PREDICTION OF BOW AND CROOK IN TIMBER STUDS BASED ON VARIATION IN LONGITUDINAL SHRINKAGE

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ABSTRACT

This paper presents a model that describes the change in magnitude of bow and crook between two moisture contents below the fiber saturation point. The model shows that the variation in the longitudinal shrinkage coefficient over the cross section and along the stud could explain most of the change in bow and crook in the studs. It was possible to identify evenly curved bow and crook, as well as S-shaped bow and crook. The results show that the model predicts changes in bow better than changes in crook.

The results of measurements of distorted geometry along the length of 12 studs are presented. The equipment for measuring distorted geometry is described. The distorted geometry was measured at two moisture contents. The studs were then sawn into sticks (10 × 10 × 200 mm), a total of 3,600. The longitudinal shrinkage coefficient in these sticks was obtained for a change in moisture content from 18% to 8%. The sticks were also classified visually into three groups depending on their compression wood content: no compression wood, mild compression wood, mild compression wood, or severe compression wood.

The variation in the longitudinal shrinkage coefficient was large in the studied sticks ($\bar{x}$ 0.0111, SD 0.0111). The sticks classified as containing severe compression wood had a significantly larger longitudinal shrinkage coefficient than the sticks classified as no or mild compression wood. Moreover, sticks classified as mild compression wood had a significantly larger shrinkage coefficient than the sticks classified as no compression wood.

Keywords: Compression wood, warp, model, moisture content.

BACKGROUND

To enable timber to be used more effectively as a building material, it is essential to increase the opportunity to use timber in a more industrial building process. To achieve this, the performance of timber must be predictable. The most important property to enhance is the straightness of the material. Lack of straightness is one of the main reasons for the building industry to choose materials other than timber in buildings (Johansson et al. 1994; Eastin et al. 2001). Finding ways to predict and remove material prone to warp before the material reaches the building site will improve the competitiveness of timber. Removing the material that is prone to warp will make it possible to re-engineer this material and thus make it possible to utilize it in a modern building process.

Warp is the general term that is used to describe any deviation in a piece of timber from a "true" or plane surface. It includes twist, crook, bow, and cup. This paper will deal with the two bending forms, crook and bow. Crook is the edge-wise deviation of a piece of timber from a straight line from end to end, while bow is the flat-wise deviation.

LITERATURE

Over the years, many researchers have tried to find the cause of bow and crook in easily measured material parameters. It was hoped

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that, by combining material parameters statistically, it would be possible to explain bow and crook. Some of the tested parameters were spiral grain angle, juvenile wood, sapwood and heartwood, knots and compression wood. Spiral grain angle showed no correlation with crook or bow (Kloot and Page 1959; Mishiro and Booker 1988; Beard et al. 1993; Perstorper et al. 1995; Woxblom 1999; Forsberg 1999). Studs containing both juvenile and mature wood exhibited more crook or bow than other studs (Shelly et al. 1979; Mishiro and Booker 1988). However, some investigations showed no influence by juvenile wood on crook or bow (Woxblom 1999; Beard et al. 1993). The presence of both sapwood and heartwood in the same piece of timber did not affect crook or bow (Perstorper et al. 1995; Woxblom 1999) but contributed to problems due to different rates of drying (Voorhies and Blake 1981). In the case of knots, no relationship of practical value has been shown between their presence and warp (Kloot and Page 1959; Shelly et al. 1979; Beard et al. 1993; Perstorper et al. 1995). Most researchers agree that studs with an uneven distribution of compression wood can develop crook or bow. Many researchers have tried to prove this hypothesis with varying results. In several studies, it was shown that compression wood had some effect on crook and bow, but in most studies the level of correlation was low (Du Toit 1963; Hallock 1965; Gaby 1972; Voorhies and Blake 1981; Beard et al. 1993; Perstorper et al. 1995; Warensjö and Lundgren 1998; Woxblom 1999).

Other researchers have tried to explain bow and crook theoretically. The causes of bow and crook were assumed to be twofold: residual stresses and uneven longitudinal shrinkage due to changes in moisture content. The effect of residual stresses could be seen in the fact that bow and crook were formed directly after sawing, at least to some degree (Okuyama and Sasaki 1979; Archer 1987; Mishiro and Booker 1988; Woxblom 1999; Kliger 1999). The other cause of bow and crook was uneven longitudinal shrinkage. Large longitudinal shrinkage on one edge face of a stud should result in crook towards the side with less longitudinal shrinkage (Simpson and Gerhardt 1984; Skaar 1988; Stanish 2000; Kliger et al. 1997).

Simpson and Gerhardt (1984) proposed a model for calculating crook due to differing longitudinal shrinkage on two opposite sides of a stud. Kliger et al. (1997) showed in the case of two studs of Norway spruce that it was possible to calculate crook and bow with reasonable accuracy based on variations in longitudinal shrinkage. Stanish (2000) created a simple finite element (FE) model for crook based on material properties measured along the length of a stud of loblolly pine. This model showed good agreement between measured crook and crook calculated on the basis of the variation in longitudinal shrinkage and the modulus of elasticity. A more sophisticated FE model for warp, which includes shrinkage, modulus of elasticity, and mechano-sorptive parameters in all directions, as well as annual ring orientation and other parameters, was developed by Ormarsson (1999). This model has great potential but requires a great deal of input data that are difficult to measure.

