Assessing modulus of elasticity of *Pinus silvestris* trees

HÅKAN LINDSTRÖM[1], MARCO REALE[2] & MIKA GREKIN[3]

[1]Associate Professor, Dept of Forest Products and Markets, Vallvägen 9A, Box 7060,
750 07 Uppsala, Sweden
Telephone +46 18 67 10 00
Fax +46 18 67 34 90
Email: lindstromhakan@netscape.net

[2]Senior Lecturer, Dept. of Mathematics and Statistics,
University of Canterbury, Private Bag 4800, Christchurch, New Zealand
Telephone +64 3 364 2987 ext. 7681

[3]PhD, METLA Research institute,
Joensuu Research Centre, PL 68, 80101 Joensuu, Finland
Telephone +358 10 211 3064

Abstract

This study assessed variation in modulus of elasticity of trees and logs of Scots pine (*Pinus silvestris*) trees. The study utilised 192 sample trees (c. 90-150 yrs) selected from 24 clear-felling forests in central and southern Sweden. Modulus of elasticity assessed with transit time technology on standing tree stems at 0.5-2.0m, varied more than two-fold (c. 8.6 - 17.6 GPa). Modulus of elasticity, assessed with resonance based technology, varied between 7.4 -14.1 GPa for logs cut at similar height (<6.0 m). Models of modulus of elasticity variation of tree stems were derived on factors related to growth conditions at stand and tree level, with an R^2Adj of c. 0.45-0.60.

Key words: *Acoustics, Growth conditions, Logs, Modulus of elasticity, Scots pine, Tree models, Wood quality*

Introduction

Old growth forests are gradually being replaced by forests established and managed to yield trees that reach commercial tree size at earlier age. This will change the material properties of conifer wood as fast-grown trees, in comparison to more slow-grown trees, will contain a larger proportion of juvenile wood, knots, and compression wood (Thörnqvist, 1993; Kennedy, 1995; Moberg, 2001; Lindström, 2002; Warensjö and Rune, 2004). As the character of the forest resource changes, it will mean that a larger volume of trees and logs with unsatisfactory material properties will be available for industrial use. Using such logs in the sawmill industry would bring higher production costs and lower revenue of solid wood products as the proportion of sawn lumber with unacceptable drying distortion, low modulus of elasticity, and large knots would increase Kennedy (1995). However, the ongoing trend towards a general decline in average wood quality will be blurred by the fact that there still will be plenty of average-good quality trees in the future forests. In other words, an increased emphasis on methods to improve log sorting and optimised crosscutting of tree stems will take place to get optimal industrial use of a more mixed future forest resource (Roos et al., 2002). This has been seen already in the research initiatives that aimed at improving grading of logs and trees according to their material properties (Perstorper 1994; Oja et al., 2001; Tsehaye et al., 2001; Albert et al., 2002; Beall, 2002; Huang et al., 2003; Oja et al., 2004; Edlund et al., 2006) where derived technologies and methods are aimed at directing stems and logs to best industrial end-use.

One important wood property is the modulus of elasticity (MOE), often referred to as material stiffness. High MOE means that a material can carry a high load without strain or deformation. Furthermore, MOE of wood is correlated with the strength of wood: modulus of rupture (Dinwoodie, 2002). Because MOE of sawn lumber can be tested non-destructively by machine stress grading (Anon., 2006a) and by acoustics (Anon., 2006b) it is used as grading criteria for construction lumber (Anon. 1995; Anon. 2000). Moreover, as there is clear agreement between structural lumber grade vs. the assessed MOE of saw logs (Ross et al. 1997; Edlund et al. 2006) measurements of log MOE could possibly be used to pre-sort logs into objective property classes.

Acoustic analysis of wood variation have been performed with methods based on transit-time-, and resonance, ultrasound, and wavelength spectra analysis (Bucur 1995; Ouis, 1999; Lindström et al., 2002 and 2005; Solodov et al., 2004; Bucur and Bohnke, 2005; Chauhan et al., 2005; Dyk and Rice, 2005; Gozdecki and Smardzewski, 2005; Chauhan and Walker, 2006). These studies have shown that acoustics, in addition to assess MOE of wood, can be used to describe wood features that affect visual appearance and drying distortion of solid wood products *e.g.* knot structure, wood rot, fiber dimension, and microfibril angle. Accordingly, acoustics has been used as a practical low cost method to assess wood quality of standing trees, cut logs, and sawn lumber for a range of softwood species (Marchal and Jacques, 1999; Wang et al., 2001; Huang et al., 2003; Lindström et al., 2004; Xu and Walker, 2004; Grabianowski et al., 2006; Wang and Simpson, 2006; Watt et al., 2006). Nevertheless, there are still no studies that explored the MOE variation of mature *Pinus silvestris* timber trees as a result of growth conditions.

The current study utilises 24 mature clear-felling forests to explore the approximate range of MOE found in Scots pine (*Pinus silvestris*) timber trees selected from two regions of central Sweden (Fig. 1). The objectives of the study were to:

1. Assess the MOE variation in Scots pine tree stems.
2. Model MOE variation in tree stems based on factors related to tree growth.

Materials and methods

This study is part of a collaborative research project between the Finnish Forest Research Institute (METLA) and the Swedish University of Agricultural Sciences (SLU). The aim of this project was to explore and model wood property variation in mature Scots pine timber trees throughout Finland and Sweden. However, only trees on Swedish sites (Fig. 1) were available for transit-time- and resonance frequency assessment. The Swedish forest sites were selected from inventory records of forests belonging to the forest company Sveaskog. This gave access to suitable clear-felling forests, c. 90-150 yrs old, representing forests with low-, average-, and high site index in the Dalarna region and in the Småland region (Fig. 1). For each selected forest a comprehensive set of standardized stand- and tree data was gathered either from inventory data or recorded at time of tree sampling. All selected sites had to meet the following selection criteria:

- ✓ Selected sites should represent the variation in site index for each region (low – medium - high site indexes) with a vegetation cover representing Calluna type (CT) – Vaccinium type (VT) – to more fertile Myrtillus type (MT);
- ✓ Selected tree stands should grow on mineral soil;
- ✓ Selected tree stands should be dominated by Pine trees (more than 50% of the total stem basal area per hectare);
- ✓ Selected tree stands should be planned for commercial clear-felling within 2 yrs;
- ✓ Selected tree stands should have had no extreme silvicultural treatment;
- ✓ Selected tree stands should be close to road for easy access & transport.

