MOISTURE-RELATED DISTORTION OF TIMBER BOARDS OF RADIATA PINE: COMPARISON WITH NORWAY SPRUCE

Sigurdur Ormarsson

Assistant Professor
Department of Structural Engineering and Mechanics
Computational Mechanics
Chalmers University of Technology
SE-412 96, Göteborg, Sweden

and

Dave Cown

Senior Scientist
Wood Quality and Solid Wood Products
Forest Research
Sala Street, Private Bag 3020
Rotorua, New Zealand

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ABSTRACT

Based on material data obtained by several researchers at Forest Research in New Zealand, with respect to variations in the main material properties from pith to bark, the distortion model developed earlier for Norway spruce has been further modified for radiata pine. Numerical simulations were performed for both pine and spruce to investigate how different sawn pattern options affect the shape stability of individual boards. Results for spruce presented earlier have shown clearly that warping of the timber products is strongly influenced by the annual ring patterns within the individual boards. Comparisons between the two species were performed to study how the radial variations in the basic properties such as shrinkage parameters, stiffness parameters, and spiral grain have influence on the warping. Generally, the intrinsic patterns of variation in wood properties within stems were similar, and both species show a tendency to distort with changing moisture environment. There are strong indications that intelligent re-combination of material in glued products may overcome many of the inherent problems in using biological material with predictable variation in material properties.

Keywords: Finite element simulations, *Pinus radiata,* shrinkage, spiral grain, distortions, wood, timber boards.

INTRODUCTION

Wood is a complex and moisture-sensitive material that can lead to problems in processing and in use because of changes in environmental conditions. The shrinkage and warping of boards that occur during drying or in final service are serious problems for end users. Increasingly, customers are demanding much higher quality regarding shape stability of wooden products. Ideally, lumber needs to maintain its dimensions from the time of production, through delivery, to the time it is exposed to natural environmental moisture variations in the final use situation. To solve the problems of warping, it is important to determine the underlying causes and learn how the phenomenon can be reduced.

Because of the significant inhomogeneity in both material properties and fiber orientation (e.g. spiral grain) of the wood material, analyses of distortion require the use of three-dimensional simulation models, incorporating complex spatial material formulation for wood (Ormarsson 1999; Ormarsson et al. 1998). Figure 1 shows the principal elements involved in simulating distortions in timber boards exposed to environmental loading. The distortion model consists of two parts, one for analyzing transient moisture flow and one for analyzing moisture-related deformations and stresses. For both stages, the wood material is defined as being a strongly orthotropic material, where the three material directions (*l, r,* and *t*) designate the longitudinal, radial, and tangential direction of the wood fibers in relation to the tree stem. The orientation of the wood fibers is known to have strong spatial variation because of the annual rings and the variation in spiral grain from pith to bark. The moisture model is based on information obtained from three input sources: the drying schedule (wet and dry bulb temperature of the surrounding air), diffusion properties in the material directions, and the orientation of the wood fibers with respect to the product. The output from the model is a full moisture content history, which is used as an input to the deformation model. To perform accurate deformation simulations, a good material model is needed. The constitutive model used is a generalization of the models presented by Ranta-Maunus (1990) and Salin (1992) consisting of elastic, moisture-induced and mechano-sorptive strain. The influence of moisture and temperature on the material parameters is taken into account as well as their radial inhomogeneity from pith to bark. Sufficient knowledge of variation in material properties and spiral grain can normally be obtained experimentally from small specimens (Dahlblom et al. 2000c; Cown et al. 1991). The constitutive model and the transformation algorithm have been implemented into the commercial finite element software ABAQUS (Hibbitt et al. 2003). More detailed descriptions of the FE-formulations for transient flow and solid mechanics are given by e.g. Zienkiewicz and Taylor (2000), Ottosen and Petersson (1992). Figure 1 shows typical deformations of timber boards obtained by simulations where the deformations have been magnified five times.

It has been shown experimentally for Norway spruce (*Picea abies, L. Karst*) that twist deformations in boards are highly dependent on their original location in the log, (Perstorper 1994; Johansson 2002). According to Ormarsson et al. (2000), the twist was highly influenced by the annual ring curvature, whereas it was not so sensitive for how the ring-pattern is oriented within the cross-section. On the other hand, both these parameters had a significant influence on the bow and cup deformations. The current study set out to investigate radiata pine (*Pinus radiata, D. Don*) in a similar fashion.

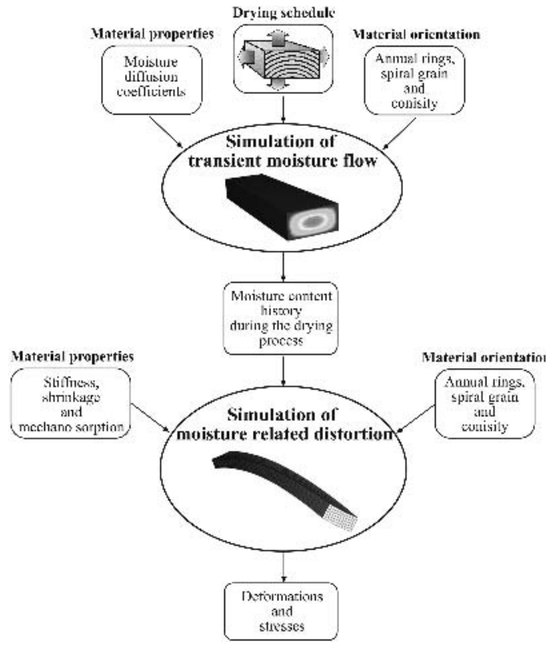

FIG. 1. The principal components of computer simulations of distortion in timber boards.

