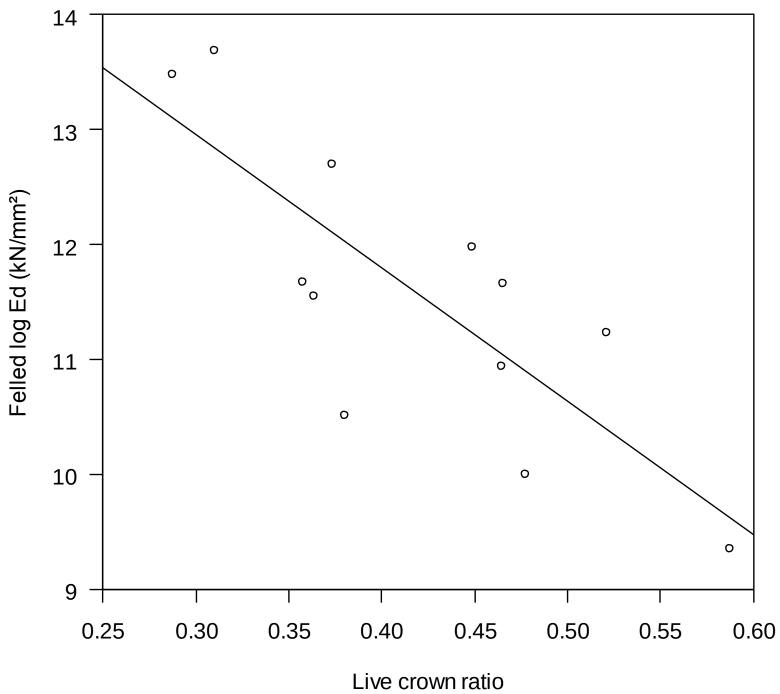

Figure 2. *Relationship between mean stress wave velocity measured on logs from an individual site and the mean bending stiffness of timber cut from a site.*

At the time of writing logs from nine of the 12 sites have been extracted, processed into structural timber and mechanically tested. For the 633 pieces of timber that have been tested there was a very strong relationship between E_s and E_d (R^2=0.88). The mean value of E_s was 8.1 kN/mm^2 and the characteristic value of bending strength (based on the 5th percentile value) was 21.4 N/mm^2. Based on these values, the timber met the requirements for the C16 strength class as presented in EN338 (CEN 2003b) although the timber was not tested with the anticipated strength governing defect deliberately placed centrally in the test span.

The mean value of E_s for timber cut from an individual site ranged from 6.8 kN/mm^2 up to 9.3 kN/mm^2 and was strongly related to the mean value of E_d calculated from measurements made on both standing trees

(R^2=0.76; RMSE=0.46 kN/mm^2) and felled logs (R^2=0.82; RMSE=0.40 kN/mm^2; Figure 3).

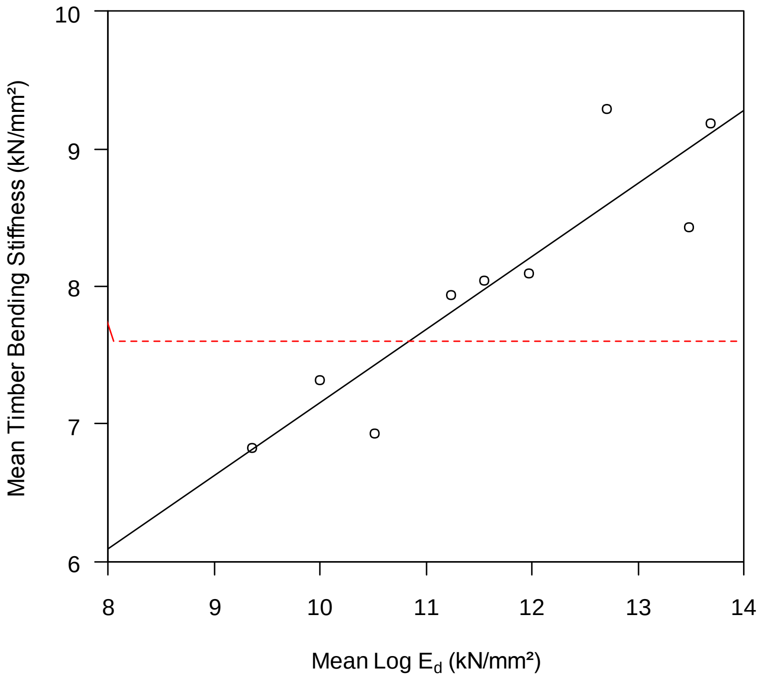

Figure 3. *Relationship between mean E_d measured on logs from an individual site and the mean bending stiffness of timber cut from a site.*