Fig. 1. Location of the 24 mature clear-felling stands of Pinus silvestris in Sweden.

Tree selection

A circular sample plot (c. 500–1000 m^2) was laid out in each selected forest stand. The geographical location (longitude, latitude, height above sea level) and the area of each sample plot were registered. The area and the location of each sample plot was decided by stand regularity and stand density in order to contain at least 16 trees whereof at least eight should be pine trees with a dbh larger than 14 cm. Tree species was recorded and diameter was measured with a caliper for all trees on the sample plot exceeding 7 cm at breast height. In order to select sample trees that represented the tree diameter distribution of each plot, all pine trees on a plot with a dbh larger than 14 cm were callipered and sorted in ascending diameter then marked with spray paint with a sequential diameter rank with the numbers {1, 2, 3…n }. The n pine trees with dbh larger than 14 cm on each plot was divided by 8:

$$\frac{n}{8} = i \tag{1}$$

The trees on the plot that had a sequential diameter number closest to the whole numbers {i, 2i, 3i,…8i} in eq.1 were selected as sample trees and marked with the diameter rank numbers {1, 2, 3,…8} to indicate tree class, where 1 = smallest sample tree, 8 = largest sample tree within each sample plot. Each of the eight sample trees was, directly after felling, marked with spray paint for the north exposure along the entire stem. This gave possibilities to evaluate any systematic difference in wood properties between the south- and north stem side of cut logs, stem bolts, and discs that were later cut from each sample tree (Fig. 4).

Transit time measurements on standing trees

Using the transit time tool “FAKOPP™” (Lindström et al., 2002, Anon. 2006c; Grabianowski et al., 2006) three piezo-ceramic steel probes were attached to the northern stem side of each selected sample tree at c. 0.1, 0.5, and at 2.0m from stump height (Fig. 2). The distance between probes was then recorded to the nearest 0,5 cm using a graded steel measurement tape. Impulse waves were launched by a hammer tap to the lowest steel probe and 10 consecutive readings of transit time (ms) were read on a digital display linked to the transit time readings fed from the location of the 2nd and 3rd steel probe. The same measurement procedure was undertaken on the south side of each stem.

The transit-time and distance measurements were used to calculate the average transit time velocity between the 2nd and 3rd probe for the north- and south side of each tree. The MOE of the north- and south side of the trees was calculated as:

$$\mathrm{MOE} = \varrho V^2 \tag{2}$$

V in eq. 2 is the measured transit-time velocity. The green density of the wood (ϱ) was not measured in the field, instead it was assumed to be 800 kg/m^3 as freshly felled Scots pine varies between c. 700-1000 kg/m^3 (Nylinder 1961). The assumption of (ϱ) being 800 kg/m^3 may have lead to an underestimation or overestimation of the MOE of ± 10-25%. For three of the trees we could not achieve consistent impulse velocity readings, as they were standing on shallow stony soil and severe wind sway of the trees triggered impulses that were received by the transit time probes. The correlation between the MOE measured on north- and south side of 189 stems can be seen in Fig. 3. The slope of the curve in Fig. 3 indicates that there is no difference in MOE between the north- and south side of a tree stem. Instead, the MOE scatter within trees (Fig. 3) was caused by differences in impulse wave velocity that reflect differences in wood structure, knot size, and defects in diametrically opposed stem sectors.

Fig. 2. To the left, transit time measurements on standing trees stems at 0.5-2.0 m with the Fakopp™ tool. To the right, resonance measurements of log fundamental frequency using a Rion-SA77 signal analyser.

Fig. 3. Transit time measurements for the north and south stem side of 189 sample trees.

Tree and knot characteristics

The 8 selected sample trees in each tree stand were felled and marked with a permanent marker on the stem end-surface with tree size number 1-8 and the plot number. These trees were then bucked without cross-cutting. A continuous color line was marked with spray paint to denote the north exposure of each stem prior to any further measurement. Stems were then cross-calipered to obtain stem diameter measurements at successive stem heights upwards each stem: 0 m, 1.3 m, 2 m, 4 m, 6 m,… to the top of the tree. A stem disc was cut at stump height for growth ring determination of tree age in laboratory. External height limits (dm) for knottiness (no visible knots), tree height, crown height and the diameters of the biggest sound and dry knots were also recorded. External defects were noted as the height where the defect starts, the height where the defect ends, and defect type. Stem discs, stem bolts, and logs were cut from stems according to the sampling scheme that is further described below and in Fig. 4. All heights were recorded starting at stump height. The assessed MOE for trees (eq. 2) and logs (eq. 3) can be seen in table 1.

Measurements of other wood properties and growth ring structure

The current study used a pre-set sampling scheme at successive stem heights for later measurements of heartwood content and growth ring structure on stem discs and measurements of wood properties on stem bolts. That is, 20 cm discs and 70 cm bolts were cross-cut from pre-determined stem heights using two alternative cross-cutting patterns (A- and B trees) yielding log lengths of c. 1.8 – 4.0m (Fig. 4).

Cross-cutting of selected trees 1, 3, 4, 6 and 8 (A-SAMPLES):

20 cm discs were cross-cut at 0m, 2m, 6m, 10m, 14m, and 18m stem height. The cross-cutting of discs were sometimes adjusted in order to avoid knots or other visible defects, which sometimes meant that the sampling height was slightly different (< 2 dm) from the sampling plan (Fig. 4). If a tree had a diameter of less than 7cm at the intended sampling height no disc sampling took place at that height.

Cross-cutting of selected trees 2, 5, and 7 (B-SAMPLES):

These trees were subject to the same sampling regime of discs as described for A-sample trees with the following exception: On the selected B-trees (tree nr 2, 5, and 7) a 70 cm stem bolt was cut instead of a 20 cm disc at 2, 6, and 10m stem height.

From all sample trees (1-8) the cut stem discs/bolts were marked with date, site, sample tree number, a line denoting north exposure, and height in tree. They were then placed in plastic bags and transported to a freezer where they were kept until further sample preparation/measurements.

