Compression wood in Scots pine and Norway spruce -Distribution in relation to external geometry and the impact on dimensional stability in sawn wood

Mats Warensjö
Department of Forest Products and Markets
Umeå/Uppsala

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Abstract

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With the aid of compression wood the conifer trees are able to maintain their predetermined growth form. Compression wood is formed as soon as the tree is displaced from its normal vertical position. Trees with expressed curvature do often contain large amounts of compression wood. Straight trees or trees that are leaning can also contain substantial amounts of compression wood.

This thesis gives a summary and discussion of results from five studies concerned with: the distribution of compression wood in relation to external stem and log geometry and the impact of the compression wood distribution on deformations of sawn timber. Moreover the straightening process of trees is discussed.

In order to study the distribution of compression wood in stems and logs, 63 trees of Norway spruce and Scots pine representing different age and curvature categories were sliced into 621 discs. In order to study the impact of compression wood on deformations of sawn timber, 146 logs of Scots pine and Norway spruce were processed into studs and battens. Before crosscutting, the external geometry of stems and logs were assessed. A 3D-logscanner was used for the assessment of logs. Deformations such as bow, spring and twist were measured on studs and battens at green condition, at 18% moisture content and at 12% moisture content. Compression wood content in thin cross sections of discs, studs and battens were analysed using transmitted light and image analysis.

The analyses showed that a majority of all discs and cross sections contained compression wood. In all studies, the pith eccentricity was significantly correlated to the discs´ compression wood content. For the 6-year-old Scots pine trees, the compression wood content was significantly correlated to the size of basal sweep but not to out-of-roundness. For the 22-year-old Scots pine trees, the compression wood content was not correlated to either bow height or size of basal sweep. For the 60-year-old Norway spruce trees, the compression wood content was significantly correlated to compression wood content in log ends, pith eccentricity and bow height. For sawn timber, the compression wood content and its position were significantly correlated to bow and spring but not twist. Twist was significantly correlated to grain angle measured on tangential faces of studs and spiral grain angle measured under bark on the surface of logs.

Results indicate that eccentric growth and compression wood formation play major roles in the development of stem straightness. Moreover, young trees with basal sweep will be straighter over time. Consequently, the straightness of a log is not a reliable measure of the compression wood content within the stem. By combining data describing external geometry with information regarding compression wood content and pith eccentricity obtained from log ends it is possible to detect logs that are prone to contain compression wood. The results also indicate that the distribution of compression wood in sawn timber influences the direction and size of bow and spring.

Keywords: *Pinus sylvestris* L., *Picea abies* (L.) Karst., stem form, reaction wood, sawn wood, deformations.

Author’s address: Mats Warensjö, Department of Forest Products and Markets, Swedish University of Agricultural Sciences, SE-901 83 Umeå, Sweden.
e-mail: mats.warensjo@spm.slu.se

Contents

Appendix

The present thesis is based on the following papers, which will be referred to by their Roman numerals:

I. Rune, G. & Warensjö, M. 2002. Basal sweep and compression wood in young Scots pine trees. *Scandinavian Journal of Forest Research 17:* 529-537.

II. Warensjö, M. & Rune, G. Stem straightness and compression wood in a 22-year-old plantation of container-grown Scots pine. *Accepted for publication in Silva Fennica*.

III. Warensjö, M., Nylinder, M. & Walter, F. 2002. Modelling compression wood in Norway spruce using data from a 3D-laser scanner. Conference article presented at the 4th IUFRO WP S5.01.04 Workshop, Harrison Hot Springs Resort, British Columbia, Canada, September 8-15. *Submitted manuscript.*

IV. Warensjö, M. & Rune, G. The impact of compression wood and grain angle on deformations of studs from 22-year-old Scots pine trees. *Submitted manuscript*.

V. Warensjö, M. The impact of compression wood on deformations of battens from Norway spruce sawlogs. *Manuscript.*

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Sollicite quærunt Lappones arborem hanc caudice nutantem, quæ ad ripas & in paludibus fæpe reperitur, cum ligni pars terram fpesstans durior fit, Buxi inftar, quod lignum Tiorn, feu Kiorn vocant; ex hocce conficiunt foleas fuas longiffimas feliffimi Solini Himantopodes, qui hyeme repunt magis, quam incedunt, qui faliunt communiter vno pede & cadendo currunt.
Arcus fuos, quibus ad Sciuros vulgares ac volitantes (qui rariores) occidendos vtantur e ligno Kiærn (x.) conficiunt, coniunsscto hocce cum ligno Betulino, conglutinatis mediante glutine ex cute Percarum confessto, quo arcus femet ipfum extendat chorda relaxata.

