Stiffness, strength and shape stability grading analysis of sawn timber based on experimentally found growth characteristics

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ABSTRACT

Stiffness, strength and shape stability analysis of sawn timber should be based on how the material properties vary in the stem due to different growth conditions. As part of an EU study, results from investigations of the modulus of elasticity, shrinkage coefficient and spiral grain angle of spruce are presented. The variation in properties with the position in the stem has been investigated. The specimens were sawn from 274 stems in 29 stands in five countries of the European Union. A total of about 7000 small specimens were tested. Results from the modelling of stiffness and moisture-induced deformations of battens are presented. The simulations were based on material data obtained from measurements performed on specimens sawn from the same logs as the battens. The simulation results are compared with experimental results and are of interest for the development of new grading procedures for sawn timber.

INTRODUCTION

Sawn timber for structural use and other building purposes should satisfy quality requirements regarding strength, stiffness and shape stability. To improve the stiffness and strength grading process for sawn timber, and also considering grading with respect to shape stability, it is important to clarify how the material properties and the internal structure affect the stiffness, strength and shape stability of timber. Numerical simulations (see e.g. Ormarsson et al. 1998a, 1999a, 1999b, 1998b and Ormarsson 1999) have shown that variations in material properties and fibre direction in the log have a considerable influence on both the stiffness and the development of moisture-induced deformation. To quantitatively predict the development of deformations and stiffness properties, it is necessary to have detailed information on the variation in material properties and fibre direction. The distributions of material properties and fibre direction in spruce trees from different stands have been investigated in an EC project. On the basis of the data obtained, computer simulations have been performed in order to predict batten stiffness and moisture-induced deformation. The computational results have been compared with experimental results. In the present paper, some results are presented from the experiments and simulations performed.

EXPERIMENTAL INVESTIGATION OF MATERIAL PROPERTIES AND FIBRE DIRECTION

Material properties and fibre direction have been investigated in specimens from 274 trees from 29 stands. To gain knowledge on the variation of the properties with the position in a log, specimens from different distances from the pith and from different heights in the stem were investigated. The stands from which the trees were harvested are situated in five countries of the European Union, namely Sweden, France, Finland, the United Kingdom and Germany. The location of the stands and the number of trees studied are listed in Table 1. The identification codes used for the different stands are also given. Stand, tree and log properties have previously been presented by Björklund et al. (1998).

The longitudinal modulus of elasticity, E_l, was measured in 2349 specimens from 143 trees from stands 11-14, 21-28, 31-34 and 51-58 (Dahlblom et al. 1999a) using a tensile test. The specimens used had a length of 200 mm and a square cross-section of 12 by 12 mm. Typically, the longitudinal modulus of elasticity increases with the distance from the pith. There are significant differences between the modulus of elasticity in different trees and also between different stands.

The longitudinal shrinkage coefficient, α_l, was measured in 3517 specimens from 183 trees from stands 11-14, 31-34, 71-72 and 81-83 (Dahlblom et al. 1999b). To determine shrinkage properties, measurements were performed in two

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climates. Specimens of the same size as those described above were used. The specimens were stored at 20°C and 85% RH until moisture equilibrium was obtained, after which the length and weight were measured. The specimens were then conditioned at 20°C and 40% RH, after which the length and weight were once again measured. The longitudinal shrinkage coefficient, α_l , was determined as the strain developed during moisture change divided by the change in the moisture content. Typically, the longitudinal moisture shrinkage coefficient decreases with the distance from the pith.

The fibre structure of wood makes the material properties strongly direction dependent. The fibre direction often deviates from the longitudinal direction of a tree or a batten. This fibre deviation may be due to local effects around knots, but this type of local deviation was not of primary interest in this investigation, which was focussed on fibre misalignment such as spiral grain. The spiral grain angle was measured in 2942 specimens from 143 trees from stands 11-14, 21-28, 31-34, and 51-58 (Dahlblom et al. 1999c) using a slope-of-grain indicator. The specimens studied had a length of 200 mm and a rectangular cross-section of 12 by 12 mm or 12 by 22 mm. The spiral grain angle is usually to the left close to the pith and decreases towards the bark.