Fig. 4. Cross-cutting points for disc and stem bolt samples. The crosscutting pattern seen in the upper stem is representative for A-trees (sample trees 1, 3, 4, 6, 7) and the lower stem is representing the cross-cutting pattern for B-trees (sample trees 2, 5, 7).

Modulus of elasticity of logs

After that tree stems had been cross-cut to generate stem discs and stem bolts according to Fig. 1, the resulting logs (c. 1.8 – 4.0 m) were measured in length with a steel measurement tape to the closest 0.5cm. Then, longitudinal resonance frequency was measured using a Rion SA-77 FFT signal analyser (Edlund et al., 2006) coupled with an accelerometer (Fig. 2). The logs were hit on the log end-surface with a hammer and the accelerometer picked up the signal pattern from the resonating log. The signal pattern was displayed with a graphical interface where a cursor was used to mark the peak position of the fundamental resonance frequency, which was recorded to the closest 10 Hz. Using the recorded log length (l), fundamental resonance frequency (f), and the assumption that Scots pine timber has a green wood density (ϱ) of c. 800 kg/m^3 (Nylinder, 1961), dynamic modulus of elasticity was calculated using eq.3:

$$MOE = 4\varrho l^2 f^2 \tag{3}$$

Equation (3) has been chosen because earlier studies have shown that stem bolts and logs exceeding a diameter:length ratio of 1:3 give reliable readings of resonance frequency (P. Harris, personal communication, August 2001). Moreover, validation studies have shown that dynamic MOE (calculated according to equation 3) has high correlation with the MOE determined with static loading at 12% moisture content when using stem bolts exceeding a diameter:length ratio of 1:3 (Lindström et al., 2002; Lindström et al. 2004). The correlation between dynamic and static MOE measurements is high, meaning that dynamic and static MOE denote the same property (material stiffness). This said, it has been noted that MOE determined with acoustics yield systematically higher values than if determined with static loading (Ouis, 1999 and 2002; Lindström et al., 2002, Huang et al., 2003).

Statistics

The software used in calculations and statistical interpretation are EXCEL for Windows XP, the statistical software R ver. 1.8 R Development Core Team (2003), and MATLAB Hanselman and Littlefield (2005). A Model (MODEL 1) of the MOE measured on standing trees (eq.2) was developed using the transit time data of the 189 sample trees. A second model (MODEL 2) was developed based on the MOE assessed with resonance based technology (eq.3) on 953 logs cut from the sample trees. Here, graphical modelling Edwards (2000) and stepwise regression were first used to screen possible models. Moreover, to avoid an overfit of the data to any of the models the Schwarz information criterion Schwarz (1978) was employed. A set of models were developed with step wise regression that utilised 3, 5, 7, 9 and all available variables. Finally, models (eq.4) were constructed using variables that met the following model selection criteria:

i) Variables should be significant at $p < 0.001$ level.

ii) Each model variable should add a partial R^2Adj > 0.01.

$$(MODEL\,1) = \sum_{i=1}^{k} a_i x_i + \varepsilon \qquad (4a)$$

$$(MODEL\,2) = \sum_{i=1}^{h} b_i y_i + \nu \qquad (4b)$$

where the a's and b's are the parameters, x's and y's are the explanatory variables and ε and ν are the residuals.

The used variables in MODEL 1 and MODEL 2 can be seen in Table 3, 4.

Table 3. Variables used in the regression models

Table 4. MOE Regression model of the 189 standing trees (MODEL 1) and on the 953 logs (MODEL 2).

Results

MOE assessed on standing trees

The MOE derived from transit time data for the south and north side of 189 individual trees can be seen in Fig. 3 and in table 1, 2. Averaging the transit time measurements from the south- and north side on stems gave a calculated MOE variation of c. 8.6 – 17.6 GPa (Fig. 3, Table 1) in the outerwood of standing trees. The more than two-fold variation in MOE of standing trees agrees with the MOE values on logs cut from similar tree height. Both results indicate large differences in MOE between trees (Table 2).

The transit time measurements on standing trees indicated that there is considerable impulse velocity variation on the south and north side of tree stems. As the regression slope is close to 1 (Fig. 3) it is obvious that MOE does not vary systematically with the south or north side of a tree stem. The variation in impulse velocity, on opposite sides of the tree stems, is thought to represent differences in *e.g.* microfibril angle, knots, compression wood, grain deviations, and/or wood defects. As the within tree variation in MOE (impulse velocity) seems more pronounced in low MOE trees (Fig. 3) it might be that these trees also have larger wood variability and/or defects.

MOE assessed on logs

The variation in log MOE, assessed with resonance technology, on 953 logs cut from the 192 sample trees can be seen in Fig. 5, 6, and table 1. Again, the close to two-fold MOE variation found in logs cut at similar height from differing trees signals that there are large differences in MOE between trees. The change in MOE measured on logs taken at increasing stem height for the 192 trees can be seen in Fig. 6. It indicates a pattern of increased MOE in the first c. 2-4 m of a tree stem then being held fairly constant, whereafter MOE decreases with increasing stem height. Similar results, *i.e.* an initial increase of MOE, followed by a more or less constant MOE, then a gradual decline with increasing stem height have been obtained in other studies Xu and Walker (2004). Still, it was surprising that a MOE development pattern seem to exist for the studied trees as they are sampled from forests with varying site index and/or belong to differing tree classes. The observed MOE development with increasing stem height may reflect that:

a) There is a cambial maturity phase in the first c 1-5m from stump height, i.e. cyclophysis (Olesen, 1982), which means that the vascular cambium will not have reached full maturity at lower stem height.

b) Logs cut from successively higher stem positions (Fig. 6) contain fewer growth rings leading to a higher content of juvenile wood with high microfibril angle & low wood density.

Fig. 5. Variation in MOE of all 953 logs cut on sites 1-24

Fig. 6. Modulus of elasticity measured with resonance of the 953 logs sampled at increasing stem height from the 192 trees used in the study, note that the cross-cutting patterns of A- and B logs given a systematic difference in log sampling position and that 2 logs were cut slightly off the intended sampling position.

Table 1. Min-, max-, and mean values of the MOE measurements on standing trees and cut logs.

