Holz als Roh- und Werkstoff (2005) 63: 423–429
DOI 10.1007/s00107-005-0058-8

ORIGINALARBEITEN · ORIGINALS

J. Eriksson · S. Ormarsson · H. Petersson

An experimental and numerical study of shape stability in laminated timber columns

Published online: 3 November 2005

Abstract The study concerns the question of how the shape stability features of laminated columns of Norway spruce can be improved in terms of twist through optimal orientation of the individual laminates. Both experimental testing and numerical simulations were employed for evaluating twist stability. In all the columns studied, deformations were measured experimentally at different moisture content levels. A number of columns were also selected for numerical analysis in order to obtain a more thorough understanding of the twist behavior involved, their geometries and material properties of interest being determined. The experimental results showed the twist stability of the columns to be highly dependant upon the internal orientation of the individual laminates. It was also found that high quality columns in terms of shape stability could be manufactured, even when the center-core material has a strong twist tendency. The numerical simulations performed were in close agreement with the experimental results.

Experimentelle und rechnerische Untersuchung der Formstabilität von Kreuzholzbalken

Zusammenfassung Diese Studie befasst sich mit der Frage, wie die Verdrehung von Kreuzholzbalken aus Fichte durch optimale Anordnung der zu verklebenden Teile reduziert und dadurch die Formstabilität der Balken verbessert werden kann. Die Formstabilität der Balken wurde sowohl experimentell als auch mit Simulationsrechnungen untersucht. Bei allen untersuchten Balken wurden Verformungen bei unterschiedlichen Holzfeuchten experimentell gemessen. Um das Verdrehungsverhalten besser zu verstehen, wurde dieses bei einigen Balken rechnerisch untersucht. Dazu wurde deren Aufbau und die relevanten Materialeigenschaften bestimmt.

Die Versuchsergebnisse belegten die große Abhängigkeit der Formstabilität von der Anordnung der Einzelteile. Außerdem zeigte sich, dass hochwertige formstabile Balken auch aus marknahem Holz mit starkem Drehwuchs hergestellt werden können. Die rechnerische Simulation stimmte mit den Versuchsergebnissen sehr gut überein.

J. Eriksson (✉) · S. Ormarsson
Department of Applied Mechanics, Chalmers University of Technology, Göteborg, Sweden
E-mail: john.eriksson@sem.chalmers.se

H. Petersson
School of Technology and Design, Växjö University, Växjö, Sweden

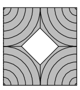
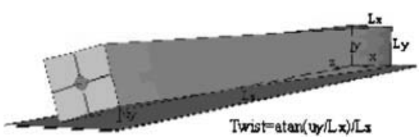
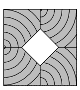
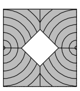
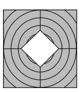
1 Introduction

Distortions in sawn timber often come about through climatic variations or through growth stresses present in the log when it is sawn into planks or boards. These distortions are a serious problem, both for the sawmill industry and for the building industry, since users often experience serious difficulties in handling distorted boards. It is not satisfactory for the user to get straight boards from the sawmill if these later become markedly distorted. Customers thus need timber and timber products that show a high degree of shape stability when exposed to climatic changes, particularly since timber structures are normally subjected to considerable climatic variations frequently. The moisture-related deformations that occur are often divided into four types: twist, cup, spring and bow. Twist is the type of distortion considered to be the most severe. It represents the main cause of the rejection of studs at building sites in Sweden (Johansson et al. 1994, Perstorper 1994, Forsberg 1999, Johansson 2002). During the last decade, the use of engineered wood products in the building industry has increased. Most studies of shape stability have been concerned, however, with individual boards (e.g. Forsberg 1999, Woxblom 1999, Ormarsson et al. 1999, Serrano and Cassens 2000, Johansson 2002, Cooper and Maun 2003, Eriksson et al. 2004). The features of many composite wood products are clearly in need of investigation.