Examples of results from the measurements by Dahlblom et al. (1999a, 1999b, 1999c) for two stems from stand 13 are shown in Figs. 1 and 2. In the diagrams circles and solid lines refer to the easterly direction and crosses and dashed lines to the westerly direction from the pith. Results from measurements of all specimens studied in stands 13 and 14 are given in Figs. 3 to 5. The results in Fig. 3 illustrate the fact that the longitudinal modulus of elasticity usually increases with the distance from the pith, and that the distribution varies between different trees. The longitudinal modulus of elasticity is in general significantly greater in stand 13 than in stand 14. It can also be observed that the longitudinal shrinkage coefficient is, in general greater in stand 14 than in stand 13. The spiral grain angle in stand 13 typically decreases with the distance from the pith, whereas in stand 14 it is more or less constant with respect to the distance from the pith.

Table 1. Identification codes and location of stands. Number of stems examined.

Stand	Country	Altitude	Latitude	Longitude	Number of stems
11	Sweden	220 m	61°N	14°E	14
12	Sweden	225 m	57°N	15°E	15
13	Sweden	180 m	57°N	15°E	23
14	Sweden	170 m	57°N	13°E	14
21	Sweden	95 m	57°N	13°E	6
22	Sweden	120 m	58°N	16°E	6
23	Sweden	310 m	63°N	14°E	6
24	Sweden	310 m	63°N	14°E	6
25	Sweden	310 m	63°N	14°E	6
26	Sweden	270 m	64°N	14°E	6
27	Sweden	270 m	64°N	14°E	6
28	Sweden	270 m	64°N	14°E	6
31	France	750 m	48°N	7°E	12
32	France	605 m	48°N	7°E	12
33	France	625 m	48°N	7°E	12
34	France	860 m	48°N	7°E	12
51	Finland	140 m	61°N	25°E	6
52	Finland	170 m	63°N	24°E	6
53	Finland	170 m	63°N	24°E	6
54	Finland	135 m	61°N	25°E	6
55	Finland	45 m	61°N	22°E	5
56	Finland	45 m	61°N	22°E	6
57	Finland	64 m	61°N	27°E	5
58	Finland	65 m	61°N	27°E	6
71	U.K.	450 m	51°N	4°W	16
72	U.K.	450 m	51°N	4°W	8
81	Germany	460 m	51°N	9°E	15
82	Germany	670 m	51°N	9°E	13
83	Germany	400 m	51°N	9°E	14

