INFLUENCE OF MATERIAL CHARACTERISTICS ON WARP IN NORWAY SPRUCE STUDS

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ABSTRACT

The aim of this study was to find parameters that cause warp. The study comprised 190 studs (45 × 95 × 2500 mm) of Norway spruce (*Picea abies*) from Sweden. Warp was measured five times in different moisture conditions. A number of parameters were registered on the studs, for example, average distance from the pith, grain angle, amount of juvenile wood, ring width, compression wood distribution on the surfaces, knots, cracks, wane, density, and modulus of elasticity. Grain angle and annual ring curvature were found to explain 73% of the variation in twist. Bow and crook were not possible to explain with statistical models. However, the distribution of compression wood on the surfaces of the studs could most often reveal the direction of bow and crook.

Keywords: Twist, bow, crook, compression wood, grain angle.

INTRODUCTION

The major disadvantage of timber as a building material in a rational, mechanized building process is warp (Johansson et al. 1994). Timber is losing market shares to steel sheet products because of the lack of straightness that timber products too often exhibit. Understanding the mechanisms that govern warp is vital. With an increased knowledge of these mechanisms, the relevant wood properties can be identified. Then processing and development efforts can be directed towards the most important parameters that have direct impact on the quality of the timber product.

During recent decades, many research groups have worked with warp of timber and the influence of material characteristics on warp (Mishiro and Booker 1988; Fridley and Tang 1993; Danborg 1994; Perstorper et al. 1995; Taylor and Wagner 1996; Simpson and Tschernitz 1998; Forsberg 1999; Woxblom 1999; Johansson 2000, among others). Many statistical models have been constructed to try to explain the development of warp from measured material properties.

The origin of warp has also been the subject of a large European research project (STUD 1997–2000). The aim of the "STUD" project was to increase the use of spruce timber in Europe. One method of achieving this was to find the causes of warp and try to find methods to reduce it. This paper describes the relationships found between measured parameters and warp.

LITERATURE REVIEW

Much research effort has been put into finding the reasons for warp. Most studies show that warp increased with decreasing moisture content. The method of drying affects the

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magnitude of warp (Arganbright et al. 1978; Simpson and Tschernitz 1998). However, it is not possible to eliminate warp completely with these methods, and some of the material will be too warped for building purposes. This material would be of great interest to sort out before drying. It could also be of interest to sort material into different batches before drying, depending on their ability to warp, for different drying methods.

The parameters that have been shown in most studies to have a large influence on the amount of twist are spiral grain angle (Rault and Marsh 1952; Brazier 1965; Balodis 1972; Mishiro and Booker 1988; Danborg 1994; Perstorper et al. 1995; Cown et al. 1996; Forsberg 1999; Woxblom 1999; Johansson et al. 2001) and distance from the pith (Kloot and Page 1959; Shelly et al. 1979; Mishiro and Booker 1988; Danborg 1994; Perstorper et al. 1995; Warensjö and Lundgren 1998; Woxblom 1999; Johansson et al. 2001). Some studies show that presence of juvenile wood results in large twist (Woxblom 1999; Merforth and Seeling 2000), while others have found that, when the effect of distance from the pith and spiral grain angle are taken into account, juvenile wood has little additional influence (Cown et al. 1996; Johansson et al. 2001). Most other parameters—for example, knots, compression wood, ring width, density—have little or no effect on twist (Hallock 1965; Beard et al. 1993; Perstorper et al. 1995; Johansson et al. 2001).

The causes of bow and crook are twofold: residual stresses and uneven longitudinal shrinkage. The effect of residual stresses can be seen in the fact that bow and crook are to some degree formed directly after sawing (Okuyama and Sasaki 1979; Archer 1987; Mishiro and Booker 1988; Woxblom 1999; Kliger 1999). The other cause of bow and crook is uneven longitudinal shrinkage. Large longitudinal shrinkage on one edge face of a stud will result in crook towards the side with less longitudinal shrinkage (Simpson and Gerhardt 1984; Johansson and Kliger 2000). Uneven longitudinal shrinkage can also be caused by a number of factors such as juvenile wood, compression wood, and knots. These are factors that in several studies have shown to have influence on bow and crook (Hallock 1965; Gaby 1972; Shelley et al. 1979; Voorhies and Blake 1981; Beard et al. 1993; Perstorper et al. 1995; Warensjö and Lundgren 1998). Some studies have also shown that the location of compression wood in the stud explains bow and crook (Du Toit 1963; Lind af Hageby 1998). Most other parameters have proved to have little or no influence on bow and crook.