Uneven longitudinal shrinkage can be caused by a number of factors, such as juvenile wood, compression wood, and knots (Voorhies and Groman 1982; Saaranpää 1994; Bengtsson 2001; Perstorper et al. 2001). The relationship between microfibril angle and the amount of longitudinal shrinkage has been demonstrated in several studies (Meylan 1972; Voorhies and Groman 1982, for example). Both juvenile wood and compression wood have a large microfibril angle, which explains their large longitudinal shrinkage (Timell 1986; Zobel and Sprague 1998). Around knots, the wood fibers deviate and the wood will therefore display large-scale shrinkage in the main direction.

OBJECTIVES

The objectives of this study were:

- to show the relationship between variations

in the longitudinal shrinkage coefficient and moisture-induced bow and crook;
- to describe a model that shows the relationship between variations in the longitudinal shrinkage coefficient and moisture-induced bow and crook;
- to show the relationship between the compression wood content and the degree of longitudinal shrinkage coefficient;
- to describe equipment for measuring the 3D geometry of a warped timber stud.

The bow and crook studied here is the change in shape between two moisture contents below the fiber saturation point. The change in moisture content was made without any outer restraint on the timber studs. This was done to enable a study of the effect of the material properties and avoid the effect of outer restraint.

In this study, warp and the longitudinal shrinkage coefficient were measured in the same material. In the first moisture cycle, the distorted geometry was measured and, in the second moisture cycle, the variation in the longitudinal shrinkage coefficient was measured in sticks sawn from the studs. This approach was chosen as this is the only way to identify the true variation in the longitudinal shrinkage coefficient that causes bow and crook in a single stud. It has been shown in several studies that bow and crook under the fiber saturation point is reversible during moisture cycling (Johansson 2000; Stanish 2000; Kliger et al. 1997). The longitudinal shrinkage coefficient has also been shown to be reversible in several moisture cycles at normal temperatures (Bengtsson 2001). Longitudinal shrinkage in spruce wood has been shown to be almost linear with moisture content level from 4% to 25% moisture content (Skaar 1988).

MATERIAL AND METHODS

Test material

The raw material (Norway spruce) for the test specimens came from two sources. Half the material, from southern Sweden, included 30 studs with dimensions of 45 × 95 × 2500 mm (small studs). These studs were part of another study that contained 200 studs for which trials were made to model moisture-induced warp statistically. The 30 studs were selected to obtain a large variation in the amount of bow and crook and compression wood content. The material was dried in a kiln at conventional temperature (~65°C) but without any outer restraint on the material. A description of the material, the preparations, and the results of this study can be found in (Björklund et al. 1998; Kliger 1997; Johansson and Kliger 2002).

The other half of the material came from 10 logs selected at a log yard in northern Sweden. The criterion for selecting this material was that the logs had to have at least 25% visible compression wood at the butt end. The 10 logs were sawn to dimensions of 45 × 120 × 3000 mm (large studs) at a commercial sawmill. Five logs with a small diameter were sawn to obtain two studs from each log, and the remaining larger diameter logs were sawn to obtain four studs from each log. The material was kiln-dried at conventional temperatures (~75°C) on top of a stack, i.e. without outer restraint.

The material selected in this study should be seen as individual studs. The comparison between variation in longitudinal shrinkage and bow and crook is made for each stud separately and should not be used to try to interpret differences between different origin, stud size or drying regimes as the number of studs is much too small for statistical analysis.

Test procedure

A new measurement device was developed to measure distorted geometry every ~5 centimeters along the length of the stud. This device consists of four transducers placed on a carriage which moves along a rail parallel to the measured stud (see Fig. 1). Three transducers were fastened in a horizontal position on the carriage in a straight line above each other with spacing of 35 mm when measuring studs with a depth of 95 mm. The spacing was

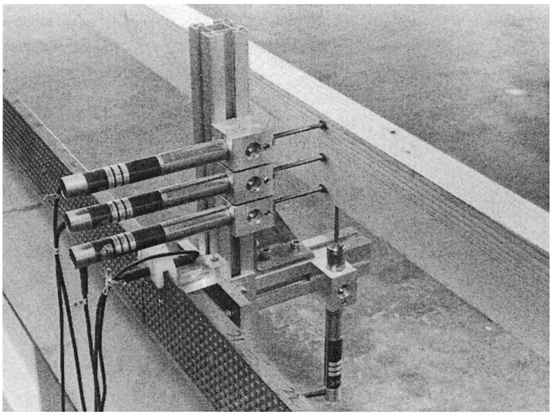

FIG. 1. Detail of equipment for measuring distorted geometry along the length of a stud. Carriage with three horizontal transducers and one vertical transducer.

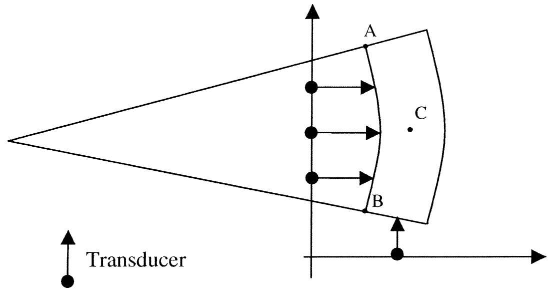

FIG. 3. Definition of the coordinate system for calculating warp values based on measurements of distorted geometry. Bow and crook are calculated as the displacement of point C in relation to the coordinate axis.

42 mm when measuring studs with a depth of 120 mm. The fourth transducer was placed vertically on the carriage and perpendicular to the edge face of a stud (Fig. 1).