MATERIALS AND METHODS

Data source

Wood samples of radiata pine were obtained from a clonal trial, established in 1968 and thinned to a final stocking of 350 spha at age 13 yrs. In 1995 (age 27 yrs), 10 clones were selected to represent a range in wood density. Two members of each of the 10 clones were felled in 1996 and discs (50 mm thick) obtained from the base of the stem and the top of subsequent 5-m log lengths to a top diameter of approximately 200 mm. The discs were processed to yield samples for spiral grain, shrinkage, and samples for Silviscan-2 analyses (wood density and microfibril angle). Figure 2 shows the sampling strategy, yielding disc samples for material properties and sawlogs for recovery of dimension lumber.

Spiral grain.—Diametrically opposed strips were assessed for average spiral grain for every alternate ring from pith to bark at all heights according to the method of Young et al. (1991). The positive definition of the spiral grain angle is when the fiber slope is upwards to the left of the stem axis.

Shrinkage.—Shrinkage values were determined (transverse and longitudinal) by 5-ring sections from the pith at all stem heights, Cown (1999). The shrinkage data were then used to derive shrinkage coefficients for the material directions.

Silviscan-2.—Sample radii were selected from each disc to avoid compression wood and processed to yield values for wood density and microfibril angle (Evans et al. 2000). All radial strips were resin-extracted in acetone and precision-machined to a tangential thickness of 2.0 mm. The radial strips were conditioned at 20°C and 40% RH (7% moisture content) before Silviscan-2 analyses, with a radial resolution of 0.2 mm. Ring width, wood density, and average microfibril angle data were collected and summarized in annual ring increments to give pith to bark trends.

Modeling

Material properties of radiata pine were summarized by individual stems and clones according to distance from the pith at the various height levels Cown et al. (2002a). For the purposes of this study, the data for all height classes were combined. Radial inhomogeneity of the wood properties is in most cases presented as a function of the number of the annual rings from the pith i.e. a biological basis. To be able to use such

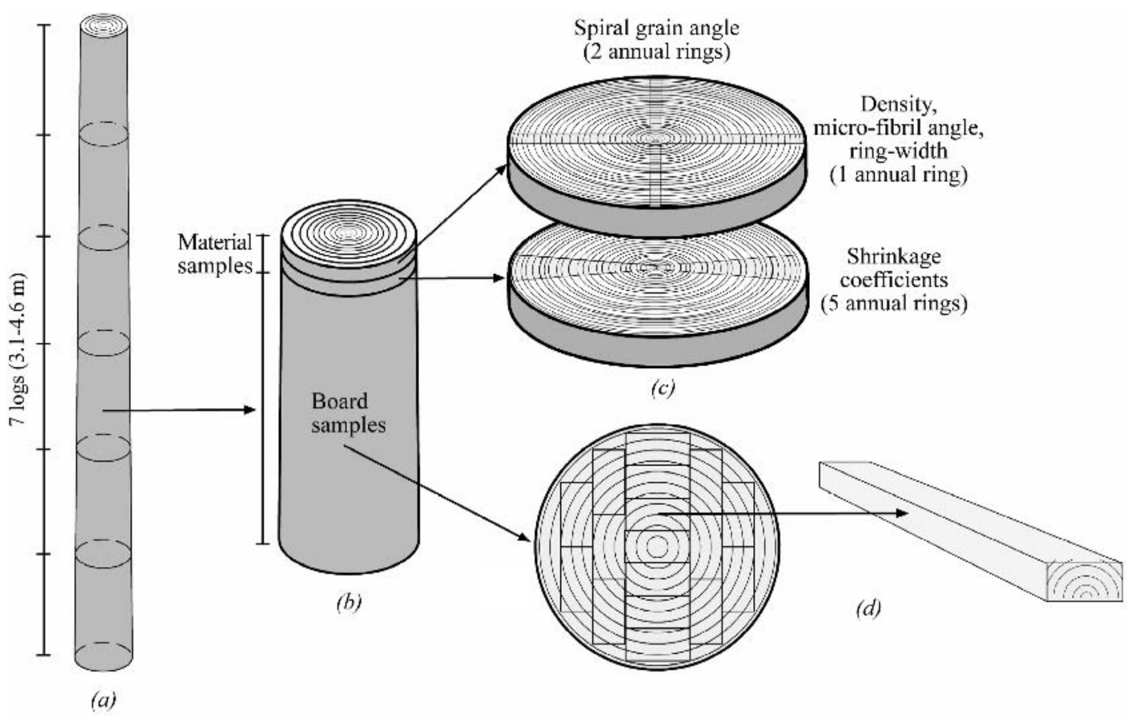

FIG. 2. Illustration of the experimental procedure, (*a*) Cutting pattern for experimental stems (20 trees); (*b*) Collection sample discs from logs for material properties; (*c*) Cutting of discs for the material samples; (*d*) Saw pattern to produce individual boards.

data as input sources for numerical simulations, the data have to be converted to spatial variation – distance from the pith. The data thus obtained enabled shear properties distribution to be calculated based on the relationships between wood density, microfibril angle, and shear moduli, outlined in Astley et al. (1997). The relationships are based on a micro-mechanical model developed by Harrington (2002) for fiber structure in wood. Based on this type of material data, computer analyses have been performed for radiata pine and Norway spruce using a full three-dimensional simulation model. To get valuable variation in board positions, four different sawing patterns have been studied, representing alternative options.

EXPERIMENTAL RESULTS OF RADIATA PINE

Growth rate and density

For the trees studied, Fig. 3*(a)* shows relationship between annual ring-numbers and their distances from the pith. Growth rate differences between stems remain fairly small for the first 5 yrs or so, after which the cumulative differences increase. By the time of sampling—after 27 yrs—the largest stems were approximately twice the size of the smallest individuals. For every individual these results have been used to create the radial spatial variation for the material properties. Figure 3*(b)* shows the overall pattern of wood density according to distance from the pith, averaged over all heights. The density increases up to ca 0.15 m radius, but the trend (slight decrease in outer rings) is somewhat different from that observed when height in the stem and ring number are used as separate criteria. In the latter case, wood density levels off in the mature wood and tends to remain constant with ring number and with distance from the pith within individual stems, as previously noted (Cown 1999; Cown and Ball 2001; Cown et al. 2002a). The three curves shown in Fig. 3*(b)* and in the following figures are used, in the simulations, to describe the radial variation in the material data. The superscripts *l*, *m* and *u* refer to lower, average, and upper limits curves for the used material data.