Transit time velocity

The agreement between the averaged transit time data measured on the north- and south side of standing trees between 0.5-2.0m and the 1st, 2nd, 3rd, 4th, 5th, 6th and 7th log cut from the trees can be seen in table 2. The results should be seen in the perspective that transit-time measurements will measure the MOE of the stiffer mature outerwood while resonance frequency measurements will assess the average MOE for the entire log (Chauhan and Walker 2006). In other words, table 2 shows the correlation between the impulse velocity of outerwood in trees at low stem height vs. the MOE of logs cut from successively higher stem positions where the stem cross-section increasingly consist of juvenile wood. This may partly explain why there is high correlation ($r^2 = 0.72$) between the transit-time measurements on trees at 0.5-2.0m *vs.* the MOE assessed with resonance frequency on the 1st logs (cut from c. 2.0-6.0m stem height), while there is weak correlation between transit-time measurements *vs.* the MOE of logs cut from higher stem positions ($0.02 < r^2 < 0.44$).

Table 2. Correlation between transit time measurements on standing trees vs. the resonance frequency measurements on logs cut from increasing stem heights.

Statistics

The variables found significant in the regression models indicate that the MOE development in trees (Fig. 6) would be influenced by growth conditions and tree characteristics. It is here assumed that the variables that were found significant, e.g. tree dominance, stem taper, tree height, knot placement and knot size, mirror the historic growth conditions of individual trees (Table 4). Similar results have been reported for Radiata pine by Watt et al. (2006). For instance, there seems to be a negative effect on MOE by increasing tree dominance. At the same time, trees that are tall relative to their diameter (often seen in trees that experienced moderate-high crown competition) seem to have higher MOE.

Discussion

The current study – used material

This study was based on 192 Scots pine trees selected from 24 sites representing clear felling forests, c. 90-150 yrs old, with yearly growth rates varying between c. 3-12 m^3 per hectare. Although the selection of stands and trees in this study was designed to cover as much variation in growth conditions as possible, it is a rather limited material. Therefore, it is assumed that the natural MOE variation of Scots pine trees would be larger than the two-fold variation seen in the descriptive data (Table 1) of the current study.

Another result of the study herein was that impulse wave velocity does not vary systematically with the north- vs. south side of stems. The observations of large deviations in impulse velocity on opposing sides of a tree stem may instead represent uneven distribution and presence of compression wood, large knots, compression wood, grain deviations, rot, or other defects in the tree stem. More detailed studies would be necessary to determine the agreement between impulse wave velocity and wood defects.

The current study supported the assumption that variation in MOE can be linked to growth conditions and tree characteristics. However, the model explanation was rather limited as the coefficient of determination ranged between c. 0.4-0.6. It may be that more sophisticated models where more detailed growth- and tree data is used could provide better explanation of the MOE variation. In that case, models of tree and log MOE may guide strategic selection of trees suitable for a given range of solid wood products. Such models could also be used when designing silvicultural strategies that yield trees with high MOE. As for now, the current study only shows that there is large variation in MOE between trees and that the MOE variation, in part, is linked to growth and tree characteristics.

Models – significant variables

Our main model interpretation is that trees that are tall relative to their diameter (relatively slender) are higher in MOE. We base our assumption on that variables found significant in the MOE models, either acts as indicators of the previous development of the tree crown, or indirect reflections of tree/cambium maturity. For instance, trees that have high onset of their first visible dead knots, will have higher MOE. According to the derived models, trees are more likely to have high MOE if they are (having):

a) Non-dominant in the stand
b) Tall in relation to diameter (have low taper)
c) High onset of visible dead knots (due to crown competition)
d) High stem volume (mature older trees)
e) Circular stem cross-section

Still, there seems to be plenty of exceptions from the outline above which is probably due to genetic differences and complex interactions that go beyond the scope of this explorative study.

Transit-time- & resonance based assessment of MOE

The overall variation in MOE assessed by resonance technology largely follows the MOE assessed with transit-time technology on standing trees. Nevertheless, the transit-time measurements are inherently giving higher values of MOE as the highest impulse wave velocity is found in the mature outer wood, whereas resonance based technology averages the MOE for the entire wood volume of a log (Chauhan and Walker 2006). It should be noted that there has been no measurement of green density. In this study, it has merely been assumed that the green density of fresh Scots pine timber is equal to 800 kg/m^3. As the sapwood is probably closer to 1000 kg/m^3 and some logs may have lower green density i.e. about 700 kg/m^3 according to (Nylinder, 1961), there may be an underor overestimation of the assessed MOE by ± 10-25%. If actual measurements of green density had been done, giving more precise assessment of density in eq.2, 3, it should have amplified the systematic differences between the MOE found in the outer mature wood measured by transit-time technology (eq.2) *viz.* the MOE averaged for the entire log by resonance frequency measurements (eq.3).

Resonance measurements of logs indicates a height dependent MOE pattern

A large variation was found in MOE at varying stem height of the studied trees (Fig. 6). From the appearance of Fig. 6 and from the statistical analysis it seems as there might be a height dependent pattern in MOE. Here, the observed change in MOE is assumed to depend on complex interaction between genetics and growth conditions of an individual tree. It has for instance been argued that the vascular cambium has a genetically predetermined wood structure formation that is modulated by wind load of a tree stem. Here, the survival of a tree is reliant on that the stem wood structure is able withstand wind failure/breakage (Schwendener, 1878; Mattheck, 1991; Watt et al., 2006). The distribution of wind load and it's displacement onto the cross-stem section would mean that the tree adjust the wood stiffness to be highest in the last formed growth rings in the stem section situated close to the mid point of the living tree crown where maximum strain would occur. This has been indirectly corroborated by studies that shown that the longest tracheids can be found in the last formed growth rings at the onset of the living crown Atmer and Thörnqvist (1982). It should here be noted that long tracheids are associated with lower microfibril angle (Albert et al., 2002; Lindström et al., 2005) causing higher MOE of wood (Cave 1968, 1969; Cave and Walker, 1994; Lindström et al. 2002; Huang et al., 2003).

In this perspective, it would be possible to model MOE development in a tree stem based on factors that regulate or mirror crown-size and wind load distribution. However, such factors only explain part of the MOE variation as genetic differences also will influence MOE (Lindström et al. 2004).