For laminated boards, it has been shown experimentally that gluing them in an appropriate way can substantially decrease the distortions that occur, particularly twist (see Serrano and Cassens 2000, Cooper and Maun 2003, Eriksson et al. 2004). Studies that have been carried out have involved varying the orientation of the component parts, their dimensions and the tree species utilized, such as Sitka spruce, yellow poplar and Norway spruce. Numerical simulations have been performed earlier for investigating the influence of the material properties, cross-sectional size and annual ring orientation on the shape stability of individual boards; (see for example Ormarsson 1999, Ormarsson et al. 1999, Ormarsson et al. 2000). The model used in these simulations has been validated by studies of separate boards, (see Dahlblom et al. 2000, Dahlblom et al. 2001), close agreement with experimental observations being obtained. The moisture-induced distortion studies of laminated boards presented in Ormarsson (1999) and Ormarsson et al. (2001) concern numerical simulations, experimental support for the findings obtained numerically being presented recently in Eriksson (2004) and in Eriksson et al. (2004). It was concluded that if the laminates are oriented in an optimal way, boards of excellent shape stability could be produced. Other timber products, such as columns and doors, have likewise been studied numerically in (Ormarsson 1999, Ormarsson et al. 2001, Ormarsson et al. 2002). The results obtained are of particular interest in the present investigation and will be taken as a starting point in examining the twist stability of columns made of four laminates.

Some of the findings reported in Ormarsson (1999) are summarized in Table 1, which shows the degree and direction of twist that developed in columns of four types with the dimensions of $3 \times 0.1 \times 0.1\ \mathrm{m}^3$, when dried from about 27% moisture content (MC) to 12% MC. The results are given in degrees of twist per running meter of the column (°/m). A square $35 \times 35\ \mathrm{mm}^2$ hole was made at the center of the cross-section in each column. The material data used throughout the simulations was that one typical for Norway spruce under normal growth conditions. Case C4 shown at the bottom has the largest twist of all the columns presented in Ormarsson (1999), but is not part of this investigation, being included for comparison purposes only. It shows almost twice as much twist as C1. Note that C1 and C4 are of opposite twist direction. An example of positive twist is shown in the diagram at the right in Table 1. Moving the pith in theoretical terms from its being in the corners in C1, to its being at the center of the product in C4 results in a −7.3 °/m change in twist. This large difference implies that products of this type can be very sensitive to changes in the pith position. Note too, that the cases C2 and C3, although consisting of the same material, show very good twist stability as compared with that of the C1 and C4-types.

Table 1 Computed twist of various columns dealt with in Ormarsson (1999)
Tabelle 1 Errechnete Verdrehung verschiedener Balken. Aus Ormarsson (1999)

Name	Cross-section	Twist (°/m)	A column exhibiting positive twist
C1		2.80	
C2		-0.23	
C3		-0.27	
C4		-4.53	

2 Material and method

On the basis of previous findings, three different types of columns were manufactured, the orientation of the laminates used in columns C1–C3 being employed, see Table 1, although the columns studied in Ormarsson (1999) had larger holes and somewhat larger cross-sections than those studied here. Each of the columns consisted of spruce timber (Norway spruce) stemming from the central part of Sweden. To investigate the twist stability of the manufactured products, both experimental testing and numerical simulations were employed.

2.1 Geometry and sawing pattern

Each of the products manufactured was cut to 2.4 m in length and was planed to $93 \times 93\ \mathrm{mm}^2$ in cross-section, an $18 \times 18\ \mathrm{mm}^2$ square hole being made through the center of it. Each product stemmed from two center boards with split pith, as shown in Fig. 1. The sawn boards were cut through the pith once more to produce the four laminates that made up each column. On the basis of observations reported in Forsberg (1999) and Johansson (2002), it was concluded that boards sawn close to the pith develop a roughly equal degree of twist when taken from the top end of a log as when taken from the butt end. Accordingly, no consideration was taken of a board's longitudinal position in the tree. Note that C3 can be obtained from C2 by rotating and shifting the two lamellas on the right side. Moreover, columns of the C1 type, which are quite common on the market, can be manufactured from round timber, taking advantage of its wane when the square hole is made, thus saving material.