During the years, many trials have been done to model warp. Most of these models have been statistical (Kloot and Page 1959; Brazier 1965; Balodis 1972; Beard et al. 1993; Perstorper et al. 1995; Cown et al. 1996; Taylor and Wagner 1996; Johansson and Kliger 2000; Johansson et al. 2001, among others). These models differ from each other and some can explain up to 65% of the variation in twist. For bow and crook, they are less accurate. Some analytical models have also been made. For bow and crook, they are based on different longitudinal shrinkage on different sides of a stud (Simpson and Gerhardt 1984; Kliger et al. 2001). The analytical models for twist are more complicated. One model was made by Stevens and Johnston (1960) for twisting of cylindrical wooden shells during adsorption. Balodis (1972) applied this model on twist in studs cut parallel to the pith of a log. There are also numerical models for warp (Ormarsson 1999). This model can explain twist rather well but has problems with bow and crook. The difficulty when modeling bow and crook is lack of adequate input data, for example, the variation in longitudinal shrinkage along the stud (Kliger et al. 2001).

MATERIAL AND METHODS

The material in this study came from four Swedish stands with different properties. A detailed description of the stands and the trees can be found in (Björklund et al. 1998). From each of these stands, 6 or 7 trees were harvested. From each tree the butt, middle, and top log were collected to be used in this study. The logs from different heights were sawn with different sawing patterns (Fig. 1). The sawing of the logs took place at a small sawmill in order to have the time to ensure that the prescribed sawing pattern was obtained. The studs were sawn to the dimensions of 47 × 100 mm and were planed and cut to the dimensions of 45 × 95 × 2500 mm after drying. The sawing patterns were designed to study the influence of different annual ring orientation within the studs. In total, 190 studs were obtained. After sawing, the material was kiln-dried to the target moisture content (MC) of 18% with a normal temperature kiln schedule. The material was dried without outer restraint; i.e., all the material was free to move to allow maximum warp to develop (Kliger 1997).

The warp in the studs was measured five times: directly after sawing, after drying, and at three different moisture contents (18%—10%—17%) in the laboratory. The three last changes in moisture content were made in a climate-controlled room without external restraint on the material, i.e., the material was hanging freely. This was done to avoid the influence of gravity and restraint and only to study the effect of the wood material on warp. Warp was registered with a measurement device, as described by Perstorper et al. (2001). The warp modes twist, bow, and crook were measured. This paper will deal with magnitude of warp at 10% moisture content and the change in magnitude of warp between the moisture contents of 18% and 10% (Δtwist, Δbow, and Δcrook). Positive twist was defined as S-twist as described by Mishiro and Booker (1988). Bow and crook were defined as positive when following the direction of the (small) arrows in Fig. 1.

The following parameters were measured on the material: position of each stud in relation to the pith (X, Y) in both ends of the stud, ring width (RW), percentage of juvenile wood determined in one end of each stud (JW), grain angle (GA), percentage of compression wood on all four longitudinal faces of the studs (CW-f1, CW-f2, CW-e1, CW-e2), cracks, knot area ratio (KAR), wane width (WW), wane length (WL), density (dens), and eigenfrequency (freq). From the density and eigenfrequency, the dynamic modulus of elasticity (MOE) was calculated.

From the measurement of position of the stud in relation to the pith (X and Y cf. Fig. 1), a number of parameters were calculated: average distance from the pith ($\bar{r}$), skew sawing angle (SSA), the annual ring orientation (ARO), and annual ring curvature (ARC). The average distance from the pith for each stud was calculated using Eq. (1).

$$\bar{r} = \frac{\iint \sqrt{X^2 + Y^2}\, dx\, dy}{\iint dx\, dy} \qquad (1)$$

The average distance from the pith was used to calculate the annual ring curvature (ARC = $1/\bar{r}$). The skew sawing angle (SSA) was expressed as an angle in the space between the straight line representing the pith and the straight line through the center of the stud in each end. The annual ring orientation (ARO) was determined as the angle between the tangent to the annual rings in the center of each stud and one flat face of the stud. This angle varied between 0° and 90°.

The percentage of juvenile wood was determined by referring to the 12th annual growth ring, which was outlined on the log ends prior to sawing. Grain angle was measured in three longitudinal positions along each stud on the tangential face by using a scribe, and was recorded in relation to the edge of the stud. Three scribed lines were made at each longitudinal position to secure the validity of the measurements. The average value of the measurements, in the three longitudinal positions, was used in the analysis. In the case of some studs (butt log, position 3) it was not possible to measure grain angle on the tangential face, and an average value of grain angle of studs 2 and 10 was used instead.