Control of MOE

This study showed that there is considerable MOE variation of *Pinus silvestris* trees. The developed models indicate that it is possible to predict the MOE of trees and logs by using factors related to tree growth. According to the models it seems likely that forest management that aim for tall, slender trees with high set crowns will on average produce trees with higher MOE. However, the modest explanation of the developed models ($0.46 < R^2Adj < 0.62$) underlines the problem of using prediction models of MOE based on factors related to growth conditions. Instead of using models, it may be that future development in non-destructive measurement technologies could give possibilities of direct MOE measurements of standing trees at time of thinning and/or at final tree harvesting. This could, for instance, reduce the number of trees/logs with unsatisfactory wood properties that eventually arrive at sawmill.

Conclusions

MOE assessed with transit time technology on standing tree stems at 0.5 - 2.0m, varied more than two-fold (c. 8.6 - 17.6 GPa). MOE, assessed with resonance based technology, varied between 7.4 - 14.1 GPa for logs cut at similar height (<6.0 m).

Using transit-time technology, large differences in impulse wave velocity were observed on the south- vs. north side of some trees. No systematic difference in impulse wave velocity could be seen when comparing the impulse velocity data for the south- vs. north side of all trees. Instead, large variation in impulse wave velocity of individual tree stems was interpreted as local defect- and/or wood structure differences in diametrically opposed stem sectors.

Models of MOE in tree stems were derived on factors related to growth conditions at stand and tree level, with an R^2Adj of c. 0.45-0.60.

Acknowledgements

We acknowledge help and support by Professor Mats Nylinder and Mr. Hans Fryk, both at the Swedish University of Agricultural Sciences, Dept. of Forest Products & Markets, Uppsala, Sweden (SLU) and by Professor Erkki Verkasalo at METLA, Joensuu, Finland. This work has been funded by SLU, the research foundations FORMAS, Sweden & TEKES, Finland, and the Swedish companies SveaSkog AB & SETRA Group AB.

References

Albert, D.J., Clark, T.A., Dickson, R.L. & Walker, J.C.F. (2002). Using acoustics to sort radiata pine pulp logs according to fibre characteristics and paper properties. International Forestry Review. 4(1), 12-19

Anon. (1995). SS-EN 519 Structural timber – Grading – Requirements for machine strength graded timber and grading machines. Swedish Standards Institute, SIS Förlag, Stockholm

Anon. (2000). SPCR 078 Certification rules for machine strength graded timber. Swedish national testing & research institute. http://www.sp.se/cert/cert_prod/spcr/spcr078.pdf

Anon. (2006a). http://www.metriguard.com

Anon. (2006b). http://www.dynagrade.com

Anon. (2006c). http://www.fakopp.com

Atmer, B. & Thörnqvist, T. (1982). Fiber properties in Norway spruce (Picea abies Karst.) and Scots pine (Pinus silvestris L.) Report 134. (In Swedish with English abstract, ISBN 91-576-1272-2) The Swedish University of Agricultural sciences, Dept. of Wood Science. Uppsala, Sweden.

Beall, F.C. (2002). Overview of the use of ultrasonic technologies in research on wood properties. Wood Science and Technology. 36, 197–212

Bucur, V. & Bohnke, I. 1994. Factors affecting ultrasonic measurements in solid wood. Ultrasonics 32:385-390.

Bucur, V. 2005. Ultrasonic techniques for nondestructive testing of standing trees. Ultrasonics 43:237-239.

Cave, I.D. (1968). The anisotropic elasticity of the plant cell wall. Wood Science and Technology. 2, 268-278.

Cave, I.D. (1969). The longitudinal Young's elasticity of Pinus Radiata. Wood Science and Technology. 3, 40-48.

Cave, I.D., & Walker, J.C.F. (1994). Stiffness of wood in fast-grown plantation softwoods: the influence of microfibril angle. Forest Products Journal 44(5), 43-48.

Chauhan, S.S., Entwistle, K.M., Walker, J.C.F. (2005). Differences in acoustic velocity by resonance and transit-time methods in an anisotropic laminated wood medium. Holzforschung. (59): 428-434.

Chauhan, S.S., & Walker, J.C.F. (2006). Variations in acoustic velocity and density with age, and their interrelationships in radiata pine. Forest Ecology and Management 229 (2006), 388-394.

Dinwoodie, J.M. (2000) Timber - its nature and behaviour, second edition. ISBN: 0-419-25550-8. Routledge. 272p.

Dyk, H., & Rice, R.W. (2005). An assessment of the feasibility of ultrasound as a defect detector in lumber. Holzforschung. (59): 441-445.

Edlund, J., Lindström, H., Nilsson, F., Reale, M. (2006). Modulus of elasticity of Norway spruce saw logs vs. structural lumber grade. Holz als Roh und Werkstoff 2006. (64):273-279.

Edwards, D. (2000). Introduction to graphical modeling. Springer-Verlag. New York.

Gozdecki, C., & J. Smardzewski. (2005). Detection of failures of adhesively bonded joints using the acoustic emission method. Holzforschung. (59): 219-229.

Gustavsen, H. G. (1980). Talousmetsien kasvupaikkaluokittelu valtapituuden avulla. Summary: Site index curves for conifer stands in Finland. Folia Forestalia 454. 31 p. (In Finnish with English abstract)

Grabianowski, M., Manley, B., Walker, J.C.F.. 2006. Acoustic measurements on standing trees, logs and green lumber. Wood Science and Technology. (40): 205-216.

Hanselman, D. & Littlefield, B. (2005). Mastering MATLAB 7. Prentice Hall. Upper Saddle River, New Jersey.

Huang, C.L., Lindström, H., Nakada, R., & Ralston, J. (2003). Cell wall structure and wood properties determined by acoustics. Holz als Roh- und Werkstoff 61, 321-335.

Kennedy, R.W. (1995). Coniferous wood quality in the future: Concerns and strategies. Wood Science and Technology. 29, 321-338.

Kyrkjeeide, P.A., Lindström., H., & Thörnqvist, T. (1994). Building timber from large-dimension spruce – deformation and quality in wall studs (In Swedish with English abstract). Report No. 38. (ISSN 0284-379X). The Swedish University of Agricultural sciences, Dept. of Forest-Industry-Market studies. Uppsala, Sweden.

Larsson, D., Ohlsson, S. , Perstorper, M., & Brundin. J. (1998). Mechanical properties of sawn timber from Norway spruce. Holz als Roh- und Werkstoff. 1998, 331-338.