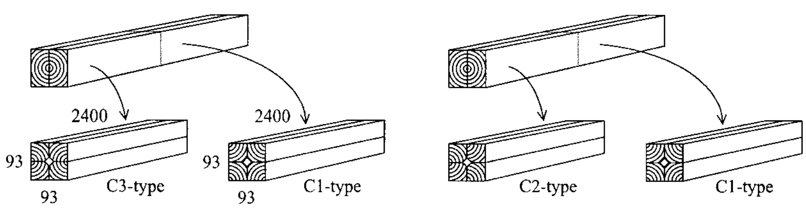


Fig. 1 Sawing patterns and glued surfaces of the columns studied
Abb. 1 Einschnitt und Anordnung der zu verklebenden Teile der untersuchten Balken

2.2 Industrial manufacturing of test specimens

The experimental work was carried out in cooperation with a Swedish sawmill. The process of manufacturing the columns involved sawing and planing the timber to form the components and then gluing them together by use of a conventional gluing procedure. All the boards used in the study were piled in timber packages and were dried without top load in a low-temperature kiln until the MC had reached a level of about 15 to 18%. When the drying had been completed, the boards that had become most twisted were selected for manufacturing of the 20 C1-type, 12 C2-type and 8 C3-type products, respectively, that were to be tested. Finally, the products were wrapped in plastic to prevent further drying during their transport to the laboratory.

2.3 Testing procedure

After arriving at the laboratory, the columns were hung in a vertical position in a room of constant humidity and temperature, at 85% RH and 20 °C, respectively. When the moisture content and the distortion had stabilized, the deformation of each column was measured. Displacements were recorded at the bottom and at one side, both in the middle and at the one end of the columns, the other end being fixed by a clamped support. A more thorough account of the frame setup and the equipment used to measure twist deformations can be found in Eriksson et al. (2004). The columns were stored then in another climate room with an RH of about 35% and a temperature of 20 °C for studying their shape stability. The experimental procedure just described was repea-

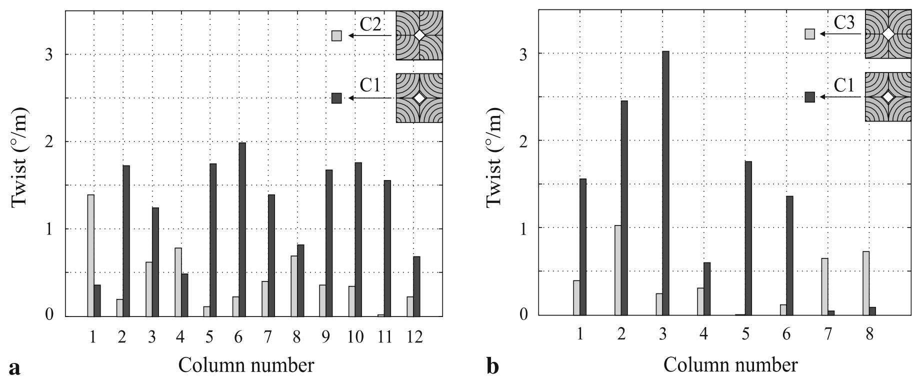


Fig. 2 Changes in twist of the wooden columns caused by a change in MC from 16.5% to 9.5%. Note that each pair of columns consists of parts from the same log. **a** Columns of the C2 type compared with those of the C1 type. **b** Columns of the C3 type compared with those of the C1 type

Abb. 2 Veränderung der Verdrehung der Balken bei einer Holzfeuchteänderung von 16, 5% auf 9, 5%. Hinweis: Jeweils beide Balken wurden aus dem gleichen Stammabschnitt hergestellt. **a** Balken vom Typ C2 im Vergleich mit Balken vom Typ C1. **b** Balken vom Typ C3 im Vergleich mit Balken vom Typ C1