Microfibril angle and spiral grain

The microfibril data shown in Fig. 4*(a)* confirmed the general pattern, commonly seen in softwoods, of a rapid decrease in average microfibril angle in the juvenile wood (Megraw et al. 1999; Donaldson 1998). By combining all heights in this analysis, the higher values commonly recorded in the inner rings at the base of

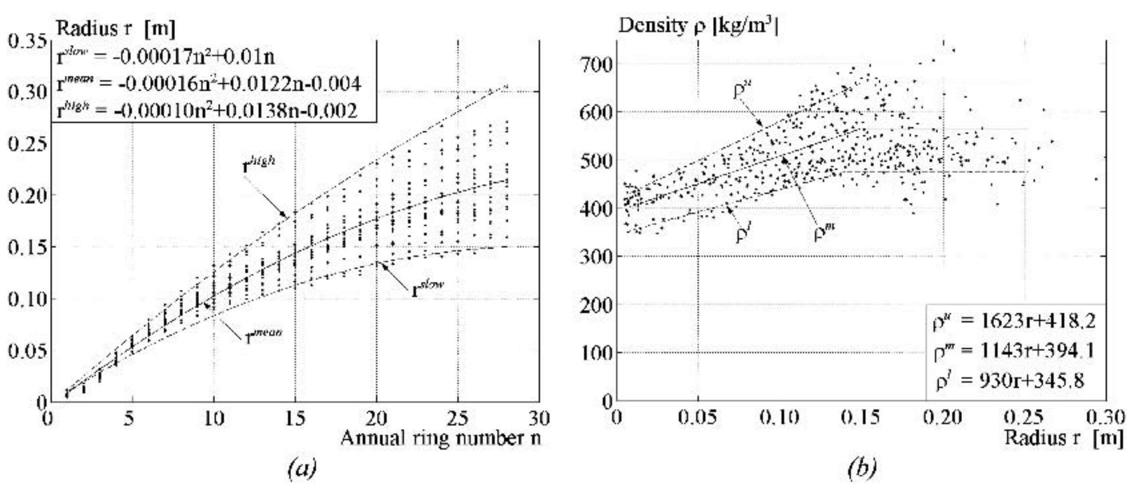

FIG. 3. (*a*) Relationship between distance from pith and annual ring-numbers (20 trees); (*b*) Radial variation in wood density.

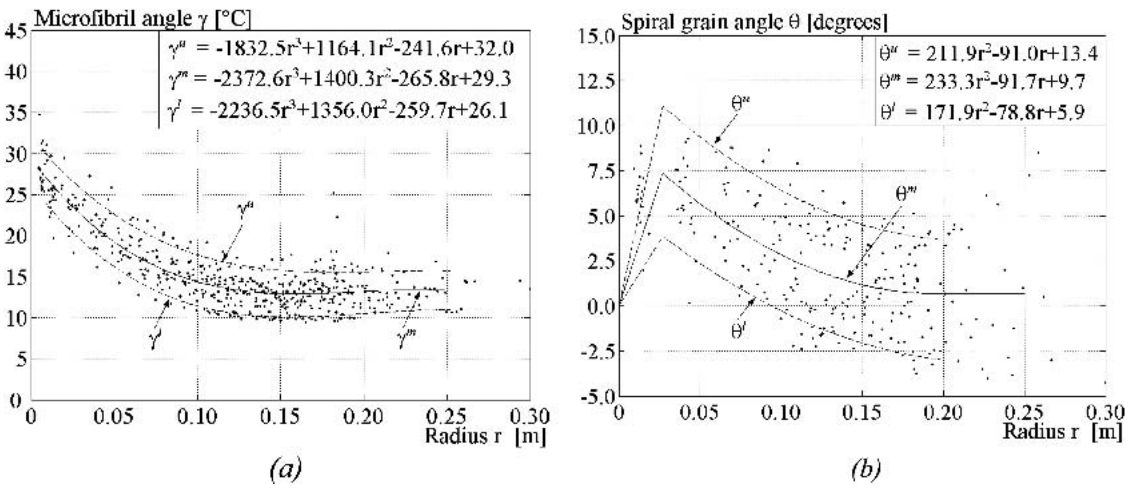

FIG. 4. (*a*) Radial variation in microfibril angle; (*b*) Radial variation in spiral grain angle.

the stem (Cown et al. 2002b) are masked. The overall spiral grain trends illustrated in Fig. 4*(b)* show high spread in the data set, and the maximum value is close to the pith followed by a rapid decrease in the radial direction. These results correspond to the published values in other studies (e.g. Cown et al. 1991; Tian et al. 1996).

Shrinkage parameters

The shrinkage patterns shown in Fig. 5 correspond closely to the data previously published for radiata pine (Cown 1999). The shrinkage coefficient in the longitudinal fiber direction decreases with distance from pith, whereas the coefficients in the transversal directions increase. Note that the spread in the data is largest for the longitudinal material direction. Once again, by averaging the various heights, within-stem patterns (particularly for longitudinal shrinkage) are masked. Based on the mean curves, the ratio between the longitudinal and the tangential shrinkage coefficients varies from 10–30, whereas the ratio between the radial and tangential directions is approximately constant 2.

