PREDICTING THE STRENGTH OF NORWAY SPRUCE BY MICROWAVE SCANNING: A COMPARISON WITH OTHER SCANNING TECHNIQUES

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ABSTRACT

In this study, 90 boards of Norway spruce (*Picea abies* (L.) Karst.) sized 48 x 148 mm in cross-section, have been examined using different scanning and measurement techniques. All of the boards originated from a sawmill located in southern Finland. Planar X-ray scanning, microwave scanning, and grain-angle measurement have been performed. In addition, strength and elastic properties were assessed for each piece by four point bending. The purpose of the study was to relate the potential of microwave scanning compared to other, industrially available techniques and to explain the physiological background of the microwave responses. The results show that the microwave signal, after transmission through wood, contains information about the bending strength and the modulus of elasticity. The correlation to density is a key factor. Annual ring width was also found to be correlated both to microwave measurements and strength properties.

Keywords: Wood, spruce, grading, microwave, x-ray, scanning, modulus of elasticity (MOE), modulus of rupture (MOR).

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INTRODUCTION

There are several factors that influence the strength properties of sawn lumber. The variation that occurs between timbers of different species can usually be graded before the logs are taken into the sawmill. However, there is also a variation within the same species and even within a single tree. By visual grading of the sawn boards with either manual or automatic systems, it is possible to sort the material. Mechanical grading machines that measure bending stiffness are commonly used for strength prediction. The drawback of this method is the need for physical contact and moving parts in the machines.

According to Dinwoodie (2000), the correlation coefficient between density and compression strength is 0.9. This correlation has been used to predict strength from X-ray measurements by Oja et al. (2000) for classification of logs and by Schajer (2001) for classification of sawn lumber. Average density alone does not explain all the variation in strength. Leban and Haines (1999) have, for example, shown that there is a correlation in annual ring width and elasticity for larch. Such information about the structure can be obtained from X-ray measurements, but X-rays can not be used to separate the dry wood density from moisture. Hence there still remains a need to develop other sensors that measure properties of wood.

Several studies have shown the potential of microwave scanning for prediction of density, moisture content, and grain angle (GA) of a timber specimen. How variations in moisture content or dry density affect a transmitted microwave signal has been described by Lundgren et al. (2006) and by Hansson et al. (2005), among others. Shen et al. (1994) proposed a microwave method for measuring grain angle that has been verified by Sjödén et al. (2005). The influence of grain angle on the microwave signal has been used by Leicester and Craig (1996) to detect knots in combination with a conventional mechanical stress grader. Microwave measurements have also been combined with X-rays for strength grading in the Finnograder, which has been tested together with two bending machines and one machine based on the speed of sound in a study by Boström (1994). Boström concludes that the best prediction of bending strength was attained from the bending machine. However, he notes that the Finnograder is less sensitive to grading speed and that a better yield might be achieved by adjusting the setting values. The response from a microwave sensor has been related to elasticity by Choffel et al. (1992) and to bending strength in studies by Johansson (2001) and by Lundgren (2005).

The aim of the present study was to compare the microwave sensor used by Johansson and Lundgren to other scanning techniques for strength grading of sawn timber. Another aim was to quantify the correlation in the measurements from the microwave scanner with grain angle and density measurements.

MATERIAL AND METHODS

The timber raw material chosen for this study was Norway spruce (*Picea abies* (L.) Karst.) from southeastern Finnish stands. The logs were randomly selected from one sawmill on two different occasions. There was a natural variation within the material, since both butt and middle logs fulfilled the requirements of a predefined top diameter of about 200 mm measured 100 mm from the top of the log. Two center pieces were straight sawn from each log to the nominal dimension 50 × 150 mm and planed to 48 × 148 mm. This resulted in 90 boards with lengths between 3.5 and 5.5 m. A conventional channel kiln was used for drying of the boards. After drying, the boards were stored for several months in an even climate so that the moisture distribution could be assumed to be uniform during scanning.

The measurements were performed on different occasions. On each of these the weight of each board was recorded for moisture content correction. Grain angle was measured by a laser scattering technique and the tracheid effect as described by Nyström (2003). After sawing, drying, and planing, a scan was performed on the sapwood side of each board. This measurement was done in the center of the board, roughly above the pith. The values represent the median grain angle for each board. X-ray scanning was done as planar X-ray in the longitudinal feeding direction on each board by a Microtec Golden Eye 706 strength-grading machine. The scanning speed was between 80 and 90 m/min.