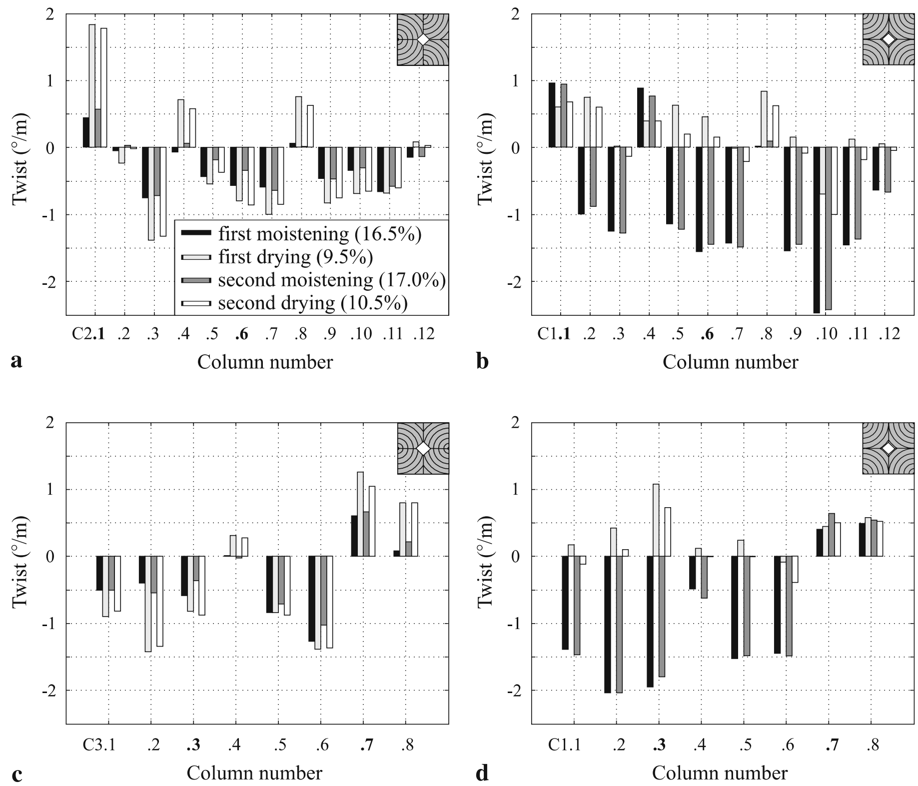


Fig. 3 Twist deformations of the columns as measured at four different moisture levels (the bold marked columns were selected for numerical simulation studies. **a** Columns of the C2-type. **b** Columns of the C1-type that stem from same log as the C2-type. **c** Columns of the C3-type. **d** Columns of the C1-type that stem from same log as the C3-type

Abb. 3 Verdrehung der Balken bei vier unterschiedlichen Holzfeuchten (die fettgedruckten Nummern wurden für Simulationsrechnungen ausgewählt. **a** Balken vom Typ C2. **b** Balken vom Typ C1 und Typ C2 stammen aus dem gleichen Stammabschnitt. **c** Balken vom Typ C3. **d** Balken vom Typ C1 und Typ C3 stammen aus dem gleichen Stammabschnitt ted once. Results for the C3 products were compared both with those for the C1 and for the C2 products stemming from the same tree, see Fig. 1.

3 Experimental results

The major results of the experimental study are presented in the following. From the standpoint of shape stability, it is the change in twist between two different moisture states that is of primary interest. The absolute changes in twist when the columns were dried from 16.5% MC to 9.5% MC are shown in Fig. 2. Clearly, the C2 and C3 columns are much more twist-stable than the C1 columns. The mean change in twist was found to be 1.33 °/m for the C1 columns, and 0.44 °/m and 0.43 °/m, respectively, for the C2 and C3 columns. Thus, for the cases C2 and C3, the average change in twist was only about a third as great. Studying the effect of repeated moistening and drying of the columns was also of interest. Looking more in detail on the results, the twist deformations at equilibrium for four different MC levels are shown in Fig. 3, where positive twist is defined in the manner illustrated by the diagram in Table 1. As can be clearly seen, twist stability was basically maintained during repeated moistening and drying. It can also be noted that for most of the C2 and C3 columns, drying led to a negative change in twist whereas for most of the C1 columns, the change in twist upon drying was positive. A few of the columns failed to follow this pattern. More specifically, the columns denoted as C2.1, C2.4, C2.8, C3.7 and C3.8 showed positive changes in twist upon drying whereas the corresponding C1-type columns partly followed and partly failed to follow the general pattern described above. On the basis of the experimental results presented, two pairs of columns that deviated from the general twist pattern and two pairs of columns that followed it were selected for further study with the aid of numerical simulations. These pairs are marked with bold numbers in the diagrams. In addition, the deformations measured were also used to obtain rough estimates of the bow at the middle of the columns. The average change in bow that moisture change led to was about 0.5 mm for the C2 and C3 products and about 1 mm for the C1 products.