Stiffness parameters

The stiffness parameters shown in Fig. 6 all correspond to the overall density pattern – i.e. a rapid increase in the juvenile wood rings, followed by a zone of constant values in the mature wood. The ratios between the different moduli are a relatively constant 10 for the longitudinal/radial ratio and close to 3 for the radial/tangential ratio.

Shear parameters (estimated with a micro-mechanical simulation model)

In the present study, the wood density and the microfibril data shown in Figs. 3*(b)* and 4*(a)* have been used as input data for calculating the shear pattern shown in Fig 7. The radial variation for the shear module G_{lr} and G_{lt} is relatively constant, whereas the variation for G_{rt} follows the overall density pattern as observed for the elastic moduli. The ratio G_{lr}/G_{rt} varies from about 30 down to 15, whereas the ratio is approximately 1.5 for the other shear moduli G_{lr} and G_{lt}. The subscripts *lr*, *lt*, and *rt* refer to planes spanned by the longitudinal, tangential, and radial material directions.

Material data (pine and spruce)

The radial variation in material data used in the simulations for radiata pine is based on the average curves (all heights) expressed in Figs. 3–7. Close to the pith ($r < 0.027$ m), the spiral

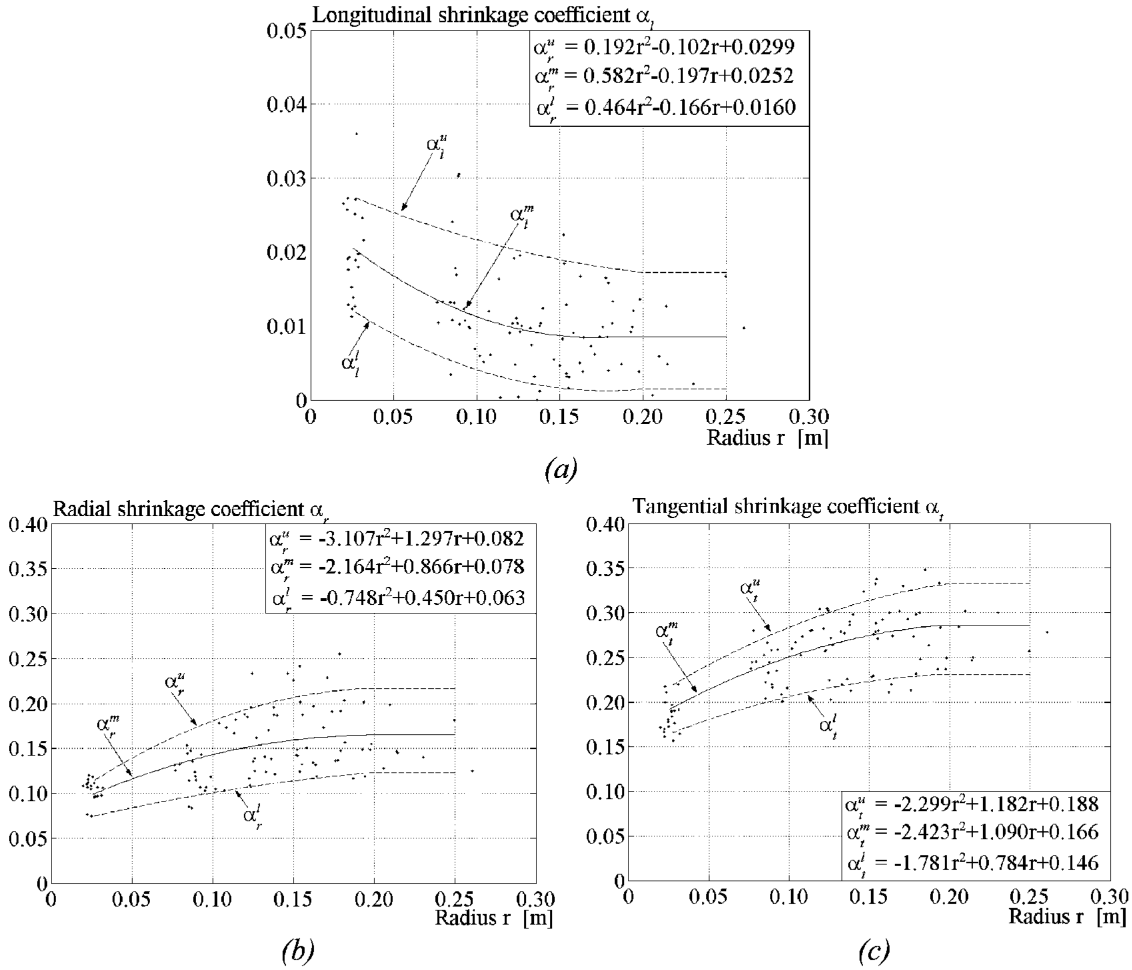

FIG. 5. Relationship between shrinkage parameters and distance from pith, (*a*) Longitudinal shrinkage coefficient; (*b*) Radial shrinkage coefficient; (*c*) Tangential shrinkage coefficient.

grain increases linearly as $\theta = 271.59r$ until it becomes the average function expressed in Fig. 4*(b)*. For $r > 0.18$ m the spiral grain angle is equal to the function value at $r = 0.18$ m. The shrinkage parameters α_l, α_r, and α_t are also set to constant values for larger distances than 0.15, 0.18 respective 0.20 m from the pith. Additionally, the stiffness parameters, shown in Figs. 6 and 7, are set to constant values for distances larger than 0.15 m. For moisture diffusion, mechano-sorption, and Poisson's ratio, the same material parameters were used for radiata pine as for Norway spruce, (see Table 1).