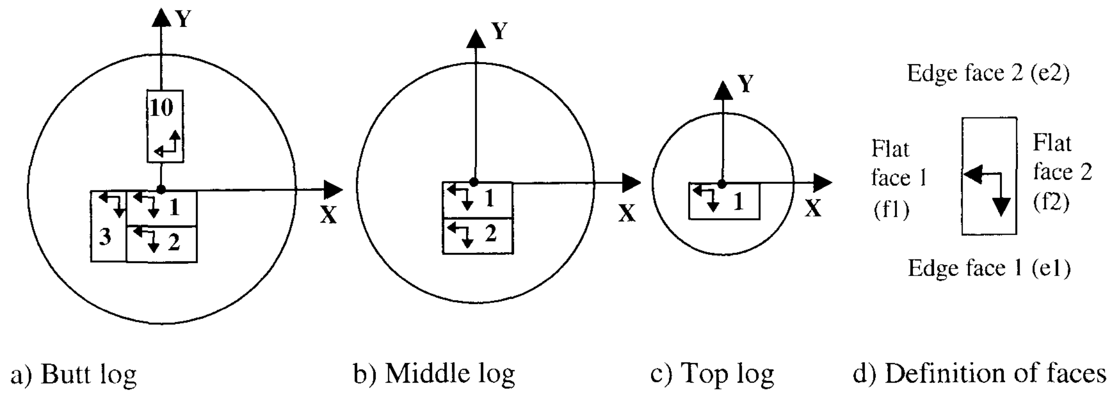


FIG. 1. Notations for the studs and definition of the coordinate system. The arrows define the positive direction of bow and crook. Face 1 is defined as the side of the stud towards which the small arrow is pointing.

Compression wood was determined visually and was defined as an area where a gradual change in the width of the latewood band between adjacent annual rings occurred. The identification of compression wood was made visually after re-wetting the timber to a moisture content of about 17%. The criterion was that the slightly darker latewood band was classified as compression wood. If the darker latewood band was larger than 50% of the annual ring width, it was classified as severe compression wood. When the compression wood areas were marked on the surfaces of the studs, a transparent grid was placed over each surface. The grid had 50 rectangles along the length of the stud, each measuring 50 × 24 mm. The rectangles that corresponded to areas with compression wood were registered. The compression wood measurement used in the analysis was the ratio between surface area with compression wood and total surface area for each face of the studs. The assessment of compression wood was made by one person in order to be as consistent as possible. The compression wood content at the ends of the studs was used in many cases as guidance to distinguish between normal wood and compression wood.

Cracks were registered as the total length of cracks for each stud. Wane length and width were registered as the largest measurement in millimeters found anywhere on the stud. Eigenfrequency was measured in the longitudinal direction of the stud, and the density of the stud was registered at the same time at a moisture content of 9%.

RESULTS

Statistical analysis

Twist.—The objective of this project was to find parameters that have strong influence on warp. The correlation matrix between warp and the measured parameters can be seen in Table 1. Twist and difference in twist between the two different moisture contents (Δtwist) were in very good agreement, $R = 0.99$.

The parameters that had strong correlation with twist at 10% moisture content were average distance from the pith ($R = -0.52$), annual ring curvature ($R = 0.55$), ring width ($R = 0.51$), juvenile wood ($R = 0.61$), grain angle ($R = 0.77$), eigenfrequency ($R = -0.53$), and modulus of elasticity ($R = -0.55$). The relationships between twist at 10% MC and grain angle, and between twist at 10% MC and annual ring curvature, are shown in Fig. 2. The design of the sawing patterns caused the annual ring curvature data to be grouped in two groups instead of being a continuous variable.

A simple linear regression model with only grain angle as variable explained 59% of the variation in twist (Fig. 2a). If annual ring curvature was included in a multiple regression model, 71% of the variation in twist could be explained. The same coefficient of determination could be obtained with grain angle and juvenile wood. When all three parameters were included in the model, the coefficient of determination increased to 0.73. Adding juvenile wood to the other two parameters did not increase the accuracy of the model significantly. This could be explained by the fact that juvenile wood and annual ring curvature varied in a similar manner; the coefficient of determination between these two parameters was 0.53. If all parameters were included in the model, the coefficient of determination increased to 0.78. This illustrated that the two parameters with the largest influence on twist were grain angle and annual ring curvature. These results are in good agreement with results found in the literature (Balodis 1972; Perstorper et al. 1995; Cown et al. 1996).