4 Numerical simulations

In order to obtain a more thorough understanding of the distortion behavior of the products that were studied, finite element simulations of the eight columns that had been selected were performed. The distortion model employed consisted of two parts, one for analyzing transient moisture flow and the other for analyzing moisture-related deformations and stresses. In all the simulations, use was made of $30 \times 16 \times 16$ elements. The sources of input to the moisture model were the initial moisture state, the corresponding equilibrium moisture content of the surrounding air, and the diffusion properties and orientation of the wood fibers. The distortions that were simulated were based on the moisture content histories obtained. The constitutive model consisted of elastic, moisture-induced and mechano-sorptive strains. Account was taken of the moisture and temperature dependency of the material parameters as well as the radial inhomogenity of the material properties and the spiral grain angle. Further theoretical considerations of the model employed have been taken up (Ormarsson 1999, Ormarsson et al. 1999, Ormarsson et al. 2000). All the columns were assumed to be stress-free at an initial MC of 14%. The products were moistened to a 16.5% MC and dried then to a 9.5% MC. Each of the columns was free to deform during the variation in moisture, fixed boundary conditions only being introduced to prevent rigid body motions.

4.1 Material data

The most important material parameters for predicting twist stability under varying climatic conditions are the cross-grain shrinkage and the spiral grain angle. In addition, the pith position and the column geometry needed to be estimated. The test specimens were manufactured from the eight columns selected earlier. The origin of the specimens within each of the columns is illustrated in Fig. 4. The cross-sectional geometry and pith positions were assessed using a graded check-patterned slide, specimens for the shrinkage test being produced from clear-wood samples. To obtain estimates of variation in the spiral grain angle and in shrinkage, four and three samples, respectively, were manufactured for determining these parameters. In cases in which the pith direction deviated from the longitudinal direction of the columns, this was compensated for during sample preparation. The values taken for the diffusion coefficients used in the simulations were those typical at 20 °C for Norway spruce, as given in the literature. The values chosen were 4×10^{-10} m^2/s in the cross-grain directions and 13×10^{-10} m^2/s in the longitudinal direction. Additional material data such as stiffness and mechano-sorption in Norway spruce were taken from Ormarsson (1999) as typical values. The coordinates used for defining the geometry of the columns were those representing the average of the coordinates as measured at the root end and at the top end of the various columns. Since each column consisted of four lamellas, the pith position of each lamella had to be specified. The pith was assumed to vary in a linear manner between the coordinates at the two ends.

Shrinkage properties. The samples were weighed continuously during moistening and drying. For each of the samples, moisture equilibrium was assumed to been reached when the change in weight was less than 0.001 g per 24 h. Shrinkage measurements

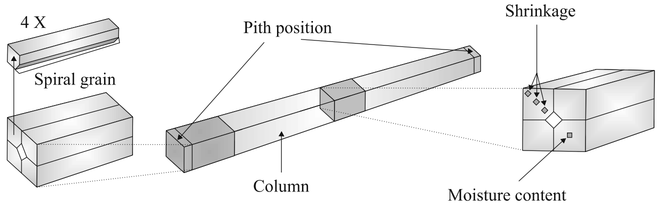


Fig. 4 Origins within the columns of the material specimens of small size
Abb. 4 Entnahmestellen der kleinen Proben aus dem Balken

were performed in a climate chamber under two different moisture conditions, 45% RH and 80% RH, corresponding to about 10% MC and 14.5% MC, respectively, the dry density of the MC samples being determined later by use of the oven-dry method (drying the sample for 24 h at 103 °C). The samples were $200 \times 10 \times 10\ \mathrm{mm}^3$ in size. A displacement gage was employed for measurements in the radial and tangential directions when the moisture in the samples had reached a state of equilibrium. The results are shown in Fig. 5, the averages obtained corresponding to typical values for Norway spruce as given in the literature, although the maximum and the minimum shrinkages that occur differ by a factor of about three in the radial direction. A high radial value appears to be accompanied by a high degree of tangential shrinkage and a low radial value by a low tangential shrinkage coefficient. On the average, the tangential shrinkage was about twice the radial. In Fig. 5, shrinkage parameters that pertain to the same column are denoted by a common symbol. The average of the three measurements obtained in each case is assumed to be representative for the column in question, the influence on the shrinkage parameters of the distance of the sample from the pith being neglected. The means of the cross-grain shrinkage parameters as measured are listed in Table 2.