Lindström, H. (2002). Intra-tree models of juvenile wood in Norway spruce trees as an input to simulation software. Silva Fennica. 36, 521-534.

Lindström, H., Harris, P., Nakada, R. (2002). Methods for measuring stiffness of young trees. Holz als Roh- und Werkstoff. (60): 165-174.

Lindström, H., Harris, P., Sorensson, C.T., Evans, R. (2004). Stiffness and wood variation of 3-year old *Pinus radiata* clones. Wood Science and Technology. (38): 579-597.

Lindström, H., Evans, R., Reale, M. (2005). Implications of selecting tree clones with high modulus of elasticity. New Zealand Journal of Forest Science 35(1), 50-71.

Marchal, M., & Jacques, D. (1999). Évaluation de deux methods acoustiques de determination du module d'élasticitéde bois de mélèze hybride jeune (*Larix x eurolepis Henry*) – comparasion avec une méthode normalisée eu flexion statique. Annals of Forest Science. (56):333-343

Mattheck, C. (1991). Trees the mechanical design. Springer Verlag. New York.

Moberg, L. (2001). Models of internal knot properties for *Picea abies*. Forest Ecology and Management. 2001; 147(2/3), 123-138.

Nylinder, P. (1961). On the effect of tree and wood properties of the raw density and buoyancy of logs. 1. Scots pine (In Swedish with English abstract). Kungliga Skogshögskolan. Report 35. Stockholm, Sweden.

Oja, J., Grundberg, S., & Grönlund, A. (2001). Predicting the stiffness of sawn products by X-Ray scanning of Norway spruce logs. Scandinavian Journal of Forest Research. 16, 88-96.

Oja, J., Grundberg, S., Fredriksson, J., Berg, P. (2004) Automatic grading of sawlogs: A comparison between X-ray scanning, optical three-dimensional scanning and combinations of both methods. Scandinavian Journal of Forest Research 19, 89-95.

Olesen, P.O. 1982. The effect of cyclophysis on tracheid width and basic density in Norway spruce. Forest tree improvement. No. 15. Akademisk Forlag, Copenhagen, Denmark.

Ouis, D. 1999. Vibrational and acoustical experiments on log of spruce. Wood Science and Technology, 33:151-184.

Ouis, D. 2002. On the frequency dependency of the modulus of elasticity of wood. Wood Science and Technology 36: 335-346.

Perstorper, M. (1994). Quality of structural timber - end-user requirements and performance control. Doctoral dissertation. (ISSN 0534-0411). Chalmers University of Technology, Division of Steel and Timber structures. Göteborg, Sweden.

R Development Core Team. (2003). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. (ISBN 3-900051-00-3) http://www.R-project.org

Roos, A., Flinkman M., Jäppinen, A., Lönner, G., & Warensjö, M. (2001). Production strategies in the Swedish softwood sawmilling industry. Forest Policy and Economics. 2001, 189-197.

Ross, R.J., McDonald, K.A., Green, D.W., Schad, K.C. (1997). Relationship between log and lumber modulus of elasticity. Forest Products Journal (47): 89-92.

Schwarz, G. (1978). Estimating the dimension of a model. Annals of Statistics, 6, 461-464.

Schwendener, S. (1874). Das mechanische princip in anatomischen bau der monocotylen. [The principle of mechanics seen in the anatomical wood structure of conifers] Wilhelm Engelmann. Leipzig.

Solodov, I., Pfleiderer, K., Busse, G. (2004). Nondestructive characterization of wood by monitoring of local elastic anisotropy and dynamic nonlinearity. Holzforschung. (58): 504-510.

Thörnqvist, T. (1993) Juvenile wood in coniferous trees. D13:1993. Swedish council of building research. ISBN 91-540-5605-5. Stockholm, Sweden.

Tsehaye, A., Buchanan, A. H., Walker, J. C. F. (2001). Sorting of logs using acoustics. Wood Science and Technology, 34, 337-344.

Wang, X., Ross, R.J., McClellan, M., Barbour, R.J., Erickson, J.R., Forsman, J.W., McGinnis, G.D. (2001). Nondestructive evaluation of standing trees with a stress-wave method. Wood and Fiber Science. (33): 522-533.

Wang, X.P. & Simpson, W.T. (2006). Using acoustic analysis to presort warp-prone ponderosa pine 2 by 4s before kiln-drying. Wood and Fiber Science. 2006; 38(2):206-214.

Warensjö, M. & Rune, G. (2004). Effect of compression wood and grain angle on deformations of studs from 22-year-old Scots pine trees. Scandinavian Journal of Forest Research. 19, 48-54

Watt, M.S., Moore, J.R., Façon, J-P., Downes, G.M., Clinton, P.W., Coker, G., Davis, M.R., Simcock, R., Parfitt, R.L., Dando, J., Mason, E.G., Bown, H.E. (2006). Modelling the influence of stand structural, edaphic and climatic influences on juvenile *Pinus radiata* dynamic modulus of elasticity. Forest Ecology and Management. 229: 136-144.

Xu, P. & Walker, J.C.F. (2004) Stiffness gradients in Radiata pine trees. Wood Science and Technology. 38, 1-9.

Tables

Table 1. Min-, max-, and mean values of the MOE measurements on standing trees and cut logs.

Variable	*Number of observations (n)*	*MOE (GPa) Minimum*	*MOE (GPa) Maximum*	*MOE (GPa) Mean*
MOE calculated according to eq. 2	189	8.6	17.5	13.9
MOE calculated according to eq. 3	953	4.7	14.1	9.8

Table 2. Correlation between transit time measurements on standing trees vs. the resonance frequency measurements on logs cut from increasing stem heights.

Relationship between the averaged MOE (GPa) calculated from transit time measurements on the south and north side of standing trees vs. the MOE (GPa), calculated from resonance frequency measurements, of log (n) from the same trees.	Log number from stump height of the tree (1-7, and appr. stem height where the log was cut)	Coefficient of determination, (R^2)	Total number of observations (n) at each position
Please observe that total number of observations at each log position varies from the total number of sampled trees (n=192) because: i. 3 stems were not measured for transit time velocity on both sides of the tree ii. 3 high diameter/short 1st logs were having to small diameter:length ratio to be measured with resonance frequency iii. The diminishing number of observations with increasing stem height are representing the variation in individual tree height and that some of the upper logs were cut from stems that had cracked in the felling process.	*1st log, (c. 0-2m)*	0.72	186
	2nd log, (c. 2-6m)	0.44	189
	3rd log, (c. 6-10m)	0.30	187
	4th log, (c. 10-14m)	0.19	177
	5th log, (c. 14-18m)	0.21	127
	6th log, (c. 18-22m)	0.09	64
	7th log, (c. 22-26m)	0.22	7

Table 3. Model variables.