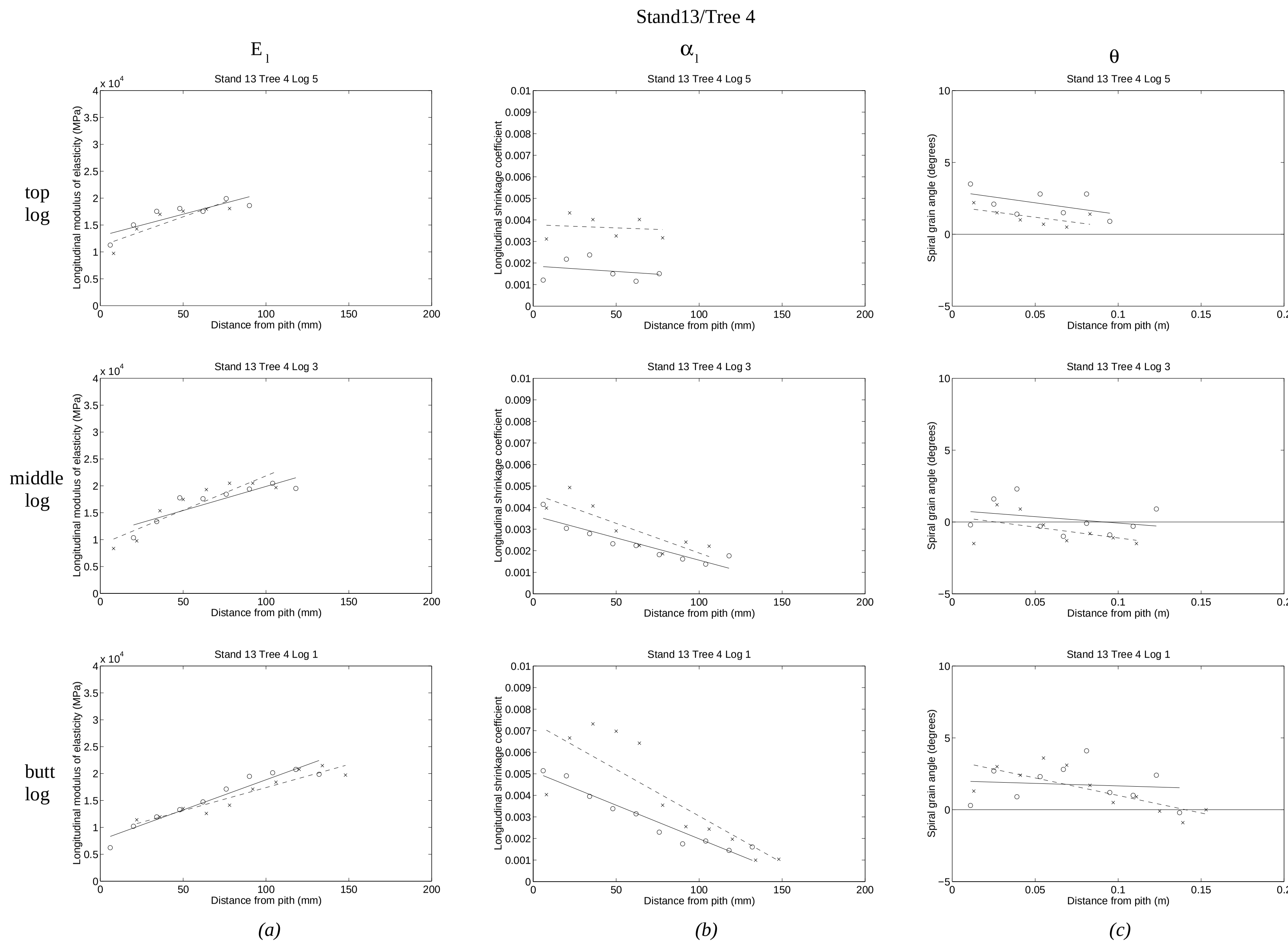

Figure 1. Influence of height and distance from pith for Tree 4 in Stand 13
(a) Longitudinal modulus of elasticity E_l
(b) Longitudinal shrinkage coefficient α_l
(c) Spiral grain angle θ