The multiple regression model for twist (at 10% moisture content) as a function of grain angle (GA) and annual ring curvature (ARC $= 1/\bar{r}$) is shown in Eq. (2).

$$\text{Twist} = -5.46 + 1.70\text{GA} + 347.8\text{ARC} \quad (2)$$

The agreement between the calculated twist, using this model, and the measured twist as shown was good, the coefficient of determination was 0.71 (Fig. 3).

Bow and crook.—None of the measured parameters showed a strong correlation with bow or crook (Table 1). The only parameter that had a correlation coefficient stronger than 0.3 with bow measured at 10% moisture content was the difference in bow between 18% MC and 10% MC ($R = 0.81$). The results appeared to be better for difference in bow (Δbow), where some parameters had a correlation coefficient stronger than 0.3: average distance from the pith and annual ring curvature (resp. $R = -0.30$ and $R = 0.30$) and juvenile wood ($R = 0.37$). All three of these parameters can be linked to large longitudinal shrinkage, which occurs close to the pith.

For crook, the obtained results were even worse than for bow. The correlation between crook measured at 10% moisture content and the change in crook between 18% MC and 10% MC (Δcrook) was weaker than for bow ($R = 0.68$). Of the other parameters, the only correlation stronger than 0.3 was between crook measured at 10% MC and compression wood on one edge face.

Although it was not possible to find any stronger correlation between the measured parameters and bow or crook, the parameters with moderate correlation were all parameters that are related to large longitudinal shrinkage. Uneven longitudinal shrinkage in a stud is one commonly believed reason for bow and crook (Skaar 1988, for example). The results found here support this explanation.

Knots or knot area ratio showed no correlation with bow and crook in this study. One reason for this is that the knot area ratio (KAR) on this material was rather small, with a mean value of 0.21 and a standard deviation of 0.11.

Analytical results

Twist.—One model that explains the causes of twist well was made by Stevens and Johnston (1960). This model explains twisting of cylindrical shells of wood cut from one annual growth ring. The model is based on geometrical calculations and the effect of tangential shrinkage on the geometry. The model includes distance from the pith, i.e., the radius of the shell, length of the shell, spiral grain angle, and tangential shrinkage. Balodis (1972) showed that this model can be used to calculate the angle of twist of studs cut from these shells. This can be done under the assumption that spiral grain angle divided by distance from the pith and the tangential shrinkage is constant through the stud. This model, Eq (3), can therefore be used to predict twist of studs:

$$Twist = \frac{l}{r} \cdot \frac{2s\theta}{(1 + s)} \quad (3)$$

where l is stud length, s is tangential shrinkage strain, θ is spiral grain angle, and r is the dis-

TABLE 1. *Correlation (R) matrix for warp and material and other parameters. Correlation values (absolute values) stronger than 0.3 are marked with bold. Significant correlations are marked with ** for p < 0.001 and * for p < 0.05. Twist 10%, twist measured at 10% MC. Δtwist, change in twist between 18% MC and 10% MC. Bow 10%, bow measured at 10% MC. Δbow, change in bow between 18% MC and 10% MC. Crook 10%, crook measured at 10% MC. Δcrook, change in crook between 18% MC and 10% MC. X and Y, coordinates for the center of the stud in relation to the pith (cf. Fig. 1).* $\bar{r}$*, average distance from the center of the stud to the pith. ARC, annual ring curvature. SSA, skew sawing angle. RW, ring width. JW, juvenile wood. GA, grain angle. CW, percentage of compression wood on the four longitudinal faces (flat face 1 − f1, edge face 1 − e1, flat face 2 − f2, edge face 2 − e2, cf. Fig. 1). KAR, knot area ratio. WW, wane width. WL, wane length. Dens, density at 9% MC. Freq, eigenfrequency in longitudinal direction. MOE, modulus of elasticity measured dynamically at 9% MC.*