The boards were scanned with a microwave sensor from Satimo working at 9.375 GHz in combination with a computer and a conveyor as described by Johansson (2001). The scanner shown in Fig. 1 functions as a line-scan camera with a resolution of 8 mm. For the present study, the boards were manually fed through the scanner with a speed of approximately 10 m/min. Each line in the resulting image represents average values from measurements covering a length of between 50 and 100 mm of the board. The sensor is based on electromagnetic transmission through the wood and modulated scattering technique, which is described by Bolomey and Gardiol (2001). The electromagnetic field was measured in two orthogonal polarization angles. From the measured variables, the amplitude and the phase shift of the signal were calculated. Differences in the sensors were minimized by subtracting a measurement without an object in the scanner. The measured variables can be reduced to three components that describe amplitude, phase shift, and polarization of the transmitted field. Finally, the modulus of rupture (MOR), the local and the global modulus of elasticity (MOE) in edgewise four-point loading were tested according to the European standard EN408 (2003). The test was performed on full-sized beams. It was recorded whether the most serious defects influencing strength were on the top or the bottom side of the board. A mean value for the annual ring width (ARW) was taken from a cross-section close to the point of failure.

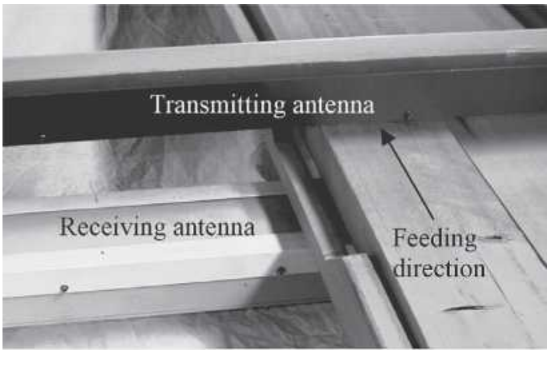

FIG. 1. Microwave scanner.

Multivariate modeling was done using Partial Least Squares (PLS) regression (Geladi and Kowalski 1986) and the software Simca P 10.0.2.0 (Anon. 2002) from Umetrics. The data were divided into a training set consisting of 80% of the observations, which the models were based upon, and a test set (the remaining 20%) to which the models were applied. Key figures used to evaluate the models are the goodness of fit (R^2) when the models were applied to training set and test set and the goodness of prediction (Q^2).

RESULTS

Three observations were removed from the data set prior to modeling due to scanning errors (first board in the microwave scanning sequence) and missing values. Average values and variation in some of the variables for the remaining observations are shown in Table 1. The correlation matrix in Table 2 shows that local MOE has a higher correlation with amplitude and phase from microwave measurements than with X-ray scanning.

Since the result from destructive bending is affected by local defects, there will be deviations from the correlation to average density, as can be seen in Figs. 2 and 3. This was the case both when the largest defect was turned down (circles) and when it was turned up (triangles).

Figure 4 shows how some of the remaining variables are correlated to MOR and MOE. A principal component analysis (PCA) was per-

TABLE 1. *Average values of wood properties.*

	Density [kg/m^3]	ARW [mm]	MOR [MPa]	Local MOE [MPa]	Global MOE [MPa]	MC [%]
Mean	452	2.1	47	11500	10800	11.9
Std. Dev.	31	0.6	11.7	1560	1965	0.3

TABLE 2. *Correlation matrix for the measured variables (R^2 values).*

	Amplitude	Phase	X-ray	ARW	GA	MOR	Local MOE
Amplitude	1.00						
Phase	0.81	1.00					
X-ray	0.79	0.86	1.00				
ARW	0.2	0.20	0.17	1.00			
GA	0.001	0.004	0.000	0.006	1.00		
MOR	0.32	0.26	0.17	0.41	0.08	1.00	
Local MOE	0.45	0.40	0.32	0.36	0.01	0.62	1.00