Spiral grain. The spiral grain angle was determined using a slope-of-grain indicator that included a scriber and a protractor setup, the angle of the scriber groove being measured. The average of two spiral grain measures was obtained for each of the four laminates. To estimate the radial variation in the spiral grain angle, a few annual rings were peeled off after each reading. The measurement results are shown in Fig. 6. The average values obtained are similar to those given in literature. The coefficient of determination was found to be 0.12 for the linear variation of the spiral grain angle as seen in relation to the distance from the pith. This is comparable to what was found in a more extensive spiral grain study concerning Norway spruce, (see Perstorper et al. 2001). Although it may appear that the spiral grain angle is poorly correlated to the distance from pith when all the samples are examined at the same time, when each column is studied separately, the assumption of a linear relation appears justified, see Fig. 7. Note that the spiral grain angles shown in Fig. 7 vary rather much if one bears in mind the fact that all the material stems from the same tree. On the basis of the experimental observations, the function for the spiral grain angle θ (°) was taken to be linearly dependent upon the distance from pith r (mm), such that

$$\theta = A + B \times r \tag{1}$$

The coefficients A and B were determined by a least square fit of the measured data to Eq. 1, see Table 2.

4.2 Simulation results

The numerically simulated twist results together with the measured ones are shown in Fig. 8. In most cases, the numerical predictions agree well with the experimental findings. The behavior of the twist stable column C2.6 and the corresponding twist-prone one column C1.6 is closely predicted by the numerical results. Simulation showed that the twist stability of C3.7 and C1.7 was approximately equal and the experimentally measured twists were in reasonable accordance. In the simulations, C3.3 showed only a small change in twist upon drying in contrast to C1.3. The experimental results support the behavior of both types, the deviation from the predicted twist value being

Table 2 Coefficients for the spiral grain function and the cross-grain shrinkage parameters as measured for the eight columns selected for numerical simulations
Tabelle 2 Koeffizienten der Gleichung für den Faserwinkel sowie gemessene radiale und tangentiale Schwindmaße der acht für die Simulationsrechnung ausgewählten Balken

	C2.1	C1.1	C2.6	C1.6	C3.3	C1.3	C3.7	C1.7
A	3.79	4.02	5.43	4.22	7.30	6.21	1.38	2.28
B	−0.131	−0.056	−0.043	0.006	−0.086	−0.067	−0.034	−0.058
α_r	0.106	0.199	0.164	0.230	0.176	0.171	0.186	0.214
α_t	0.290	0.308	0.295	0.330	0.384	0.314	0.339	0.365

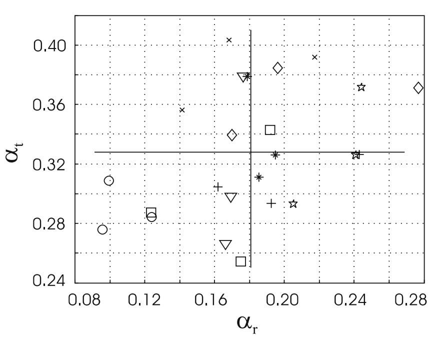


Fig. 5 The radial versus tangential shrinkage parameters. Each symbol corresponds to one particular column and the solid lines denote the overall average
Abb. 5 Zusammenhang zwischen radialen und tangentialen Schwindmaßen. Jedes Symbol entspricht einem bestimmten Balken. Die durchgezogenen Linien geben die Gesamtmittelwerte an

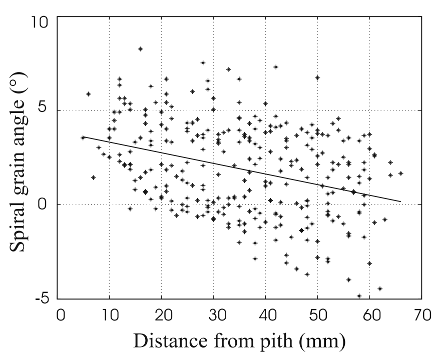


Fig. 6 Spiral grain angle versus distance from the pith for eight tested columns. The solid lines denote the average linear relation and the cross marks the measured value of the spiral grain angle
Abb. 6 Zusammenhang zwischen Faserwinkel und Abstand vom Mark von acht untersuchten Balken. Die durchgezogenen Linien geben die mittlere Abhängigkeit an. Die Kreuze den einzelnen Messwert