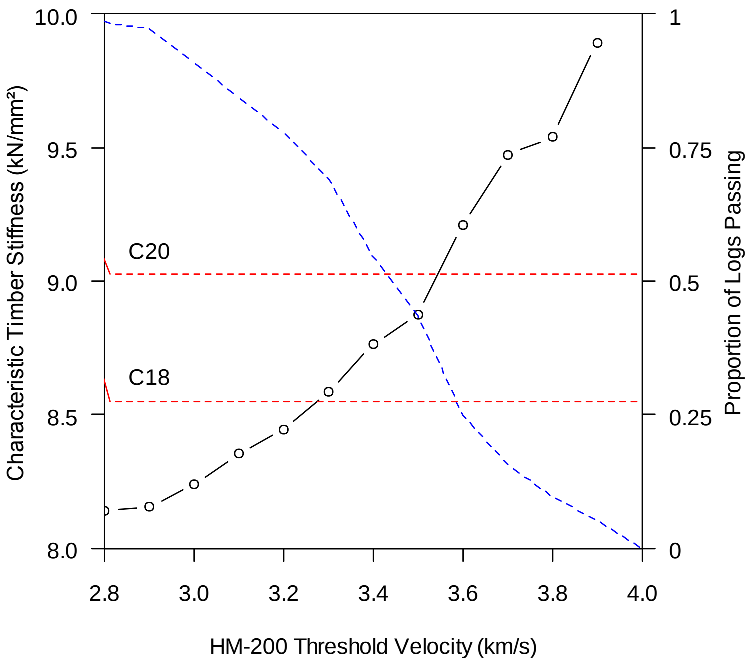

Figure 4. *Effect of log segregation using the HM-200 on the characteristic stiffness of sawn timber. The dashed line indicates the proportion of logs meeting this threshold.*

At the individual log level, there was a moderate relationship between the stress-wave velocity measurement made on the log and the mean bending stiffness of timber cut from the log (R^2=0.47). This relationship was used as the basis for investigating the effect that setting different thresholds for stress wave velocity on the population of logs being processed has on the mechanical properties of the timber that are cut from these logs. As the threshold stress-wave velocity increased from 2.8 km/s there was a monotonic increase the mean value of E_s of the timber sawn from those logs which had a velocity greater than the threshold value (Figure 4). As expected, there was a corresponding decrease in the proportion of the population of logs which had a stress-wave velocity greater than this threshold.

If no segregation was applied, then the timber cut from this population of logs would have had a value of E_s that was sufficient for it to achieve the requirements of the C16 strength class. If a sawmill wishes to produce timber which has a mean value of E_s sufficient to meet the requirements for the C18 strength class (assuming that the strength and wood density requirements have been met), they would need to set a threshold stress-wave velocity for logs of approximately 3.3 km/s. At this threshold approximately 30% of logs from the current population would be rejected. This type of segregation approach could be applied by a sawmill in their log sorting line.

While stress wave measurements made on standing tree provide a good means for differentiating between sites, the large amount of within-site variation in wood properties indicates that a segregation strategy based on assessing every tree might be more effective; especially if the technology could be incorporated in to the harvester head. This would ensure that better quality trees and logs from sites which are generally poorer quality are not rejected.

Conclusion

This study has shown that there is a large amount of variation in the mechanical properties of Sitka spruce timber, and that stress-wave based non-destructive tools can be successfully used to evaluate these properties at an early stage in the forest-to-mill supply chain. By following material from standing tree through to sawn timber, it has been possible to develop relationships that can be used to predict the mean bending stiffness of timber from a site based on stress-wave velocity measurements made on either standing trees and logs. Because of the relationship between a log's stress-wave velocity and the stiffness of timber cut from it, it is possible to improve the mechanical properties of sawn timber through log segregation.

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