Description of significant variables	
Growth condition and stand variables	
Siteindex	Site quality (H100, Gustavsen 1980)
Tree variables	
Dbh	Cross calipered diameter at 1.3 m (mm)
Tree dominance	8 trees that represented the diameter distribution were sampled within each stand and assigned number 1-8, where 1 = smallest tree, …, 8 = largest tree within the sample plot of each stand
Tree height	Tree height (dm)
D22A/B	Diameter between A and B diameter at 22 dm stem height
HighestDKnot	Highest dead knot height (dm)
Stem volume	The total stem volume of a tree (m3sk)
Log height	The stem height (m) that a log was cut from, using the calculated midpoint position of each log.

Table 4. MOE Regression model of the 189 standing trees (MODEL 1) and on the 953 logs (MODEL 2). Both models are based on selection criteria i) and ii), and best SIC respectively.

Model	Criteria	Number of variables in model	R^2Adj	RMSE	$b_{i\text{-}n}$[a]	T-Value	$X_{i\text{-}n}$
1	i) and ii)	7	0.46	1.21	14.5663***	27.5605	Intercept
					-0.1163***	-5.9007	Site index
					-0.2329***	-8.8909	Tree dominance
					-0.0212***	-14.6725	Dbh
					-0.0100***	-5.7904	D22A/B
					0.0264***	8.0146	Tree height
					0.0110***	5.0013	HighestDKnot
					2.6021***	7.5353	Stem volume
2	i) and ii)	5	0.62	1.20	8.1570***	33.7054	Intercept
					-0.1295***	-5.3665	Tree dominance
					-0.0055***	-5.8129	Dbh
					-0.2128***	-33.8873	Log height
					0.0137***	7.2056	Tree height
					0.0149***	7.0935	HighestDKnot

[a] *, **, and ***, indicate $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively (R development core team 2003).

FIGURE LEGENDS AND FIGURES

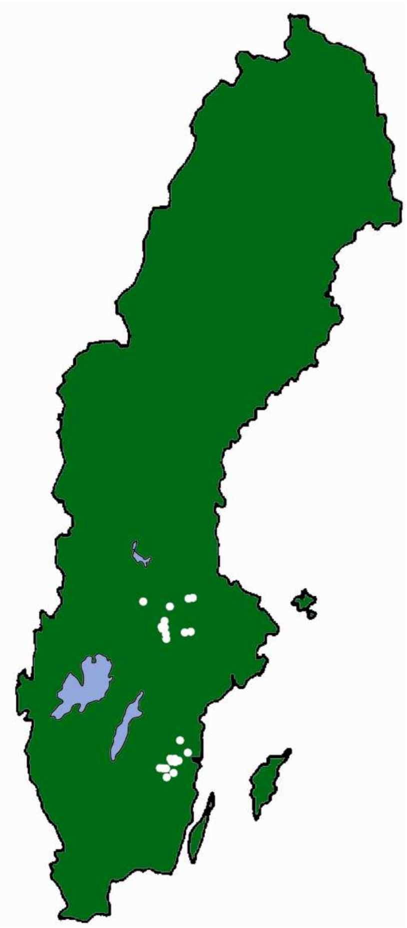

Fig.1. Location of the 24 forests in Sweden.

Fig. 2. To the left, transit time measurements on standing tree stems at 0.5 - 2.0 m with the Fakopp™ tool. To the right, resonance measurements of the fundamental frequency of logs using a Rion-SA77 signal analyser.

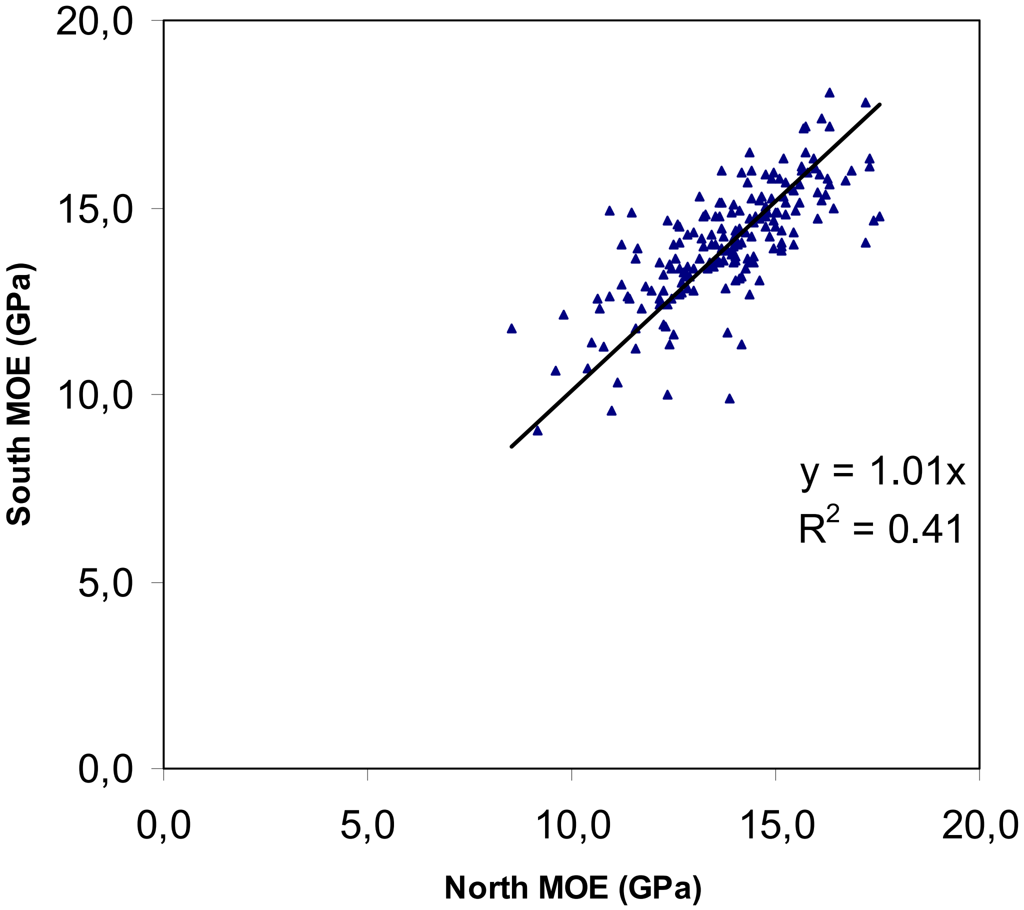

Fig. 3. MOE calculated from transit time measurements for the north and south stem side of each tree in the study.