It has been observed experimentally for Norway spruce that wood density, microfibril angle, elasticity properties, shrinkage coefficients, and spiral grain angle vary more or less predictably from pith to bark, see e.g. (Persson 2000; Dahlblom et al. 2000a-c). The material data used here for spruce, (see Table 1), are based mainly on these experimental results and on relationships between material properties created with the micro-mechanical model developed by Persson (2000). The average spiral grain function is $\theta = -40r + 4$ for $r < 0.125$ m and constant $\theta = -1°$ for larger r-values. For $r > 0.10$ m, the stiffness parameters and the shrinkage coefficients shown in Table 1 are set to respective function values at

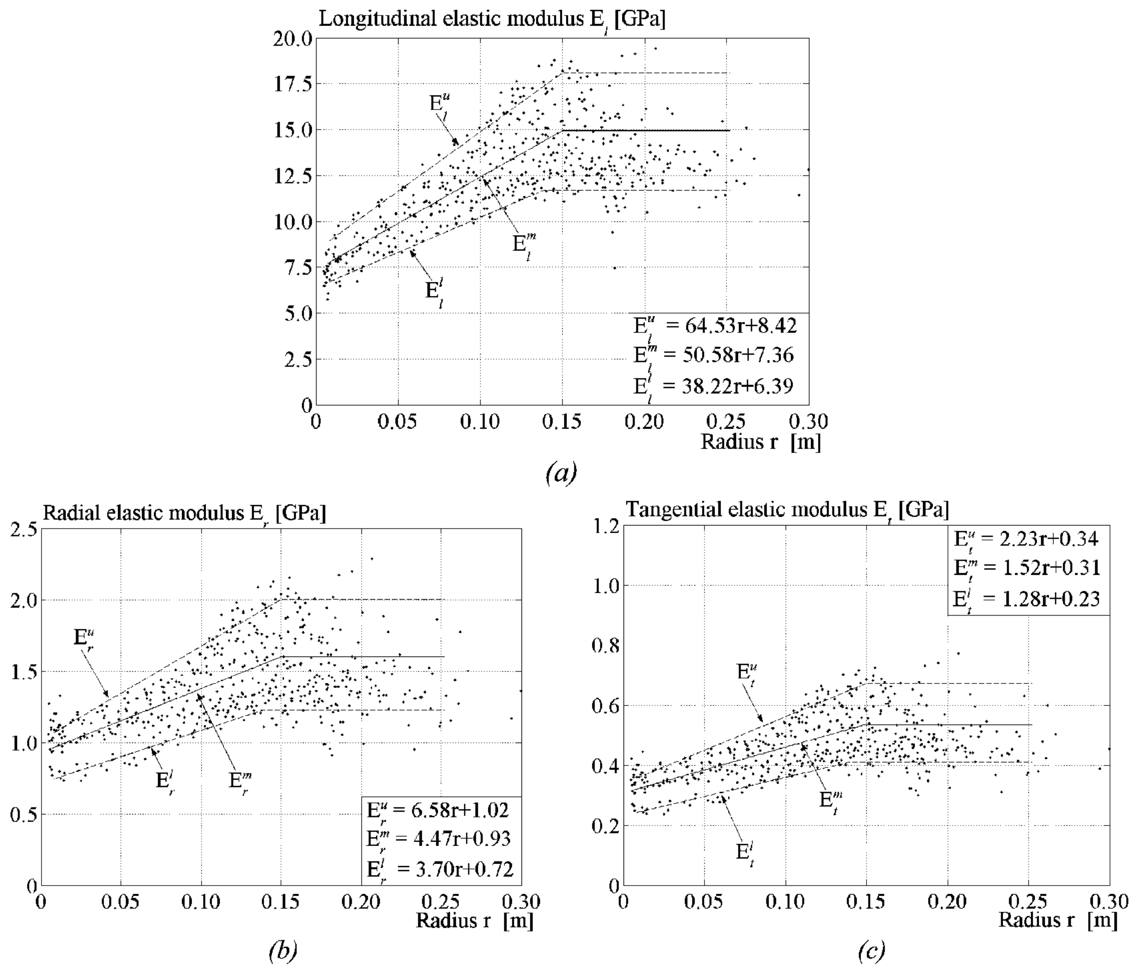

FIG. 6. Variation in elastic moduli from pith to bark, (*a*) Longitudinal elastic modulus; (*b*) Radial elastic modulus; (*c*) Tangential elastic modulus.

r = 0.10 m. The remaining parameters used here for spruce are based primarily on experimental data from Siimes 1967; Santaoja et al. 1991; and Hisada 1986 obtained for a constant temperature of 20°C. The diffusion data are based on data in Rosenkilde and Arfvidsson (1997).

MOISTURE RELATED DISTORTION IN TIMBER BOARDS

Based on the material data presented for spruce and pine, three-dimensional finite element simulations have been performed to study how moisture-related distortions of studs are influenced by their individual annual ring patterns. All the boards were dried from their fiber saturation point 27% MC down to approximately 10% mean MC.

Sawn pattern (pine and spruce)

Figure 8 shows the four saw patterns investigated, board dimensions, and the displacement degrees of freedom for calculating the twist, bow, crook, and cup deformations. Boards A1-A8 represent the center-board and all the flatsawn boards located with different radial offsets