The stud was placed edgewise on the supports. At one end, the stud was supported along one flat face and one edge face. At the other end, it was supported at one edge, while the flat face was supported only by a pin (Fig. 2). Before measuring the studs, a straight profile of aluminum was measured and these data were used to calibrate the warp measurement data for each stud.

This form of measurement, which measures the distance between the device and the stud along a straight line, makes it necessary to recalculate the measured values and transform them into warp values. The cup in the stud was assumed to describe a part of a circle (Fig. 3). With the help of the three horizontal transducers, this circle could be defined. The fourth vertical transducer made it possible to calculate the co-ordinates at the corners of the stud (A and B). Bow and crook were defined as the horizontal and vertical displacement of the center-point (C) of the stud in relation to the co-ordinate system. Twist was calculated as the angle between the upper and lower corners (A and B) in relation to the coordinate axis.

The bow and crook of the material was measured twice for the large studs, at 16% MC and at 12% MC. The small studs were measured with the device described above on only one occasion, at a moisture content of 16%. These studs had been measured previously at 10% MC using another measurement device, described in Perstorper et al. (2001), equipped with two extra transducers. This device made it possible to measure bow and crook at three points along the length of the stud. The warp was assumed to be linear between these measurement points. During the change in moisture content, each piece of timber was hung

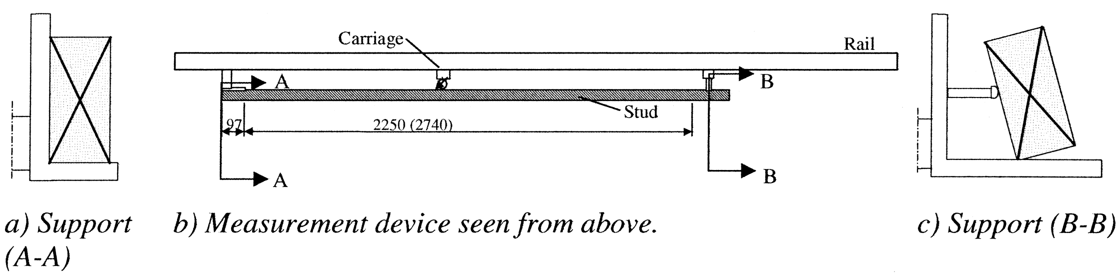

FIG. 2. Measurement device for measuring distorted geometry along the length of the studs.

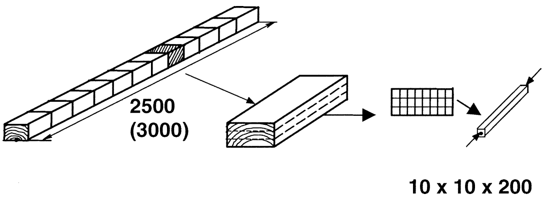

FIG. 4. Cutting the studs into blocks and sticks.

vertically in a conditioning room under ambient conditions. The purpose of hanging the timber vertically was to maximize the surface exposed to the air and eliminate any outer constraints on the material.

The measurement device described above worked very well, despite the fact that the transducers had to slide along the timber. Slight problems occurred with the holes after loose knots, but only a few of these knots were present in the measured material.

After measuring warp, 12 studs (six of each dimension) were sawn into blocks with dimensions of 45 × 95(120) × 200 mm. These blocks were sawn into sticks with dimensions of 10 × 10 × 200 mm (Fig. 4). The 12 studs were selected to obtain a large variation in measured bow and crook and in compression wood content. This was done to show that the model for bow and crook was valid for a large variety of cases.

The sawing produced 3 × 8 × 12 = 288 sticks from each of the small studs. From each of the large studs, 3 × 10 × 14 = 420 sticks were sawn. This left only 40–80 mm of the ends of each stud that were not sawn into sticks. The length and weight of each stick were measured when the sticks were conditioned to equilibrium moisture content at 90% relative humidity (RH) and 21°C and when the sticks were conditioned at 30% RH and 21°C. The oven-dried weight of each stick was also recorded after 24 h at 104°C. Longitudinal shrinkage was quantified by the shrinkage coefficient α_l, expressed as shrinkage strain (in percent) per percentage moisture content change (Eq. (1) and Eq. (2)). A description of the measurement procedure is given in (Bengtsson 2001).

$$\varepsilon_l = \frac{l_1 - l_2}{l_1} \times 100 \quad [\%] \tag{1}$$

$$\alpha_l = \frac{\varepsilon_l}{u_1 - u_2} \quad [\%/\%] \tag{2}$$

where ε_l is the shrinkage strain, l_1 is the length at 90% RH, and l_2 is the length at 30% RH, α_l is the longitudinal shrinkage coefficient, u_1 is the moisture content at 90% RH, and u_2 is the moisture content at 30% RH.

The sticks were examined visually with respect to compression wood and grouped into three groups: CW-0: No visible compression wood (no); CW-1: Widened latewood band in one or several growth rings (mild); CW-2: Dominating latewood bands in one or several growth rings (severe). This type of visual classification of compression wood has been used by Perstorper et al. (2001) and Bengtsson et al. (2001). By classifying all the sticks in compression wood classes, it was possible to study the influence of compression wood on longitudinal shrinkage.

EXPERIMENTAL RESULTS

Bow and crook

The measurements of warp showed that in most cases bow and crook were parabolic with the maximum deviation around the center of the length of the stud (Fig. 5). Generally, the measured material had fairly small knots and none of the studs therefore bent around knots forming ''knees.''