	Twist 10%	Δtwist	Bow 10%	Δbow	Crook 10%	Δcrook	X	Y	$\bar{r}$	ARC	SSA	ARO	RW
Twist 10%	1.00	**0.99****	0.17*	**0.32****	−0.05	−0.08	0.13	0.07	**−0.52****	**0.55****	−0.05	−0.09	**0.51****
Δtwist		1.00	0.18*	**0.33****	−0.05	−0.08	0.14	0.07	**−0.54****	**0.57****	−0.06	−0.10	**0.50****
Bow 10%			1.00	**0.81****	−0.22*	0.03	−0.06	0.16*	0.00	0.02	−0.14	0.14	0.09
Δbow				1.00	−0.13	−0.06	0.04	−0.02	**−0.30****	**0.30****	−0.19*	−0.10	0.22*
Crook 10%					1.00	**0.68****	0.18*	−0.17*	−0.08	0.05	0.03	−0.18*	0.05
Δcrook						1.00	−0.04	−0.14	0.01	−0.03	−0.01	−0.09	−0.04
X							1.00	0.08	**−0.43****	**0.37****	−0.10	−0.12	0.11
Y								1.00	0.10	−0.01	0.20*	**0.83****	−0.05
$\bar{r}$									1.00	**−0.98****	0.11	**0.37****	−0.22*
ARC										1.00	−0.08	−0.29**	0.21*
SSA											1.00	**0.35****	−0.13
ARO												1.00	−0.13
RW													1.00
JW													
GA													
CW-f1													
CW-e1													
CW-f2													
CW-e2													
KAR													
Cracks													
WW													
WL													
Dens													
Freq													
MOE													

tance from the stud center to the pith. All parameters except tangential shrinkage were recorded on the material in this study. The warp was registered over a length of 2410 mm; the grain angle and average distance from the pith were measured. The model explained 73% of the variation in twist; (Fig. 4). The unknown parameter, tangential shrinkage strain, was set to a value of 0.024 that produced the best fit of data, i.e., a value that gave the calculated twist the same magnitude as the measured twist.

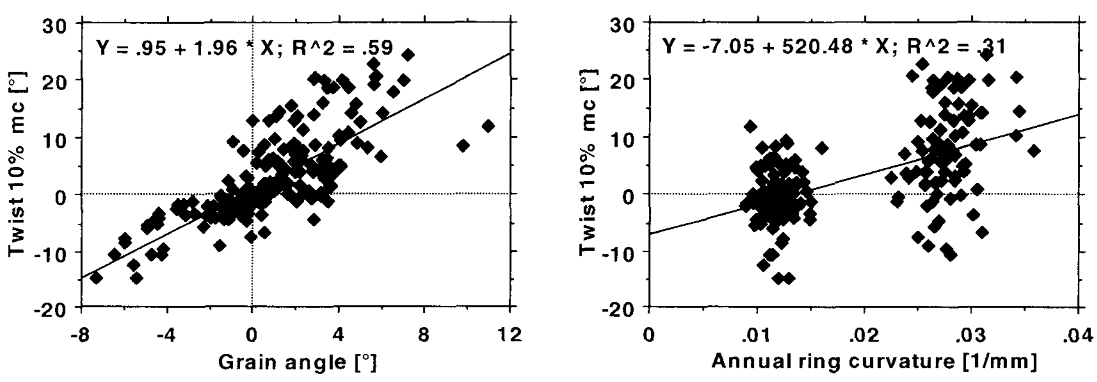
In earlier studies, tangential shrinkage strain for Norway spruce timber has been measured and found to be around 0.026 for a change in moisture content between 16% and 8% (Persson 1997; Perstorper et al. 2001). The change in moisture content for this material was between green conditions (≈27%) and 10%. This should result in a higher tangential shrinkage strain than the one measured between 16% and 8% moisture content.

Bow and crook.—Bow and crook were not possible to model using statistical methods with the data measured in this study. However, a detailed study of compression wood (CW) distribution on the surfaces of the studs reveals that on the individual stud level there was a relationship between compression wood distribution and bow and/or crook.

Compression wood shrinks a great amount in the longitudinal direction as a result of changes in moisture content (Timell 1986). A stud with large longitudinal shrinkage on one side, caused by compression wood for example, will bend and as a result the material with