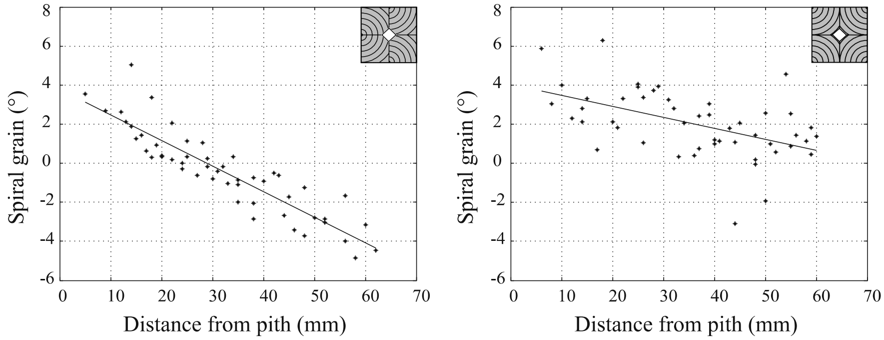


Fig. 7 Spiral grain angle versus distance from the pith for column C2.1 and the corresponding C1-type column
Abb. 7 Zusammenhang zwischen Faserwinkel und Abstand vom Mark des C2.1 Balkens und des entsprechenden Balkens vom Typ C1

greater in the latter case. The column C2.1, which showed an unexpectedly large twist during the experiments, was found to behave in basically the same way in the simulations. The behavior of the corresponding C1.1 column, however, was not predicted in a satisfactory way, showing numerically a change in twist of opposite sign to that obtained in the experiments. The spiral grain function was found to be quite unlike that for C2.1 and for the corresponding C1 column, although the lamellas stem from same tree, see Fig. 7. It could have been expected that the spiral grain function for the various products would have been similar, yet spiral grain measurements are generally difficult and may be sensitive to local anomalies in fiber directions, such as through closeness to a knot. The large differences observed and the close agreement with the results of the experiments motivates use of the function obtained for C2.1 in computation of the C1 product. The twist became -0.28 °/m instead of 0.86 °/m, the former being in closer agreement with experimental findings, see the striped bar in Fig. 8. In a manner similar to what was found for C2.1, C1.3 showed a somewhat larger twist in the simulations through use of the spiral grain function obtained for C3.3.

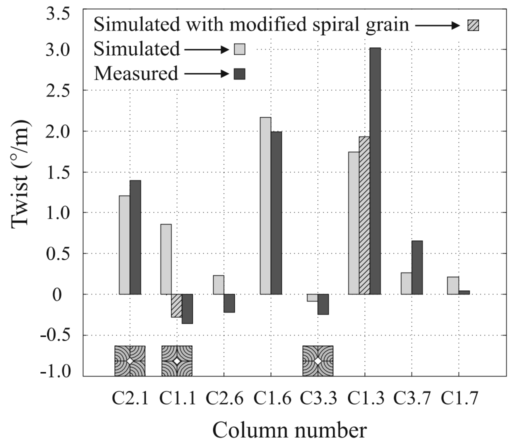


Fig. 8 Comparison of numerical and experimental results for twist for a selected set of columns following a change in MC from 16.5 to 9.5%
Abb. 8 Vergleich der rechnerisch und experimentell bestimmten Ergebnisse der Verdrehung ausgewählter Balken bezogen auf eine Holzfeuchteänderung von 16, 5% auf 9, 5%

5 Conclusions and discussion

On the basis of results presented it can be concluded that for a given change in moisture content the C2 and C3 columns were more twist-stable than the corresponding C1 columns. The columns were shown to differ in the direction of twist obtained upon drying despite their consisting of similar material. During repeated moistening and drying, all the columns maintained their shape stability in terms of twist, there being no evidence of products tending to deviate from the twist pattern found generally. None of the products studied showed any substantial moisture-induced spring or bow. In most cases, results for simulated twist agreed well with the corresponding experimental results. The C2.1 and the corresponding C1 product deviated from the general twist pattern to some extent. Numerical simulation showed that this could be explained, however, by the pith being displaced from its normal position as well as by the large slope of spiral grain angle. Deviations in the twist pattern of the C3.7 and C1.7 columns were found to mainly be due to the spiral grain function involved since the pith was located close to its intended position. The same can be thought to apply to C3.8, the spiral grain function of which was found to deviate markedly from the average, although this product was not studied further.