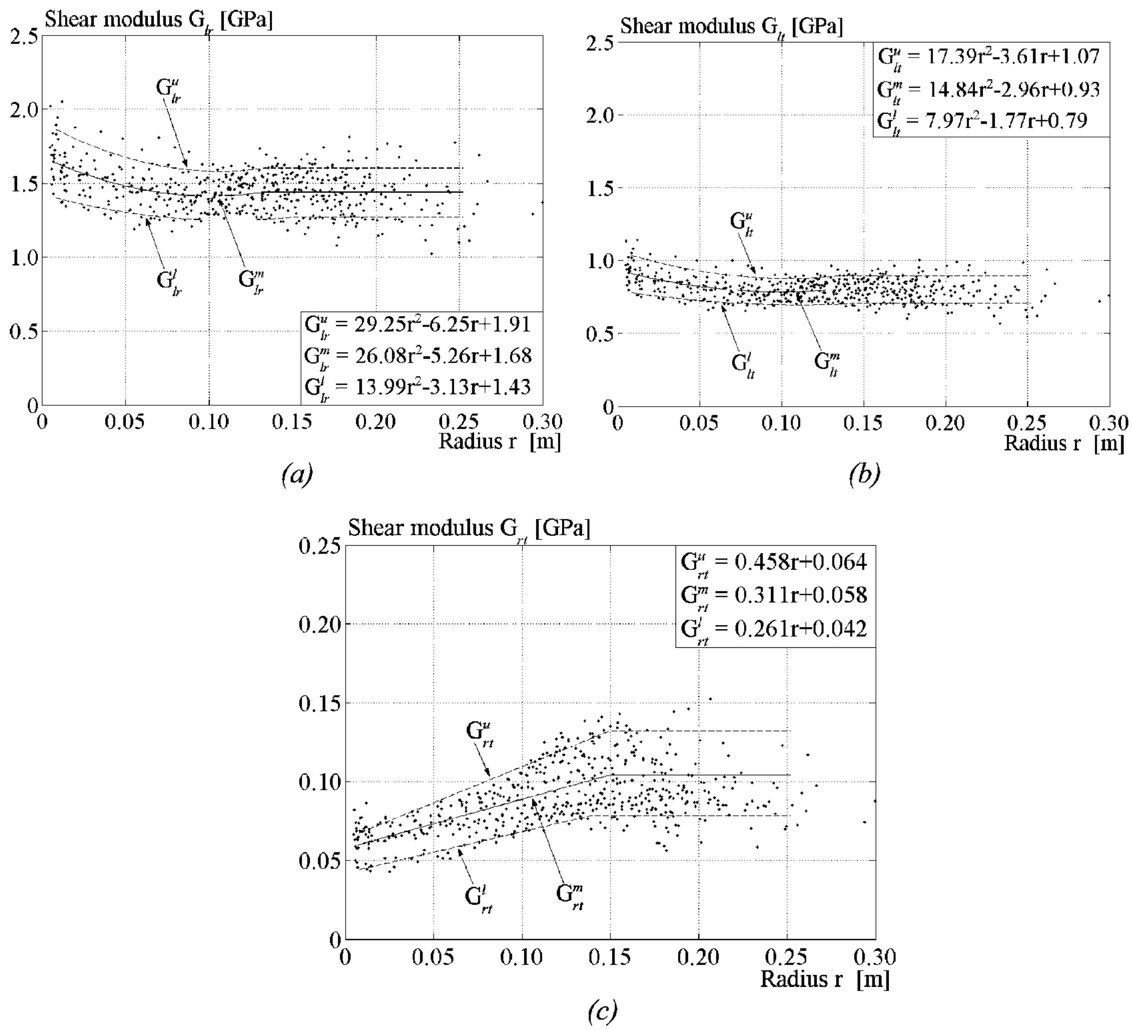

FIG. 7. Variation in shear moduli from pith to bark (*a*) Longitudinal/radial shear modulus; (*b*) Longitudinal/tangential shear modulus; (*c*) Radial/tangential shear modulus.

from the pith. Boards B1-B8 are all the boards with their one edge-side located parallel with a line through the center of the log. Boards C1 and C2 are the boards that do not fulfill the criteria for either A or B. Note that boards with higher numbers are located farther from the pith. Equations (1–4) have been used to calculate the four distortion modes: twist, bow, crook and cup. The signs of the twist deformation follow the definition of positive rotation around a longitudinal axis through the center of the board. Positive definition for bow, crook, and cup is when the average value for the two end-displacements becomes larger than the respective center-displacement of the board.

$$\text{Twist} = (\arctan((u_7 - u_9)/b) - \arctan((u_1 - u_3)/b)) \text{ (b is the width of the board)} \quad (1)$$

$$\text{Bow} = (u_2 + u_8)/2 - u_5 \quad (2)$$

$$\text{Crook} = (u_4 + u_{10})/2 - u_6 \quad (3)$$

$$\text{Cup} = (u_1 + u_3)/2 - u_2 \quad (4)$$

TABLE 1. *Material parameters used in the simulations for Norway spruce* (r = *radius in m).*

Moisture diffusivity [m^2/s]:		
$D_l = 28 \times 10^{-10}$	$D_r = 7 \times 10^{-10}$	$D_t = 7 \times 10^{-10}$
Elastic moduli, [GPa]:		
$E_l = -1199.7r^2 + 214.5r + 6.21$	$E_r = 1.51r + 1.03$	$E_t = 5.57r + 0.53$
Shear moduli [GPa]:		
$G_{lr} = 74.73r^2 - 7.36r + 0.98$	$G_{lt} = 45.40r^2 - 3.40r + 0.90$	$G_{rt} = 0.020r + 0.0106$
Poisson's ratio:		
$\nu_{lr} = 0.35$	$\nu_{lt} = 0.60$	$\nu_{rt} = 0.55$
Shrinkage coefficients:		
$\alpha_l = 0.788r^2 - 0.132r + 0.008$	$\alpha_r = -5.297r^2 + 1.132r + 0.131$	$\alpha_t = -12.76r^2 + 2.422r + 0.251$
Mechano-sorption MPa^{-1}:		
$m_l = 0.1 \cdot 10^{-3}$	$m_r = 0.15$	$m_t = 0.2$
$m_{lr} = 0.008$	$m_{lt} = 0.008$	$m_{rt} = 0.8$
$\mu_{lr} = 0.0$	$\mu_{lt} = 0.0$	$\mu_{rt} = 1.0$
Spiral grain angle [degrees]:	Conical angle [degrees]:	
$\theta = -40r + 4$	$\phi = -0.5$	