However, not all the studs displayed the nice curved form shown in Fig. 5. When it came to stud 1U1 (Fig. 6), it developed an S-shaped bow. This stud had a somewhat uneven distribution of compression wood, as well as an uneven distribution of longitudinal shrinkage.

Bow and crook in the middle of the 12 studs in both wet and dry conditions are shown in Table 1. The middle deflection was not always a good value for the maximum deflection (cf. Fig. 6), but it gave an estimate of warp that was easy to compare with the warp values that can be permitted in timber used in construc-

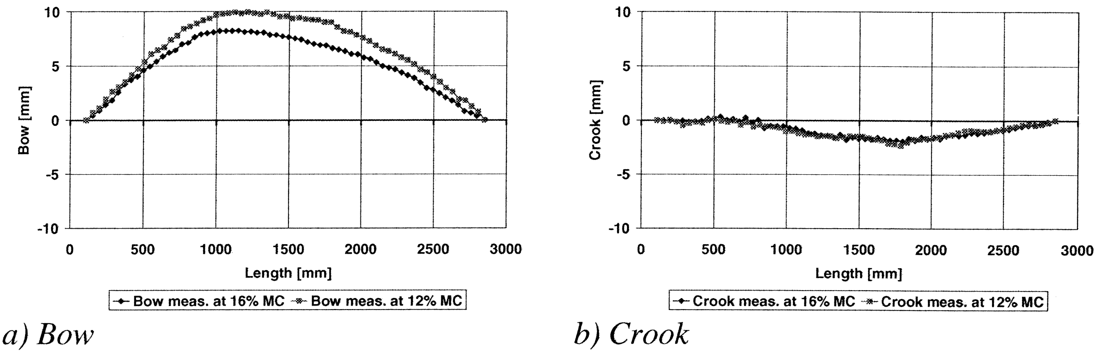

FIG. 5. Variations in deformation along the length of a stud (6U2, 45 × 120 × 3000 mm). a) bow and b) crook.

tion. It also produced a value that could be compared with the predicted warp.

For most of the studs, the deformation increased in absolute values during the change in moisture content. The magnitude of the change varied from 0.2 mm to 12.3 mm for bow and from 0.2 mm to 2.6 mm for crook. These results correlated well with the results produced in previous studies where the change in bow was always greater than the change in crook (Kliger et al. 2002).

Longitudinal shrinkage coefficient

The longitudinal shrinkage coefficient was obtained for a change in moisture content from 17.6% to 7.8%. As all the material in each stud was sawn into sticks, it was unavoidable for some sticks to have knots. In some cases, these knots were so large that the sticks were broken and no measurement of the longitudinal shrinkage coefficient could be performed. Some of the sticks had a knot on one side or had an uneven distribution of compression wood that led to the stick becoming bent during the change in moisture content, and no reliable value for the longitudinal shrinkage coefficient could be obtained. In total, it was possible to measure the longitudinal shrinkage coefficient in 3603 sticks. The results showed that the longitudinal shrinkage coefficient varies considerably; the factor between the stick with the largest shrinkage and the smallest shrinkage was 129. The results of the measurements of the longitudinal shrinkage coefficient can be found in Table 2. The longitudinal shrinkage coefficient varied considerably between studs but also within one stud.

Sticks from studs with a large mean longitudinal shrinkage coefficient also had many sticks classified as mild or severe compression

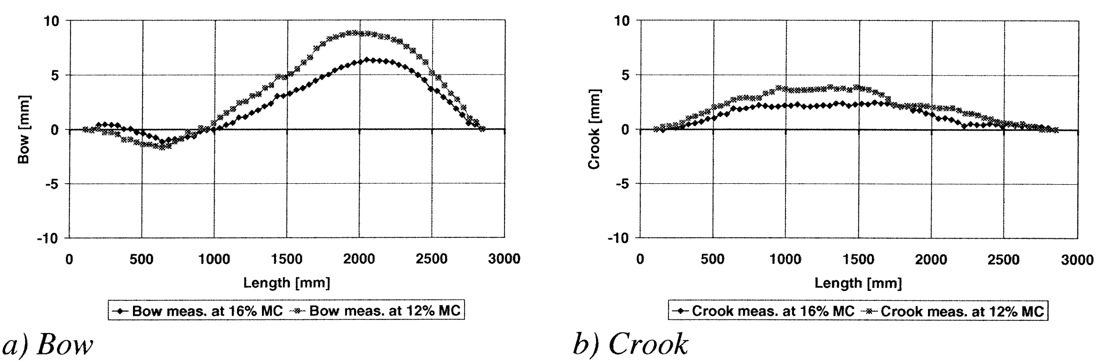

FIG. 6. Variations in deformation along the length of a stud (IUI, 45 × 120 × 3000 mm). a) bow and b) crook.