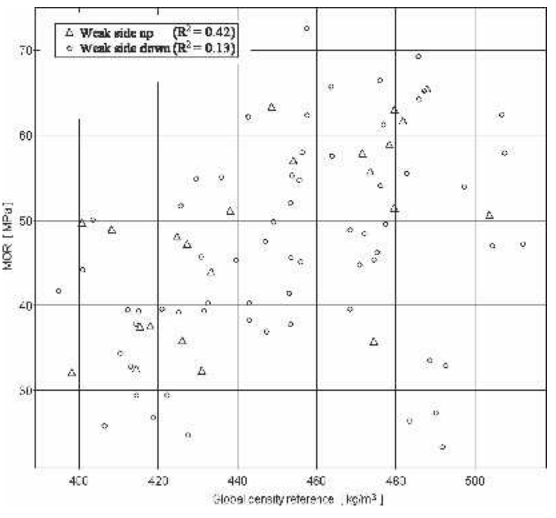

FIG. 2. Modulus of rupture (MOR) plotted against global density of the tested boards.

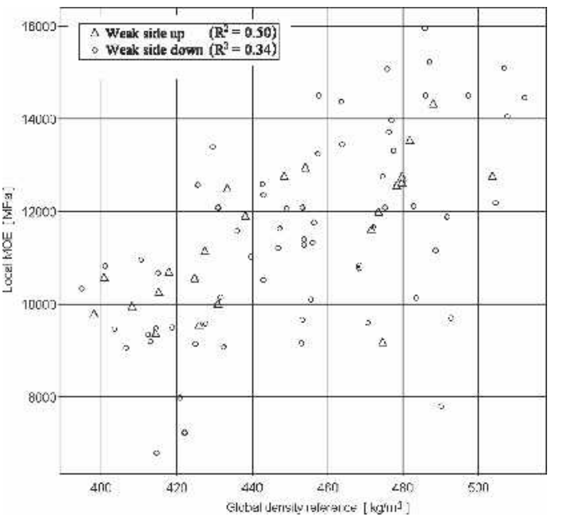

FIG. 3. Local modulus of elasticity (MOE) plotted against global density of the tested boards.

formed in order to find correlations. The result is shown in Fig. 5 where the horizontal component, P1, explains most of the variation with $R^2 = 0.64$ and $Q^2 = 0.56$. These values increase to $R^2 = 0.80$ and $Q^2 = 0.63$ when P1 is combined with P2. The vertical component, P2, indicates a correlation in grain angle, annual ring width, and MOR. However, Q^2 values are low, which means that this can not be generalized to other sets of data. The signal from the transmitting antenna was mainly polarized in one direction. Polarization was calculated as the relation between the signals in two orthogonal directions, but the amplitude in one of these directions was close to zero. Therefore, the measured signal in that direction consisted mainly of noise, and the polarization variable is strongly correlated to attenuation. No reliable model for prediction of grain angle from the microwave measurements could be established. Variations in moisture content were small, and hence the response, both in phase and in attenuation, was mainly governed by density.

The ability of different responses to predict dry density was compared, and the result is presented in Table 3. The microwave variable with the strongest correlation to density was phase. The different models for prediction of local modulus of elasticity are compared in Table 4.

DISCUSSION

As expected, a high correlation was found between X-rays and density. The correlation between density and MOE/MOR was lower for the boards where the weak side (largest defect) was turned down during the destructive bending.