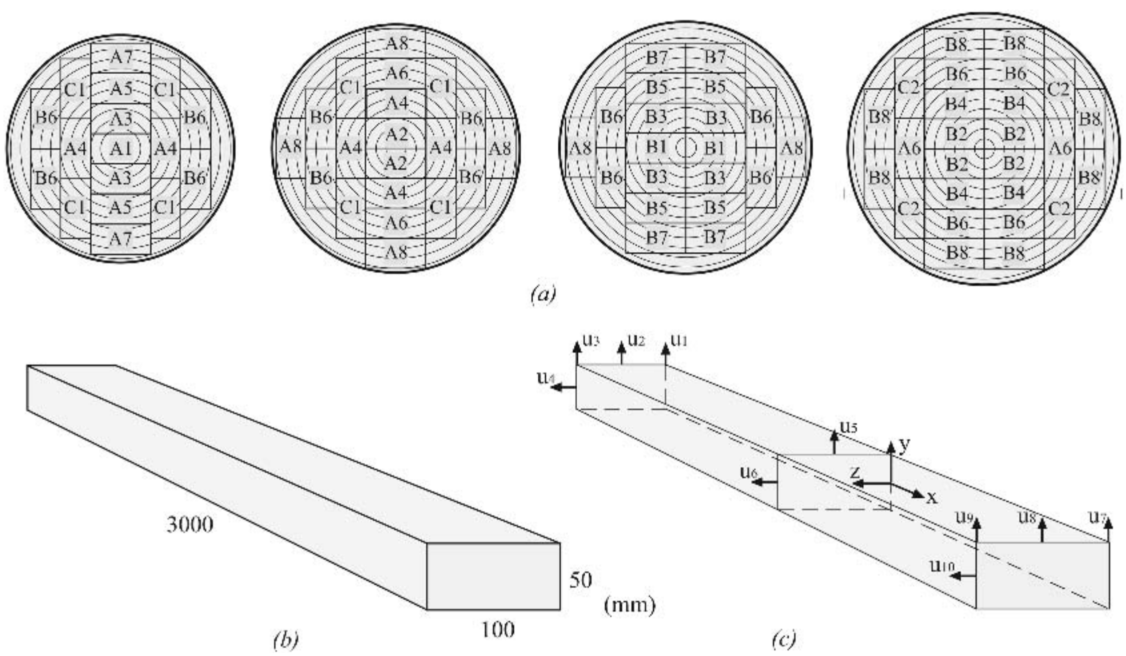

FIG. 8. Saw pattern and dimension of the boards studied (*a*) Three series of boards: A1-A8, B1-B8, C1 and C2; (*b*) Dimensions of the boards; (*c*) Displacement degrees of freedom for calculating the distortion modes.

Influence of saw pattern on drying distortions (pine and spruce)

Figure 9 shows twist and cup results for all board types that were shown in Fig. 8. The results show that the twist and cup deformations for both spruce and radiata are very dependent on the original board location. Generally, the deformation patterns are quite similar in shape for both species, but their amounts differ considerably in some cases. For juvenile wood, the twist is large for both species, but significantly greater for radiata pine than for spruce, whereas differences are small in the mature wood. The

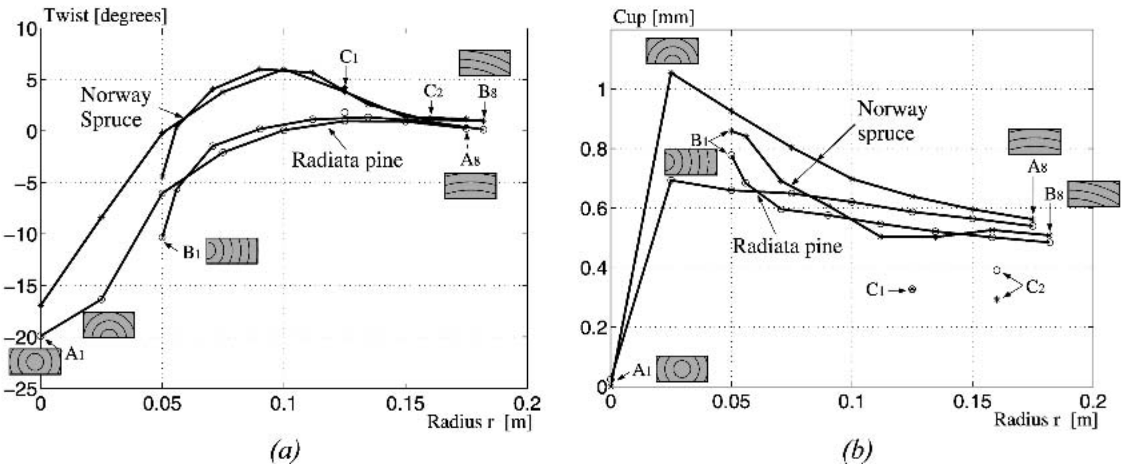

FIG. 9. Influence of saw pattern on distortions in timber boards (*a*) Twist pattern; (*b*) Cup pattern.

reason is that for juvenile wood the spiral grain is significantly higher for radiata pine than for spruce. For both species, the twist differences between A- and B-boards are quite small. It can therefore be concluded that while distance from the pith is critical, the actual orientation of the growth rings has only a small influence on twist in boards. The cup deformations of A-boards are larger for the spruce boards than for pine boards, especially in the juvenile wood. For spruce, the cup differences between A- and B-boards are both larger and have more variation than for pine.