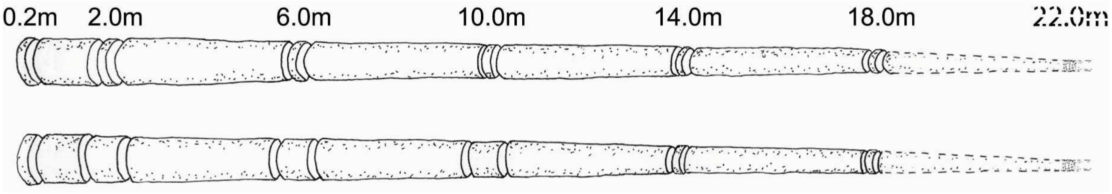

Fig. 4. Cross-cutting points for disc and stem bolt samples. The crosscutting pattern seen in the upper stem is representative for A-trees (sample trees nr 1, 3, 4, 6, 7) and the lower stem is representing the cross-cutting pattern for B-trees (sample trees 2, 5, 7).

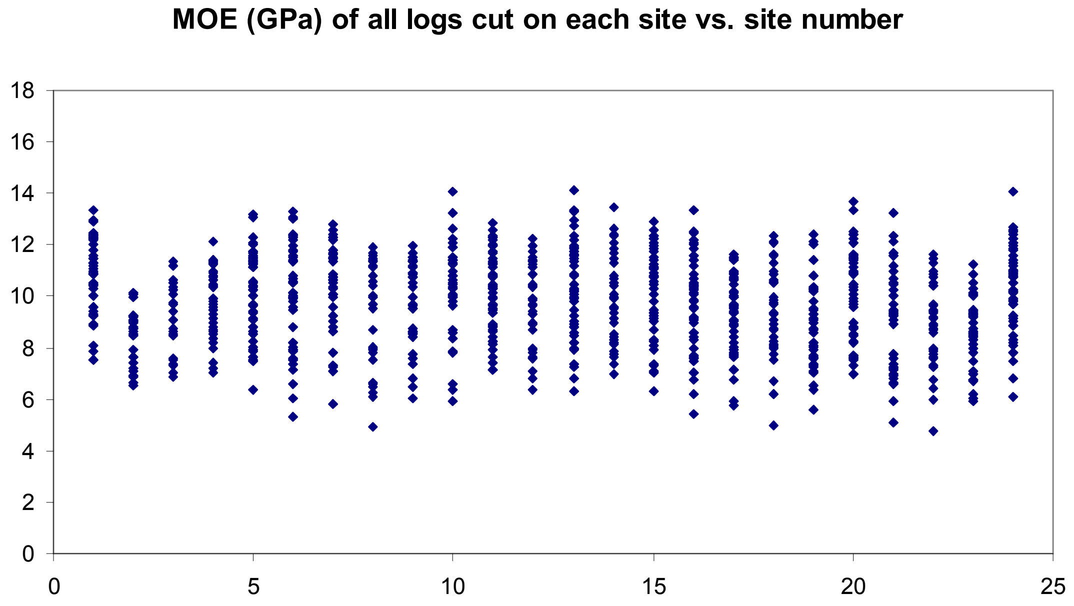

Fig. 5. Variation in MOE of all 953 logs cut on sites 1-24

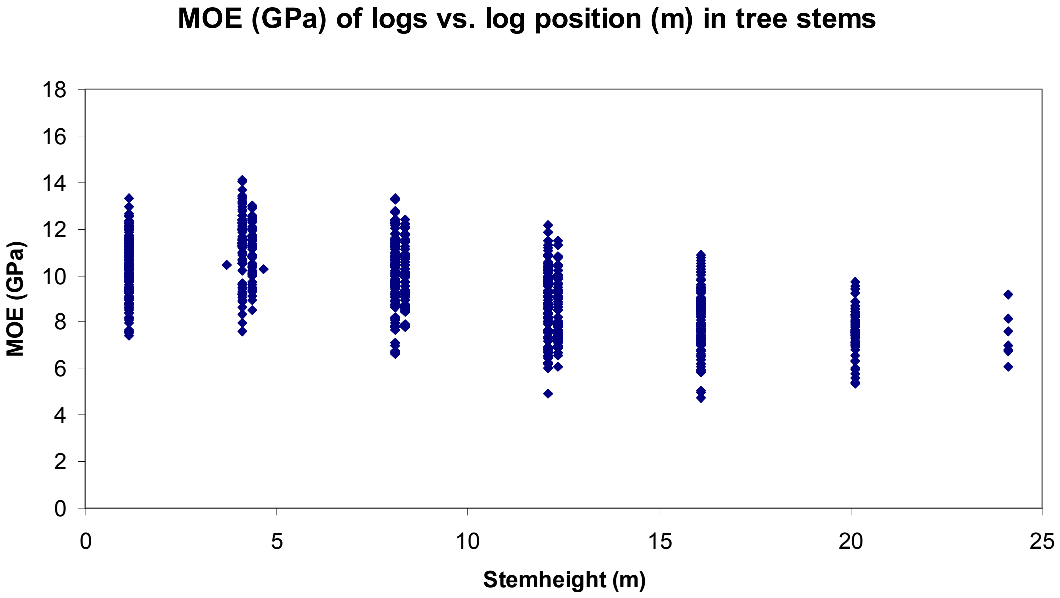

Fig. 6. Modulus of elasticity measured with resonance of the 953 logs sampled at increasing stem height from the 192 trees used in the study, note that the cross-cutting patterns of A- and B logs given a systematic difference in log sampling position and that 2 logs were cut slightly off the intended sampling position.