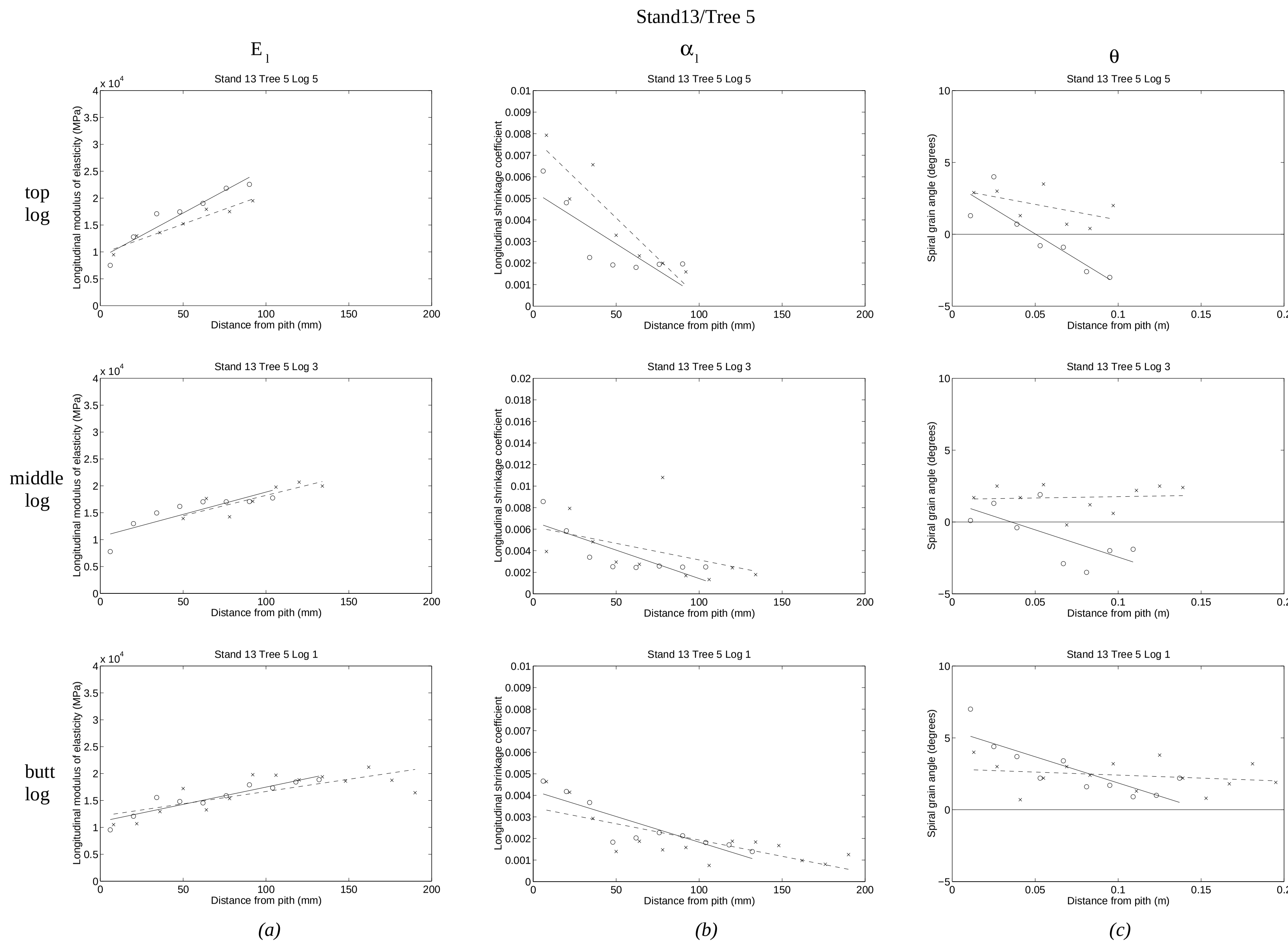

Figure 2. Influence of height and distance from pith for Tree 5 in Stand 13
(a) Longitudinal modulus of elasticity E_l
(b) Longitudinal shrinkage coefficient α_l
(c) Spiral grain angle θ