TABLE 1. *Extended.*

JW	GA	CW-f1	CW-e1	CW-f2	CW-e2	KAR	Cracks	WW	WL	Dens	Freq	MOE
0.61**	0.77**	0.06	0.01	0.07	−0.03	0.35**	0.09	−0.07	−0.16*	−0.36**	−0.53**	0.55**
0.61**	0.77**	0.07	0.02	0.07	−0.01	0.34**	0.09	−0.06	−0.16*	−0.33**	−0.53**	−0.53**
0.13	0.10	−0.24*	−0.05	0.19*	−0.18*	−0.04	0.08	0.00	−0.02	−0.06	−0.01	0.03
0.37**	0.18*	−0.19*	−0.03	0.13	−0.13	0.14	0.07	−0.07	−0.06	−0.09	−0.16*	−0.14*
0.09	−0.11	0.14	−0.14	0.04	0.30**	0.03	−0.10	−0.11	−0.03	−0.02	−0.09	−0.07
0.03	−0.17*	0.03	−0.05	0.05	0.18*	−0.02	−0.06	−0.13	0.08	0.07	−0.07	−0.01
0.27*	0.06	0.02	−0.17*	−0.07	0.11	0.12	0.11	0.04	0.04	0.05	−0.12	−0.05
0.05	0.07	−0.21*	−0.26*	−0.07	−0.23*	−0.06	0.06	0.20*	0.13	−0.07	0.13	0.04
−0.71**	−0.27*	−0.05	0.00	−0.02	−0.07	−0.37**	−0.20*	0.14	0.10	−0.01	0.41**	0.28**
0.73**	0.27*	0.00	−0.04	−0.01	0.02	0.37**	0.23*	−0.11	−0.03	0.00	−0.41**	−0.28**
−0.07	−0.04	−0.03	0.01	−0.04	−0.08	−0.15*	0.14	0.13	0.09	0.02	0.06	0.05
−0.17*	−0.13	−0.22*	−0.19*	−0.04	−0.25*	−0.17*	0.06	0.16*	0.10	−0.03	0.29**	0.18*
0.61**	0.40**	0.11	0.03	0.02	0.07	0.34**	−0.08	−0.10	−0.16*	−0.66**	−0.54**	−0.70**
1.00	0.33**	−0.09	−0.12	−0.02	−0.03	0.44**	0.04	−0.09	−0.09	−0.35**	−0.50**	−0.51**
	1.00	0.11	0.13	0.08	0.04	0.19**	−0.03	−0.03	−0.17′	−0.37**	−0.39**	−0.47**
		1.00	0.71**	0.62**	0.73**	0.22*	−0.05	−0.12	−0.08	0.17*	−0.40**	−0.19*
			1.00	0.61**	0.42**	0.12	−0.04	−0.13	−0.11	0.21*	−0.23*	−0.06
				1.00	0.64**	0.13	−0.04	−0.06	−0.06	0.27*	−0.23*	−0.02
					1.00	0.20*	−0.10	−0.09	−0.03	0.19*	−0.28*	−0.09
						1.00	−0.07	−0.19*	−0.14*	−0.19*	−0.50**	−0.45**
							1.00	−0.03	−0.03	−0.03	0.01	−0.02
								1.00	0.86**	0.09	0.12	0.14
									1.00	0.15*	0.15*	0.20*
										1.00	0.31**	0.75**
											1.00	0.86**
												1.00



a) Twist versus grain angle b) Twist versus annual ring curvature

FIG. 2. Relationship between twist at 10% moisture content and (a) grain angle, (b) annual ring curvature.

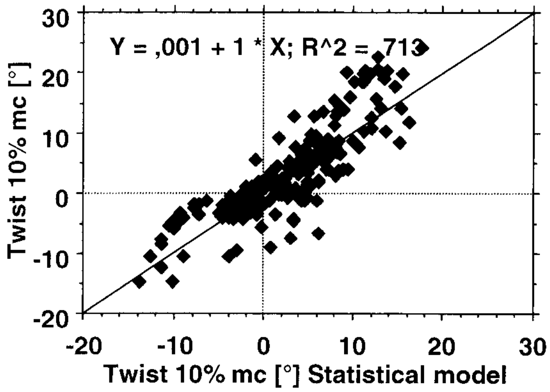


FIG. 3. Measured twist versus twist calculated with the statistical model, Eq. (2).

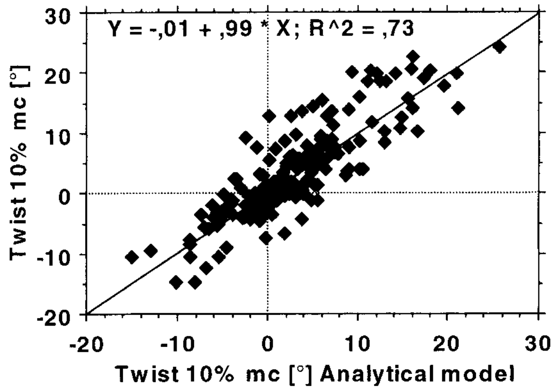


FIG. 4. Measured twist versus twist calculated with the analytical model, Eq. (3).

large longitudinal shrinkage will be situated on the concave side of the stud. From this it can be concluded that a stud with more compression wood on face 2 than on face 1 should have a positive bow (cf. Fig. 1). To test this assumption, a new set of variables was formed: positive or negative compression wood.

CWbow: "CW-f2" − "CW-f1" > 0 is defined as positive and the opposite as negative.