The results in Fig. 10 show how bow and crook distortions differ considerably for the studied species. This occurs mainly because the species have a big difference in the longitudinal shrinkage data especially for the juvenile wood. Bow is highly influenced by the radial board position, and for the juvenile wood, it is also highly affected by the orientation of the ring-patterns. The largest bow and crook deforma-

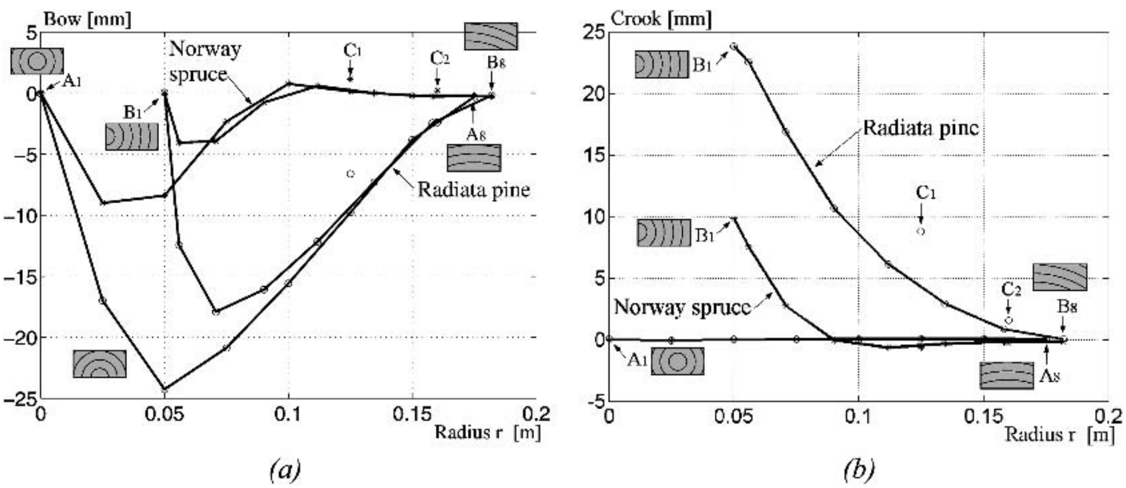

FIG. 10. Influence of saw pattern on distortions in timber boards (*a*) Bow pattern; (*b*) Crook pattern.

tions occur in boards of juvenile wood. Because of symmetry conditions, no bow deformation occurs in the center-board and no crook deformation occurs in the A-boards. Furthermore, the bow and crook become close to zero for the mature wood boards far from the pith. This is because of the assumption that the longitudinal shrinkage coefficient is a constant value for $r > 0.15$ m.

To illustrate how distortions of the boards can appear, two deformation plots are shown in Fig. 11 (exaggerated). It can be seen that the radiata board is more twisted and bowed than the spruce board. Note that to emphasize the deformations, all displacements have been multiplied by a factor of five in the figure. Because of the scaled deformations, the difference in cup deformation can also be seen at the cross-sections of the boards.

SUMMARY AND CONCLUSIONS

The basic material parameters that have the largest influence on twist and bow are spiral grain angle and longitudinal shrinkage coefficient. Because the average spiral grain function used for pine ($\theta = 233.3r^2 - 91.7r + 9.7$) is much higher than the function used for spruce ($\theta = -40r + 4$), the twist deformation for pine becomes much greater. The spruce function is close to radiata's lower limit function shown in Fig 4*(b)*. Other parameters such as radial and tangential shrinkage coefficients also had an influence on the twist deformation. In this case, these parameters will reduce the twist difference between the species since spruce shrinkages in these directions are significantly greater than for radiata. The main reason for the large differences in the bow and crook deformations is that the longitudinal shrinkage coefficient used for spruce ($\alpha_l = 0.788r^2 - 0.132r + 0.008$) is much lower than that used for radiata ($\alpha_l = 0.582r^2 - 0.197r + 0.0252$). The bow and crook deformations are also sensitive to variations in stiffness properties and spiral grain angle, which may have had a significant influence on the bow results presented.

A good knowledge of the material properties, together with computer simulation, makes it possible to improve conventional empirical approaches and to develop new solutions aimed at overcoming the problems connected with the limited shape stability of some wooden products. This can help maintain wood's competitive advantage in relation to other types of material. The simulations performed suggest it should to be possible to markedly improve the shape stability of different pine timber products by gluing wooden members together in an optimal way, as has been proven for spruce both numerically and experimentally (Ormarsson 1999; Eriksson et al. 2004 and Eriksson 2004). The results obtained are very encouraging and the suggested new ap-

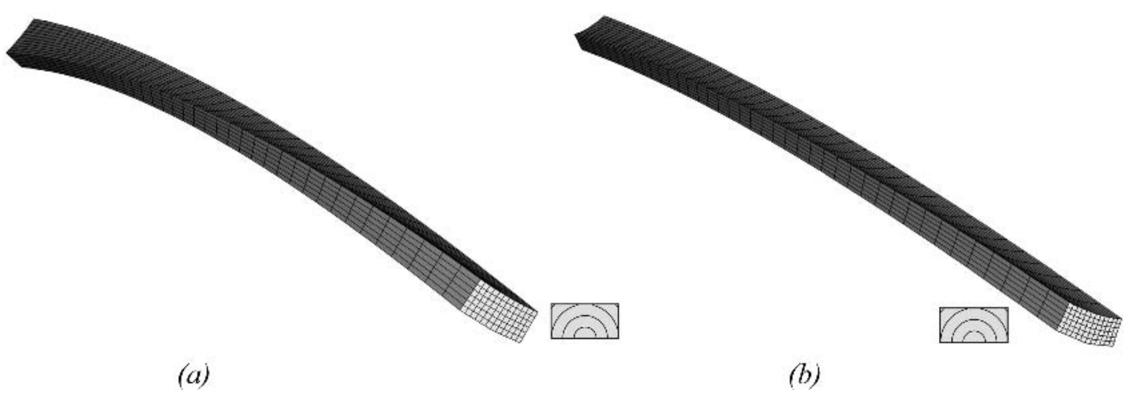

FIG. 11. Illustration of the drying distortion for boards of type A2 (*a*) Board of radiata pine; (*b*) Board of Norway spruce.

proach to design of products is therefore of considerable industrial interest.

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