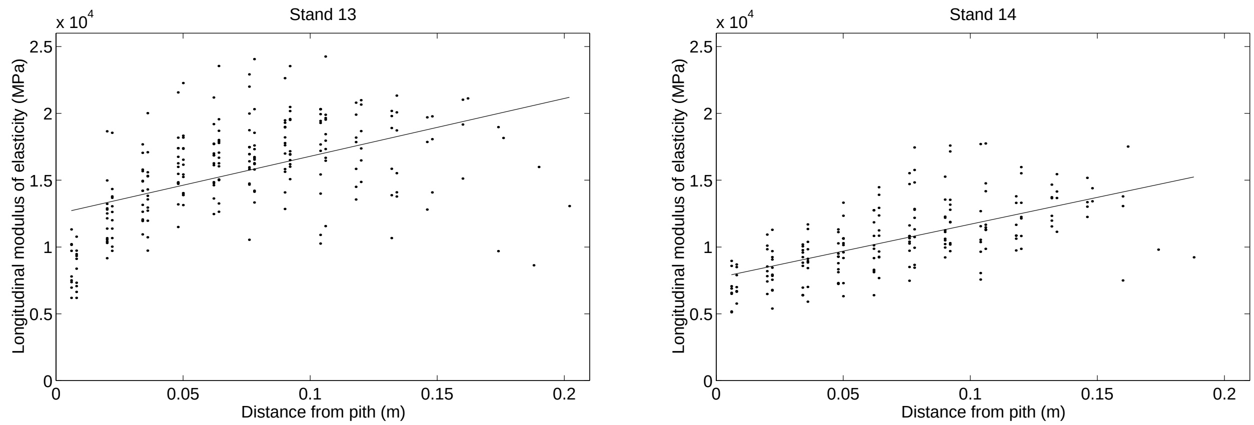

Figure 3. Longitudinal modulus of elasticity; all observations in stand 13 (left) and stand 14 (right).

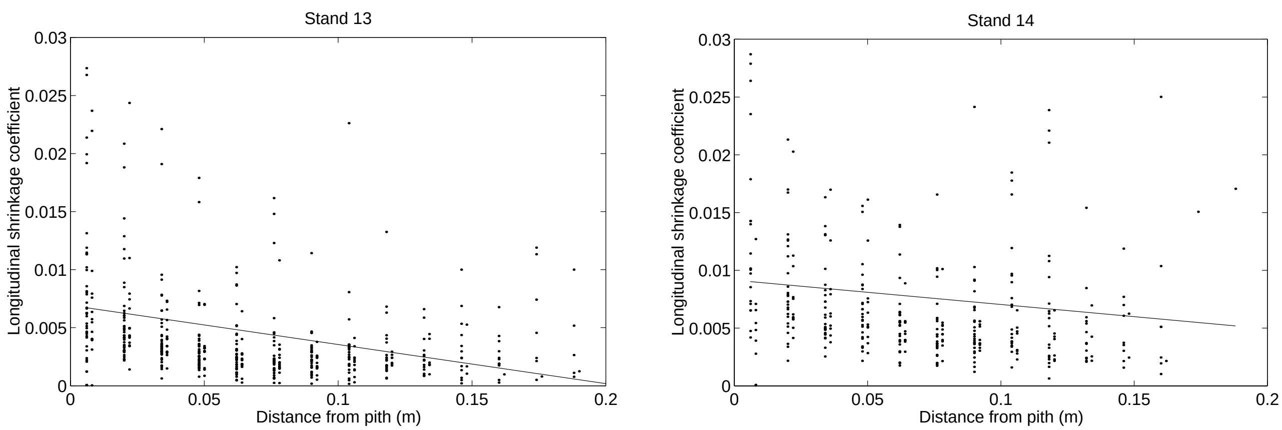

Figure 4. Longitudinal shrinkage coefficient; all observations in stand 13 (left) and stand 14 (right).