TABLE 1. *Bow and crook measured in the center of the stud for the 12 studs sawn into sticks for measurements of longitudinal shrinkage.*

No.	Dim. [mm]	Bow (wet) [mm]	Bow (dry) [mm]	Crook (wet) [mm]	Crook (dry) [mm]
110511	45 × 95	12.4	24.7	−4.2	−4.5
120632	45 × 95	3.4	2.8	−1.2	−0.6
131413	45 × 95	−0.2	0.0	3.2	4.9
140632	45 × 95	2.2	3.4	−0.6	0.2
140532	45 × 95	0.5	−7.0	−2.5	−5.0
130551	45 × 95	1.7	−2.1	−2.2	−4.3
1U1	45 × 120	3.2	4.9	2.3	3.8
4U1	45 × 120	−5.3	−8.8	3.3	5.0
6U2	45 × 120	7.6	9.5	−1.7	−1.5
7U1	45 × 120	0.4	−0.3	2.6	1.2
4U2	45 × 120	13.4	21.3	−0.2	−2.0
12N	45 × 120	0.1	1.5	−1.2	−3.8

wood. The shrinkage coefficient was significantly larger (ANOVA, Fisher's PLSD, 1% level) in sticks from the higher CW classes, CW-0 $\bar{x}$ 0.0079, CW-1 $\bar{x}$ 0.0123, and CW-2 $\bar{x}$ 0.0332. From this, it can be concluded that, if a reliable method can be found that predicts the compression wood content, it will also be possible to predict the longitudinal shrinkage coefficient.

The longitudinal shrinkage varied considerably within the same stud. Two examples of the way the shrinkage coefficient varied over a cross section of a block are shown in Fig. 7. There was a large variation in the longitudinal shrinkage coefficient from different blocks from the same stud. Figure 7a presents results in which the sticks in the back row of the cross section display the largest shrinkage coefficient, while in Fig. 7b it is the sticks in the front row that demonstrate the largest shrinkage coefficient. This would also mean that bow and crook would be in opposite directions if they were modeled on the basis of only one of these blocks.

MODEL FOR BOW AND CROOK

For the variation in longitudinal shrinkage coefficient over each block (cf. Fig. 7), a plane was adapted using multiple linear regression analysis. The regression planes were calculated on the basis of the longitudinal shrinkage coefficient of the **measured** sticks from each block. This plane was used to calculate the deformed shape of each block for a certain change in moisture content, (Fig. 8). The size of the shrinkage of one edge of the block ranged typically from 200 mm to 199.800 mm for a change in moisture content of 6%. This small change in the side length of the block was enough to cause a change in the angle between the sides of the block and the end planes.

The deformed blocks were assembled to

TABLE 2. *Values for the longitudinal shrinkage coefficient for the sticks from each stud. The table shows the number of sticks from each stud, mean, standard deviation, minimum and maximum for the longitudinal shrinkage coefficient and the number of sticks in each of the three compression wood classes.*

Stud number	Number of sticks	Mean [%/%]	SD [%/%]	Min [%/%]	Max [%/%]	Count CW-0 no	Count CW-1 mild	Count CW-2 severe
110511	259	0.0121	0.0079	0.0039	0.0573	171	64	24
120632	274	0.0069	0.0038	0.0038	0.0309	247	27	0
131413	276	0.0045	0.0021	0.0007	0.0208	225	51	0
140632	272	0.0107	0.0056	0.0055	0.0324	187	42	43
140532	227	0.0099	0.0043	0.0051	0.0297	184	29	14
130551	247	0.0066	0.0031	0.0018	0.0237	201	31	15
1U1	391	0.0141	0.0076	0.0060	0.0501	271	82	38
4U1	359	0.0117	0.0098	0.0028	0.0740	223	73	63
6U2	338	0.0084	0.0056	0.0042	0.0536	278	40	20
7U1	344	0.0255	0.0232	0.0058	0.0903	214	29	101
12N	298	0.0077	0.0062	0.0029	0.0864	242	53	3
4U1	317	0.0103	0.0111	0.0031	0.0792	225	68	24
Total	3603	0.0111	0.0111	0.0007	0.0903	2669	589	345

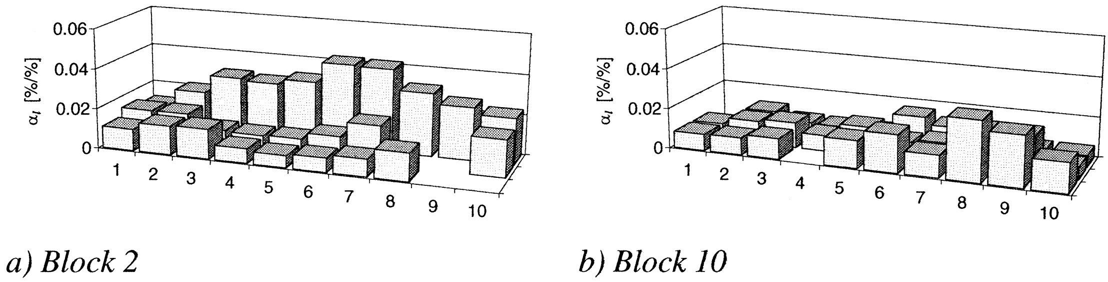

FIG. 7. Example of how the longitudinal shrinkage coefficient varies over a cross section of a block (stud IUI, cross section 45 × 120 mm). a) A block taken 250–270 mm and b) a block taken 1850–2050 mm from the end of the stud.

produce a whole stud. During the assembly, corners B1 and A2 were placed at the same coordinate so that the two end planes merged. The coordinates for corner B2 were calculated and the corner of the next block was placed at this coordinate. In the same way, the two end planes of blocks 2 and 3 coincided. In this manner, the deformed stud was built up (Fig. 9). The coordinates for the mid-point of each block end were determined. Crook and bow were calculated as the position of the midpoint of the block ends relative to the midpoint of the ends of the stud.