When the correct shrinkage parameters, the spiral grain angle and the pith position were taken into account, the simulation tool was found capable to predicting well the twist which actually occurred in the individual columns and whether or not it would obey the general pattern of twist. It appears therefore, that products sensitive to deviations in pith location should be analyzed individually with the correct pith position being taken into account. In such an analysis, one needs to clarify how the properties of the material, its internal structure and the environmental conditions affect the moisture-related deformation process. It can be concluded that the technique developed here for orientating the various component laminates relative to each other can be used to reduce twist deformation markedly in other types of products as well since columns with good shape stability are obtained, even from center-core timber with a strong twist tendency.

Acknowledgement The authors would like to express their gratitude to the following persons: Birger Åström for help with organizing the industrially manufacture of the columns and to Hannah Epmeier and Nils Nilsson for their assistance in producing the specimens used in determining the shrinkage parameters.

References

Cooper G, Maun K (2003) Reducing distortion by green gluing and reengineering. Seminar: Advances in wood drying. COST Action E15, STRAIGHT, 20 November, Limerick University, Limerick

Dahlblom O, Petersson H, Ormarsson S (2000) Stiffness, strength and shape stability grading analysis of sawn timber based on experimentally found growth characteristics. In: Proceedings of the World conference on timber engineering, 31 July–3 August Whistler, Canada

Dahlblom O, Petersson H, Ormarsson S (2001) Full 3-D FEM-simulations of drying distortions in Spruce boards based on experimental studies. In: Proceedings of the 7th International IUFRO Wood Drying Conference, 9–13 July, Tsukuba, Japan

Eriksson J (2004) Study of moisture flow and moisture induced distortions in sawn boards and laminated timber products. Lic. thesis, Publication 2004:2, Dept. of Structural Engineering and Mechanics, Chalmers University of Technology, Gothenburg

Eriksson J, Ormarsson S, Petersson H (2004) An experimental study of shape stability in glued boards. Holz Roh- Werkst 62:225–232

Forsberg D (1999) Warp, in particular twist of sawn wood of Norway spruce (Picea abies). PhD thesis, Dept of Forest Management and Products, Silvestria 119, Uppsala

Johansson G, Kliger IR, Perstorper M (1994) Quality of structural timber-product specification system required by end-users. Holz Roh- Werkst 52:42–48

Johansson M (2002) Moisture-induced distortion in Norway spruce timber: experiments and models. PhD thesis, Dept of Structural Engineering, Chalmers University of Technology, Gothenburg

Ormarsson S (1999) Numerical analysis of moisture-related distortions in sawn timber. PhD thesis, Publication 99:7, Dept. of Structural Mechanics, Chalmers University of Technology, Gothenburg

Ormarsson S, Dahlblom O, Petersson H (1999) A numerical study of the shape stability of sawn timber subjected to moisture variations, Part 2: Simulation of drying board. Wood Sci Technol 33:407–423

Ormarsson S, Dahlblom O, Petersson H (2000) A numerical study of the shape stability of sawn timber subjected to moisture variations, Part 3: Influence of annual ring orientation. Wood Sci Technol 34:207–219

Ormarsson S, Petersson H, Dahlblom O (2001) Engineering tools to construct timber products with good shape stability. In: Proceeding of the 3rd European COST E15 workshop on wood drying, 11–13 June, Helsinki, Finland

Ormarsson S, Dahlblom O, Petersson H, Eriksson J (2002) Computer analysis to design laminated timber products with good shape stability. Report 02:8, Dept of Structural Mechanics, Chalmers University of Technology, Gothenburg, Sweden

Perstorper M (1994) Quality of structural timber- end-user requirements and performance control. PhD thesis, Div of Steel and Timber Structures, Chalmers University of Technology, Gothenburg

Perstorper M, Johansson M, Kliger R, Johansson G (2001) Distortion of Norway spruce timber. Part 1. Variation of relevant wood properties. Holz Roh- Werkst 59:94–103

Serrano R, Cassens D (2000) Reducing warp and checking in plantation-grown yellow-poplar 4 by 4's revering part positions and gluing in the green condition. Forest Prod J 51:37–40

Woxblom L (1999) Warp of sawn timber of Norway spruce in relation to end-user requirements – quality, sawing pattern and economic aspects. PhD thesis, Dept of Forest Management and Products, University of Agricultural Science, Uppsala