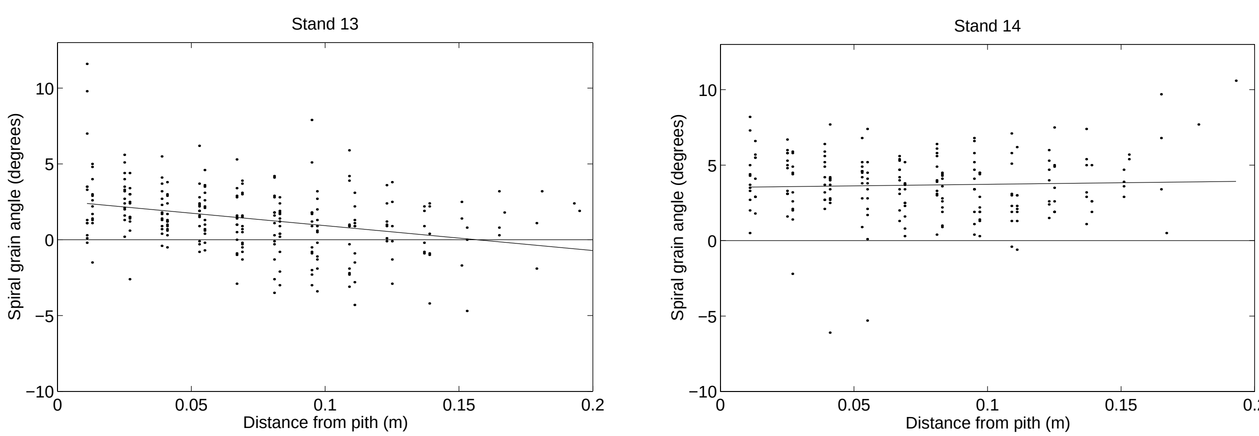

Figure 5. Spiral grain angle; all observations in stand 13 (left) and stand 14 (right).

SIMULATION OF MOISTURE-INDUCED DEFORMATION

The finite element method was used for the prediction of moisture-induced distortion. The deformation during moisture changes has been simulated in about 700 battens from trees from stands 11-14, 31-34, 71-72 and 81-83. Theoretical simulation of the deformation process during moisture changes in wood requires a suitable material model. The direction dependence of the material must be taken into account. The internal structure of wood allows it to be defined locally as an orthotropic material. The fact that the material directions vary with position, due to annual rings and spiral grain, must also be considered. The computational procedure will not be further described here; for a more detailed description, see e.g. Ormarsson et al. (1999a). The computations were performed using a commercial computer code (Hibbitt et al. 1998). Due to the complex properties of wood, the standard version of this program is not suitable for the simulation of this material. The program has therefore been supplemented with code taking into account the characteristics of this material. In the present work, input data for each batten were based on experimental results obtained in the investigations of the longitudinal shrinkage coefficient described above (Dahlblom et al. 1999c), and on results from investigations of the longitudinal modulus of elasticity (Seeling et al. 1999) and spiral grain angle (Moore and Maun 1999). For each log, quadratic relations with the distance from the pith were established. For material properties not examined for the logs used in the present project, values from the literature or from previous investigations were used. In addition to data describing the material properties and fibre direction in logs, data describing the batten geometry are necessary. The parameters specified are the batten dimensions in the x, y and z directions (L_x, L_y, L_z) and pith position in the butt end and top end (y_1, z_1, y_2, z_2). For most battens these parameters were measured in connection with the experimental investigations on distortion (Kliger et al. 1999). The values of L_x, L_y and L_z were about 2.500 m, 0.095 m and 0.045 m, respectively. The battens simulated were sawn from different positions in the logs, yielding different pith positions for different battens. For most battens simulated, the moisture content was assumed to decrease from 18% to 10%. The finite element mesh used in the computations consisted of 40 by 12 by 6 elements. No external loading was applied and degrees of freedom were prescribed to avoid rigid body motion only. The deformation of the battens simulated was also examined experimentally (Kliger et al. 1999). The deformation was expressed as the commonly used quantities twist, bow and spring. The twist values from simulations and experiments for two stands are presented in Fig. 6. The diagrams present the theoretical values on the horizontal axis and the experimental results on the vertical axis. The correlation between experiment and simulation is fairly good. It can be observed that the twist is larger in stand 14 than in stand 13. For a more detailed presentation of the simulation results, see Dahlblom et al. (1999d).