COMPARISON BETWEEN EXPERIMENTAL AND MODEL RESULTS

The model was used to try to identify the change in the magnitude of bow and crook between the two moisture contents. The change in the magnitude of bow between the two moisture contents is called Δbow and the change in crook is called Δcrook. The modeled Δbow showed good agreement with the measured Δbow when the change in moisture content in the model was set at 6% for the small studs (45 × 95 mm) and 4% for the larger studs (45 × 120 mm). The agreement between the measured Δcrook and the calculated Δcrook was not as good as for Δbow. The relationship between measured Δcrook and calculated Δcrook is reasonably good for 10 of the 12 studs. The less good agreement for some studs might be due to sticks with knots or uneven compression wood not being measured and therefore not included in the model.

A summary of all the results, measured and calculated Δbow and Δcrook, can be seen in Table 3. This table shows the magnitude of measured and calculated Δbow and Δcrook in the midpoint of the stud for each stud. The results generally showed good agreement between measured and calculated values. This

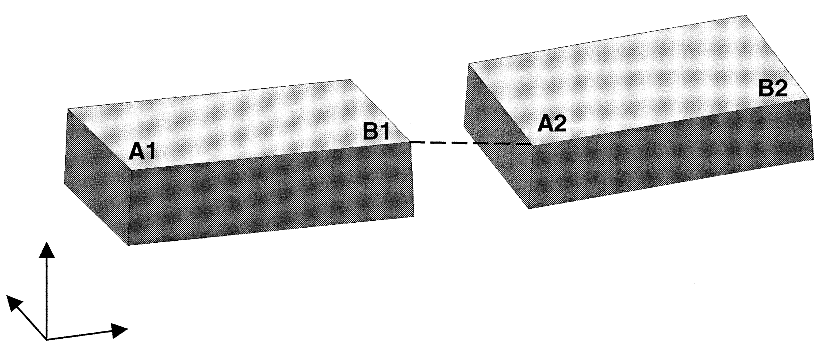

FIG. 8. Principal sketch of two distorted blocks, used as two members in the model of the distorted stud. To create a whole stud, corners B1 and A2 were joined together so that the two end planes coincided.

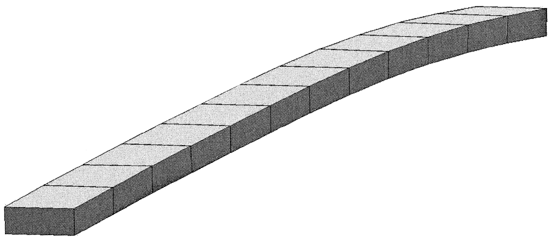

FIG. 9. Principal sketch of a stud modeled on the basis of the variation in the longitudinal shrinkage coefficient of the blocks.

indicates that a knowledge of the variation in the longitudinal shrinkage coefficient was enough to model Δbow and Δcrook with reasonable accuracy.

Figure 10 shows the result for stud 1U1, which displays good agreement between the measured and the calculated Δbow and Δcrook. With the model, it was possible to capture the behavior of the Δbow and Δcrook with good agreement, as can be seen in Fig. 10a, where both the model and the measured Δbow was S-shaped.

It was possible to model the point at which the maximum bow or crook would occur, (Fig. 11a). In addition, very small changes in warp could be modeled (Fig. 11b), which showed very good agreement with the measured change in warp.

TABLE 3. *Summary of measured Δbow and Δcrook and calculated Δbow and Δcrook between the two measurement occasions.*

No.	Dim [mm]	ΔMC [%]	Δbow (meas.) [mm]	Δbow (cal.) [mm]	Δcrook (meas.) [mm]	Δcrook (cal.) [mm]
110511	45 × 95	6.0	12.3	11.0	−0.3	0.1
120632	45 × 95	6.0	−0.6	−1.3	0.6	−0.1
131413	45 × 95	6.0	0.2	−0.8	1.7	0.8
140632	45 × 95	6.0	1.2	−3.6	0.7	0.5
140532	45 × 95	6.0	−7.4	−6.1	−2.4	−0.8
130551	45 × 95	6.0	−3.8	−4.4	−2.1	−1.1
1U1	45 × 120	4.0	1.7	1.3	1.5	1.4
4U1	45 × 120	4.0	−3.5	−4.7	1.7	0.8
6U2	45 × 120	4.0	1.8	2.4	0.2	0.1
7U1	45 × 120	4.0	−0.7	−1.5	d−1.4	1.8
4U2	45 × 120	4.0	7.9	3.2	−1.8	0.1
12N	45 × 120	4.0	1.4	1.4	−2.6	1.3

SUMMARY AND CONCLUSIONS

This paper presents the results of measurements of distorted geometry along the length of 12 studs. The equipment for measuring distorted geometry is presented. The distorted geometry was measured at two moisture contents below the fiber saturation point. The change in moisture content was made with the material hanging vertically without outer restraints. The studs were then sawn into sticks (10 × 10 × 200 mm), a total of 3,600 sticks. The longitudinal shrinkage in these sticks was obtained for a change in moisture content from 18% to 8%. The sticks were also classified visually into three groups depending on their compression wood content: no compression wood, mild compression wood, or severe compression wood.