CWcrook: "CW-e2" − "CW-e1" > 0 is defined as positive and the opposite as negative.

A statistical analysis (t-test) showed that studs with positive CWbow had statistically significant more positive bow ($P < 0.002$). The same applied for crook: studs with positive CWcrook had statistically significant more positive crook ($P < 0.001$) (Fig. 5).

The fact that the distribution of compression wood could explain bow and crook can be seen in a detailed study of a few of the studs in this study. The warp of these studs was remeasured with another measurement device that had the ability to measure the warped geometry every 5 cm along the length of the studs. The measurement device is described in detail by Johansson (2000). In Fig. 6, one example of this kind of measurement is shown. The warp was registered at a moisture content of 13%.

The warped geometry could then be compared with the distribution of visible compres-

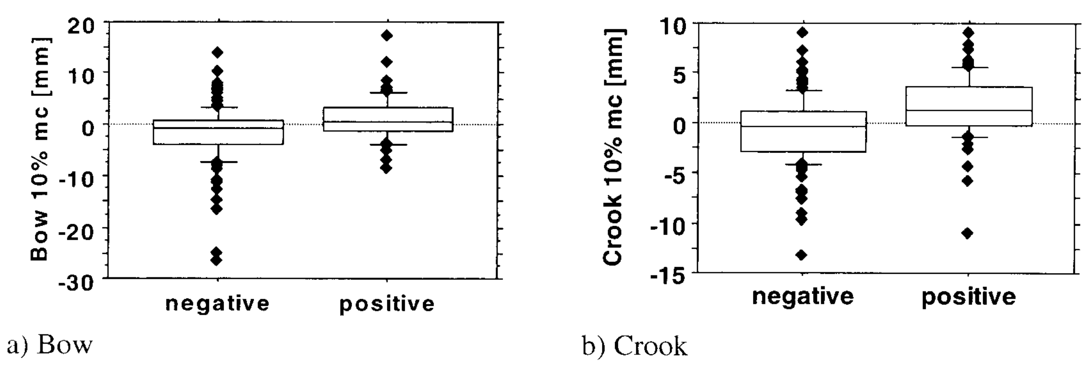


FIG. 5. Box plots of bow and crook split by positive or negative CWbow resp. CWcrook. Positive CWbow means that the difference in compression wood between the flat faces of a stud should result in a positive bow. (Box plots showing 10th, 25th, 50th, 75th and 90th percentile.)