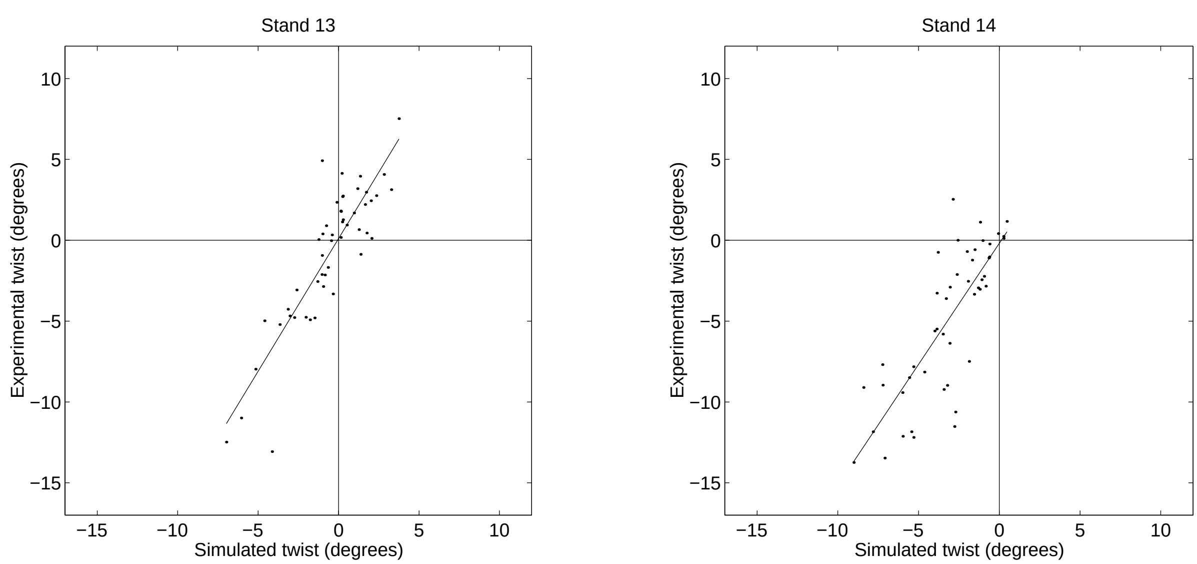

Figure 6. Predicted and experimental twist for battens from stands 13 (left) and 14 (right).

SIMULATION OF THE STIFFNESS OF BATTENS

The stiffness of about 500 battens was simulated. As for the simulation of moisture-induced deformation the finite element method was used. The main difference was that the moisture was constant and the batten was exposed to an external load. The longitudinal modulus of elasticity and the spiral grain angle can be described by quadratic relations with the distance from pith. These relations were established on the basis of the experimental data described above, and are presented in detail by Dahlblom et al. (1999a and 1999c). In addition to material descriptions, the geometry must also be described. The geometry is specified by the batten dimensions in the *x*, *y* and *z* directions (L_x, L_y, L_z) and the pith position in the butt end and top end (y_1, z_1, y_2, z_2). Since the pith positions were not determined in these measurements, they were estimated from the sawing pattern used, assuming no deviation. The finite element mesh used in the computations consisted of 152 by 20 by 10 elements.

For the battens simulated, the length L_x is related to the height of the batten cross section L_z by L_x =19 L_z. The battens have different cross sections: 45 x 70 mm, 45 x 95 mm, 45 x 120 mm, 45 x 145 mm, 58 x 145 mm, 45 x 170 mm, 45 x 195 mm, 58 x 195 mm, 70 x 195 mm, 45 x 220 mm and 70 x 220 mm. The simulations were performed assuming supports at the positions 0.5 L_z from the batten ends. The distance between the supports is thus 18 L_z. Two point loads of the same magnitude were applied at a distance 6 L_z from the supports.

It is common practice in the evaluation of bending tests to determine some kind of average value of the elastic modulus on the basis of elementary beam theory. The value obtained may be regarded as an effective value of the modulus of elasticity. The simulation results were evaluated in the same manner.

The simulation results are presented in Dahlblom et al. (1999e). Examples of results are shown in Fig. 7, where results from simulations and experiments (Kliger and Johansson 1999) performed on battens from stands 13 and 14 are compared. The diagrams present the theoretical values on the horizontal axis and the experimental results on the vertical axis. In general, the correlation is good. In the present project the material parameters were determined at one level for each of the logs from which the battens were sawn. At each level, the variation in parameters was determined in one radial direction only. The assumption of the same variation with distance from the pith in all directions, and the assumption that the material parameters are constant with respect to longitudinal position in a log, affect the values of the simulated effective modulus of elasticity. The presence of compression wood may lead to longitudinal and tangential variation in the modulus of elasticity, which also affects the effective modulus of elasticity. These types of variation were not considered in the present simulations.