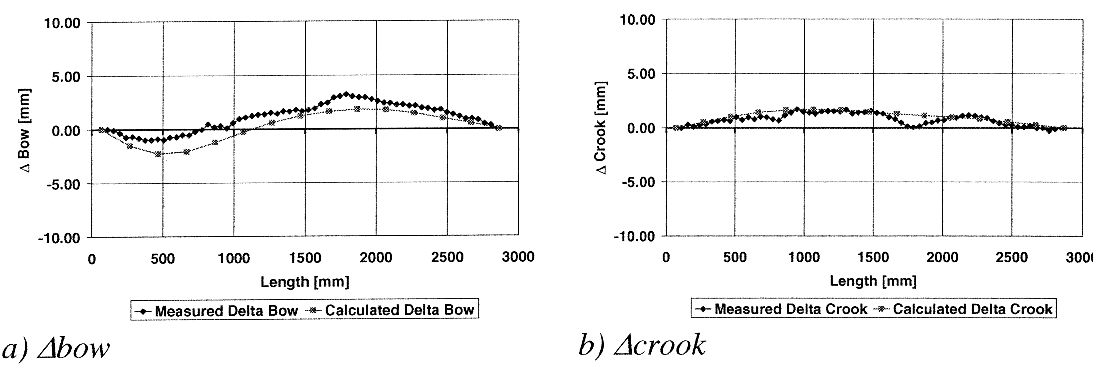

FIG. 10. Measured and calculated Δbow and Δcrook along the length of a stud (IUI, 45 × 120 × 3000 mm). a) Δbow (change in bow between the two moisture contents) and b) Δcrook (change in crook between the two moisture contents).

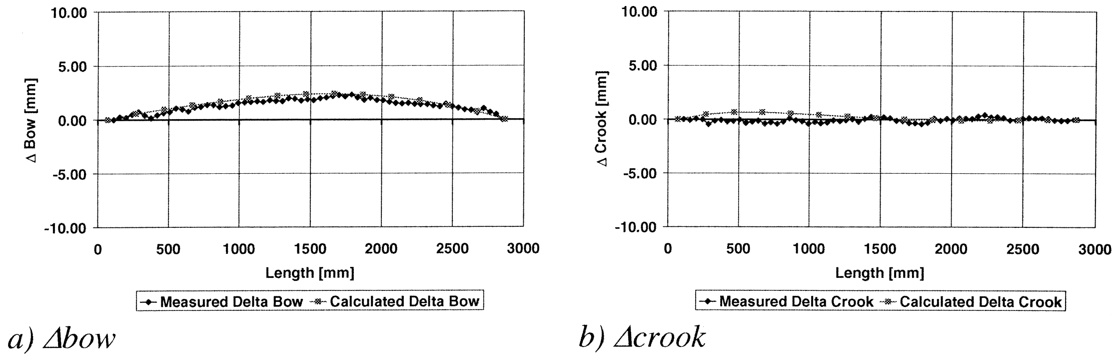

FIG. 11. Measured and calculated Δbow and Δcrook along the length of a stud (6U2, 45 × 120 × 3000 mm). a) Δbow (change in bow between two moisture contents) and b) Δcrook (change in crook between two moisture contents).

A model was made to predict the change in the magnitude of bow and crook between the two moisture contents. The model shows that the variation in the longitudinal shrinkage coefficient over the cross section and along the stud could explain most of the change in bow and crook in the studs. It was enough to use the variation in longitudinal shrinkage to model bow and crook with reasonable accuracy. The results of the model show better agreement for bow than for crook. It was possible to identify evenly curved bow and crook, as well as S-shaped bow and crook. The variation in the longitudinal shrinkage coefficient was large within the sticks studied ($\bar{x}$ 0.0111, SD 0.0111). The sticks classified as having severe compression wood had a significantly larger longitudinal shrinkage coefficient than sticks classified as no compression wood or mild compression wood. Moreover, sticks classified as mild compression wood had a significantly larger longitudinal shrinkage coefficient than the sticks classified as no compression wood.

The results in this paper reveal that material classified as having compression wood had a larger longitudinal shrinkage coefficient than material with no compression wood. It is also shown that the variation in the longitudinal shrinkage coefficient could explain most of the moisture-induced bow and crook. Using this knowledge, together with the fact that there are methods to detect compression wood, it should be possible to predict moisture-induced bow and crook. However, to fully explain bow and crook at a moisture content of 10%, it is also necessary to be able to predict or measure the bow and crook produced directly after sawing.

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REFERENCES

ARCHER, R. R. 1987. Growth stresses and strains in trees. Springer-Verlag, Berlin, Germany. 240 pp.

BEARD, J. S., F. G. WAGNER, F. W. TAYLOR, AND R. D. SEALE. 1993. The influence of growth characteristics on warp in two structural grades of southern pine lumber. Forest Prod. J. 43(6):51–56.

BENGTSSON, C. 2001. Variation of moisture-induced movements in Norway spruce. Ann. Forest Sci. 58(5):569–581.

BJÖRKLUND, L., L. MOBERG, AND H. LINDSTRÖM. 1998. Stand and tree selection—Field measurements of stand, trees, and log properties. Final Report sub-task AB1.1. FAIR CT 96-1915. Report STUD.SIMS.FR:AB1.01. Swedish University of Agricultural Sciences, Dept. of Forest-Industry-Market studies, Uppsala, Sweden.

DU TOIT, A. J. 1963. A study of the influence of compression wood on the warping of *Pinus Radiata* D. Don timber. South African Forestry J. 44:11–15.

EASTIN, I. L., S. R. SHOOK, AND S. J. FLEISHMAN. 2001.

Material susbstitution in the U.S. residential construction industry, 1994 versus 1998. Forest Prod. J. 51(9): 30–37.

FORSBERG, D. 1999. Warp, in particular twist, of sawn wood of Norway spruce (*Picea abies*). Doctoral thesis, Swedish University of Agricultural Sciences, Dept. of Forest Management and Products, Silvestria 119, Uppsala, Sweden.