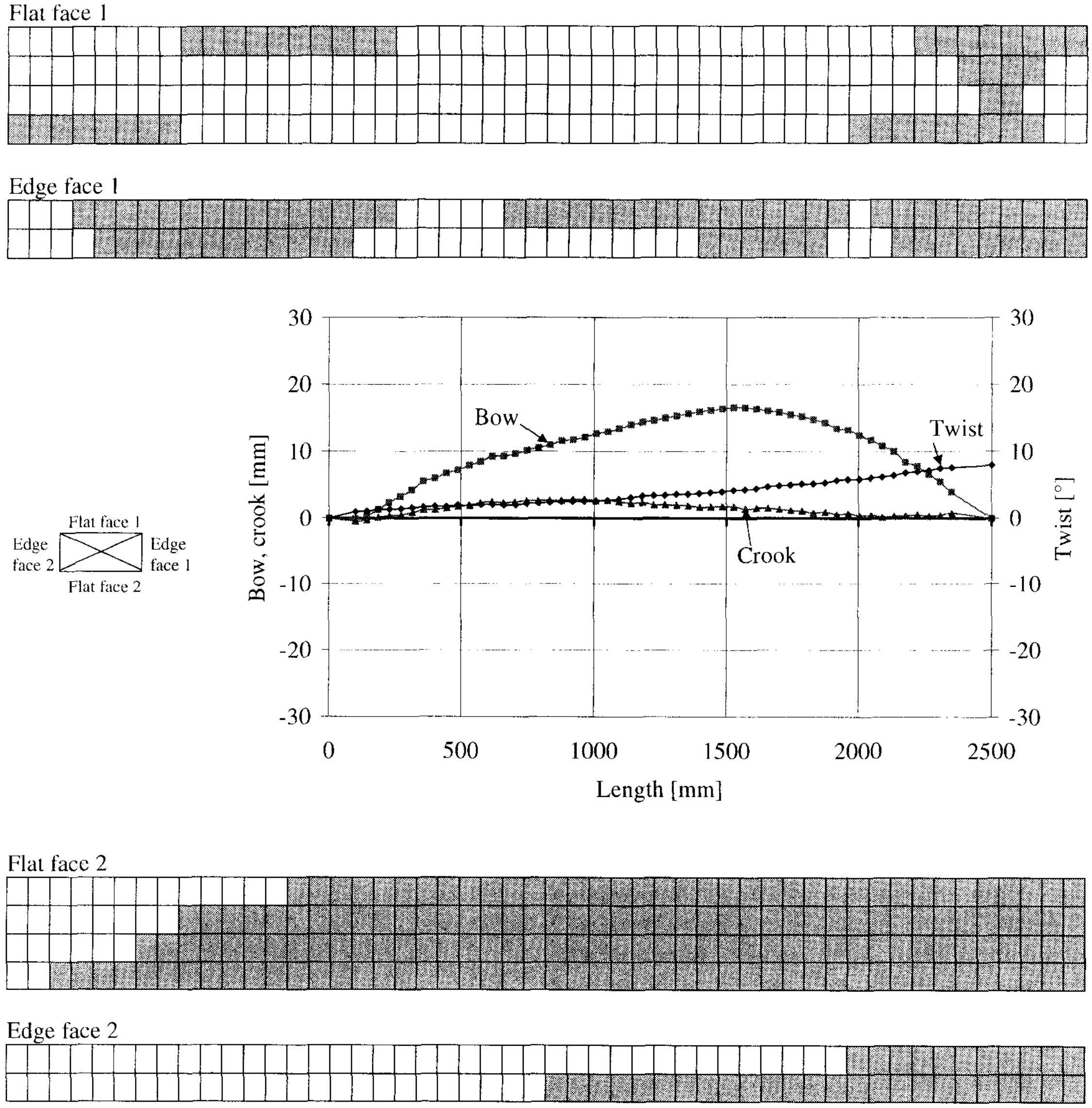


FIG. 6. Distribution of compression wood on all four faces of the stud, and distorted geometry at approximately 13% moisture content along the length of the stud. White rectangles represent areas without compression wood, and gray rectangles represent areas with compression wood.

sion wood on the surfaces of the studs. The effect of compression wood could clearly be seen for the stud in Fig. 6. Flat face 2 of the stud contained large amounts of visible compression wood. Flat face 2 of the stud has shrunk (during drying from green to approximately 13% moisture content) and caused a deformation in terms of bow in the direction of flat face 1. It was also interesting to notice that the location of the maximum bow occurred at approximately the same location as the visually determined center of gravity of the marked compression wood area on the surfaces.

The results showed that registration of compression wood distribution on the surfaces could reveal the direction of bow and crook. The amounts of compression wood on the surfaces could not be used to make a good prediction of the magnitude of bow and crook. If compression wood had been identified on green wood, where it is easier to detect visually, the result could have been better. However, with a better measurement technique for compression wood it would be possible to predict bow and crook caused by uneven longitudinal shrinkage more accurately.

CONCLUSIONS

In this study, warp of 190 studs of Norway spruce timber was examined. The influence of material characteristics on warp was studied. Based on the results of these studies regarding warp, the following conclusions can be drawn.

For twist, it has been concluded that the main reasons for a high magnitude of twist in studs are grain angle in combination with annual ring curvature. The most twisted studs were sawn close to the pith (large annual ring curvature) with large grain angle. These two parameters explain 71% of the variation in twist with a multiple linear regression model. The only problem is that none of these parameters varies as a result of changing moisture content. Since twist is very sensitive to moisture content changes, there must be some additional parameter(s) that depend on the moisture content. An analytical model described by Stevens and Johnston (1960) also explains 73% of the variation in twist. Their model includes grain angle, annual ring curvature, length of the stud, and tangential shrinkage. This model shows the same high coefficient of determination as the statistical model, but it also includes one more parameter that varies with moisture content—tangential shrinkage.

It was not possible to explain bow and crook by using the parameters measured in this study. Using statistical methods, bow and crook could not be explained with any accuracy from the measured data. The parameters that showed any tendencies to explain bow and crook were all linked to material with high longitudinal shrinkage, such as: annual ring curvature, juvenile wood, compression wood, and knots.

A detailed study of compression wood distribution on the surfaces of the studs showed that if one side had more visual compression wood than the opposite side, the bow or crook was most often in the direction away from the side with compression wood. This shows that there is a relationship between compression wood distribution and bow and crook. With a better criterion and method to detect compression wood, it might be possible to predict bow and crook. It would also be of help to find a way to detect 3D-distribution of compression wood in the studs nondestructively.

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