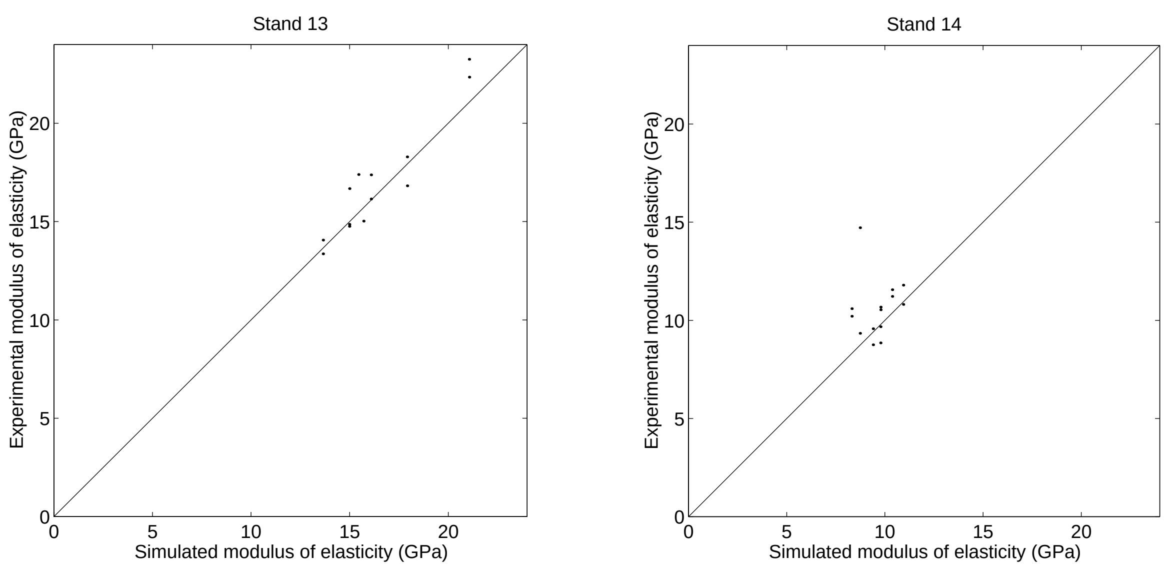

Figure 7. Predicted and experimentally obtained effective modulus of elasticity for battens from stands 13 (left) and 14 (right).

CONCLUSIONS

Some results from an investigation of basic properties of spruce have been presented. The properties examined were longitudinal modulus of elasticity, longitudinal shrinkage coefficient and spiral grain method angle. The specimens were sawn at different distances from the pith and at different heights in the stem. According to the measurements of longitudinal modulus of elasticity, the variation in radial direction is considerable. The modulus of elasticity has been observed to increase with the distance from the pith. The measurements of longitudinal shrinkage showed that this property, in general, decreases with the distance from the pith. The spiral grain angle was observed to be to the left close to the pith and decrease towards the bark. A considerable variation in the properties between different trees from one stand and between trees from different stands has also been observed. The possibility of performing numerical predictions of moisture-induced distortion and stiffness properties of sawn timber has been illustrated. To obtain relevant results it is necessary to have detailed information on material properties such as the modulus of elasticity, the shrinkage coefficient and the spiral grain angle. It is also important to have information on the pith location. Relations between material properties, fibre direction and geometrical data, and the distortion, stiffness and strength properties of battens can be used in the grading process of timber. Battens may be sorted into different quality classes depending on the predicted properties. The results obtained clearly indicate the potential of the grading analysis of sawn timber, based on measured growth characteristics.

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