GABY, L. I. 1972. Warping in southern pine studs. USDA Forest Service, Southeastern Forest Experiment Station Research paper SE-96, Asheville, NC.

HALLOCK, H. 1965. Sawing to reduce warp in plantation Loblolly pine studs. USDA Forest Service, Forest Products Laboratory. Research paper FPL-51, Madison, WI.

JOHANSSON, G., I. R. KLIGER, AND M. PERSTORPER. 1994. Quality of structural timber—Product specification system required by end-users. Holz Roh- Werkst. 52(1): 42–48.

JOHANSSON, M. 2000. Moisture-related distortion in Norway spruce timber—Influence of material properties. Licentiate thesis, Publ S 00:4, Steel and Timber Structures, Chalmers University of Technology, Göteborg, Sweden.

———, AND R. KLIGER. 2002. Influence of material characteristics on warp in Norway spruce timber. Wood Fiber Sci. 34(2):325–336.

KLIGER, R., M. JOHANSSON, AND M. PERSTORPER. 1997. Influence of three-dimensional variation in shrinkage on distortion. Pages 153–164 *in* Proc. COST Action E8, Int. Conference on Wood-Water Relations, June 16–17, Copenhagen, Denmark.

KLIGER, R. 1997. Field measurements in forests and at sawmills. Project Report sub-task AB1.1. FAIR CT 96-1915. Report STUD.CTH.PR:AB1.01. Chalmers University of Technology, Steel and Timber Structures, Göteborg, Sweden.

———, 1999. Quantification of distortion in sawn timber—Measured after sawing, after drying and during different moisture loads. Final Report sub-task B6.1. FAIR CT 96-1915. Report STUD.CTH.FSR:B6.1. Chalmers University of Technology, Steel and Timber Structures, Göteborg, Sweden.

KLOOT, N. H., AND M. W. PAGE. 1959. A study of distortion in Radiata pine scantlings. Division of Forest Products, CSIRO, Australia, Technical Paper No. 7.

MEYLAN, B. A. 1972. The influence of microfibril angle on the longitudinal shrinkage—Moisture content relationship. Wood Sci. Technol. 6:293–301.

MISHIRO, A., AND R. E. BOOKER. 1988. Warping in new crop Radiata pine 100 × 50 mm boards. Bull Tokyo University Forests 80:37–68.

OKUYAMA, T., AND Y. SASAKI. 1979. Crooking during lumbering due to residual stresses in the tree. Mokuzai Gakkaishi 15(11):681–687.

ORMARSSON, S. 1999. Numerical analysis of moisture related distortion in sawn timber. Doctoral thesis, Department of Structural Engineering, Chalmers University of Technology, Göteborg, Sweden.

PERSTORPER, M., P. J. PELLICANE, I. R. KLIGER, AND G. JOHANSSON. 1995. Quality of timber products from Norway spruce. Part 2: Influence of spatial position and growth characteristics on warp. Wood Sci. Technol. 29: 339–352.

———, M. JOHANSSON, R. KLIGER, AND G. JOHANSSON. 2001. Distortion of Norway spruce timber—Part 1. Variation of relevant wood properties. Holz Roh- Werkst. 59(1–2):94–103.

SAARANPÄÄ, P. 1994. Basic density, longitudinal shrinkage, and tracheid length of juvenile wood of *Picea abies* (L.) Karst. Scan. J. Forest Res., 9:68–74.

SHELLY, J. R., D. G. ARGANBRIGHT, AND M. BIRNBACH. 1979. Severe warp development in young-growth Ponderosa pine studs. Wood Fiber 11(1):50–56.

SIMPSON, W. T., AND T. D. GERHARDT. 1984. Mechanism of crook development in lumber during drying. Wood Fiber Sci. 16(4):523–536.

SKAAR, C. 1988. Wood—Water relations. Springer-Verlag, Berlin, Germany. 283 pp.

STANISH, M. A. 2000. Predicting the crook stability of lumber within the hygroscopic range. Drying Technol. 18(8):1879–1895.

TIMELL, T. E. 1986. Compression wood in gymnosperms. Springer-Verlag, Berlin, Germany. 2190 pp.

VOORHIES, G., AND B. R. BLAKE. 1981. Properties affecting drying characteristics of young-growth Ponderosa pine. Arizona Forestry Notes, No. 14, School of Forestry, Northern Arizona University.

———, AND W. A. GROMAN. 1982. Longitudinal shrinkage and occurrence of various fibril angles in juvenile wood of young-growth Ponderosa pine. Arizona Forestry Notes No. 16. School of Forestry, Northern Arizona University.

WARENSJÖ, M., AND C. LUNDGREN. 1998. Samband mellan tjurved och formfel hos gran—en studie vid limmareds sågverk, (Impact of compression wood on deformations of sawn spruce (*Picea abies* (L.) Karst.), in Swedish). Swedish Univ. of Agricultural Sciences, Dept. of Forest Products, Report No. 255, Uppsala, Sweden.

WOXBLOM, L. 1999. Warp of sawn timber of Norway spruce in relation to end-user requirements—Quality, sawing pattern and economic aspects. Doctoral thesis, Swedish University of Agricultural Sciences, Dept. of Forest Management and Products, Silvestria 126, Uppsala, Sweden.

ZOBEL, B. J., AND J. R. SPRAGUE. 1998. Juvenile wood in forest trees. Springer-Verlag, Berlin, Germany. 300 pp.