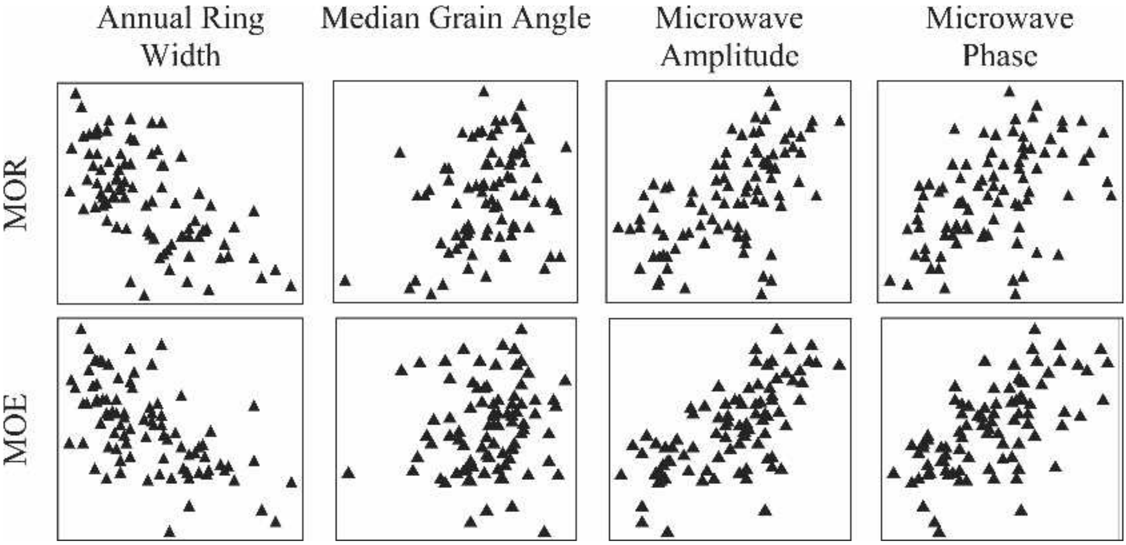

FIG. 4. Scatter plots for some of the variables in relation to modulus of rupture (MOR) and modulus of elasticity (MOE).

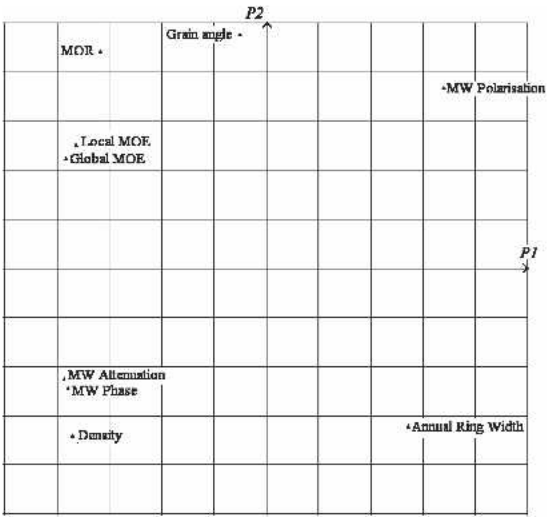

FIG. 5. Loading plot generated by Principal Component Analysis (PCA). The plot shows how microwave (MW) variables are correlated to other variables.

This was also expected, since the size and shape of defects on the tensile side affect the results more than defects on the compression side.

Some observations with high density but low elasticity were found in the training set used to calibrate the models. This could explain why better models for prediction of MOE were obtained from microwave scanning than from X-rays since properties other than average density are important. All models were improved when annual ring width was added as a variable. Annual ring width in combination with either microwaves or X-rays gave the best prediction when the models were applied to the test set. Microwaves in combination with annual ring width gave the highest correlation coefficients for the training set.

TABLE 3. *Density prediction using microwave (MW) response compared to X-rays in combination with grain angle and annual ring width.*

	Training set R^2 [%]	Training set Q^2 [%]	Test set R^2 [%]
X-ray	97.3	97.1	98.9
MW amplitude	84.0	83.7	70.1
MW phase	88.6	88.2	77.3

Some knots can be identified in the images obtained by microwave scanning, but if the aim is to find knots, a higher frequency should be used, since resolution in that case is more important than penetration depth.

CONCLUSIONS

The ability to predict elasticity from microwave scanning is mainly due to the correlation

TABLE 4. *Prediction of local modulus of elasticity (MOE) using microwave (MW) response compared to X-rays in combination with grain angle and annual ring width.*

	Training set R^2 [%]	Training set Q^2 [%]	Test set R^2 [%]
MW amplitude	42.5	40.7	55.2
MW phase	36.6	35.8	51.3
X-ray	29.3	27.2	49.5
GA	3.2	–2.6	—
ARW	33.4	30.6	55.4
Amplitude, ARW	54.2	52.0	64.7
Amplitude, GA	43.2	38.6	52.0
Amplitude, ARW, GA	54.5	51.9	62.4
Phase, ARW	50.2	47.9	64.7
Phase, GA	37.2	33.4	44.8
Phase, ARW, GA	50.3	47.9	60.9
X-ray, ARW	46.4	43.6	64.5
X-ray, GA	32	26.6	42.4
X-ray, GA, ARW	47.6	44.2	60.1

between density and elasticity, but there is more information related to strength and elasticity in the microwave signal than can be obtained from density alone. All models for prediction of elasticity were improved when information about annual ring width was added. The microwave sensor that was used in this study cannot measure variations in grain angle, but none of the models were improved when information about grain angle was added.

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