Carolus Linnæus, 1737. Flora Lapponica: exhibens plantas per lapponiam crescentes.

In old Swedish

“Ofta anträffas vid stränder och kärr träd med krokig stam; efter sådana leta lapparna ifvrigt, emedan den mot jorden vända veddelen är hårdare, liknande buxbom. Denna ved kallas *Tiörn* eller *Kiörn*, och utaf denna förfärdiga dessa lyckliga Himantopoder sina mycket långa skidor, med hvilka de om vintern mera glida framåt än gå, i det att de hoppa upp med ena foten och kila iväg genom att kasta sig framåt.

Sina bågar, vilka de begagna till att döda ekorrar, både vanliga och flygande (hvilka de senare äro sällsyntare), förfärdiga de af kiörn-trä, men foga härtill björkträ; dessa sammankitta de med ett af abborrskinn beredt lim. Härigenom kan bågen af sig själf återtaga sin form, sedan strängen lossats”

Carl von Linné, 1737. Flora Lapponica

Introduction

Background

The nature of compression wood has attracted the attention of numerous scientists, especially during the last century. One of the first to discuss compression wood was Carl von Linné, who, during his travel to the most northern county of Sweden in 1737, described crooked pines that had hard and dark wood that resembled boxwood on their lower side (Linné 1977). He also described compression wood as a desired raw material for skis and bows among Laplanders. This appreciation for compression wood is far from the opinions of today when compression wood more or less is considered to be a serious problem in mechanical wood processing due to the release of residual stresses during sawing, its high longitudinal shrinkage during drying, the brittle fracture and its high level of hardness (Timell 1986; Archer 1987; Perstorper *et al.* 1995, Warensjö & Lundgren 1998; Öhman 2001; Johansson 2002; Rikala 2003). The high lignin content and low cellulose content also make it an undesirable feature for pulp and paper manufacture (Ollinmaa 1959; Timell 1986).

Compression wood is present in all conifer trees, especially in branches and in the stem wood beneath branches (Zobel & Haught 1962; Timell 1986). Compression wood is also often associated with stem defects such as sweeps, crooks and forks, mostly in Scots pine (Tikka 1935; Uusvaara 1974). The compression wood content in stands can be regulated by silvicultural regimes, out of which the method of regeneration is considered to be important (Rune 2003). The introduction of container grown seedlings in the beginning of the seventies emphasised the problem of future wood quality. Other silvicultural regimes such as cleaning and thinning also affect the incidence of compression wood in stands (Reader & Kurmes 1996). Crooked trees and trees with forked stems are normally removed during such regimes. However, the amounts of compression wood in the remaining trees might increase due to more rapid growth and wind sway (Cown 1974; Voorhies 1982).

The introduction of a new Swedish classification system for sawlogs in 1995 emphasised the importance of compression wood as an important quality feature (Anon. 1995). According to the new system, logs should be graded according to external quality features on log surface and in log ends. The compression wood content within the yield cylinder had to be limited within most quality grades. As a consequence many butt logs, that were prone to contain compression wood, ended up as pulpwood instead of sawlogs. The forestry industry reacted to this and shortly after, more liberal limits for compression wood content were introduced. However, since curved logs more or less always contain compression wood, the limits for maximum allowed bow height was changed from 2% of log length to 1% for better grades (1-3) (Anon. 1999).

Since log grading is considered both time-consuming and expensive, new grading routines for the future have been issued. According to the Swedish Timber Measurement Council the new grading routines will mostly rely on external geometry measurements. As a consequence the compression wood content in log ends will probably not be considered during ordinary log grading. What the effects of these new grading routines will be, in terms of detecting logs containing compression wood, needs to be investigated.

Anatomical features of compression wood

On a macroscopic level, compression wood is often recognised by its characteristic colour (Timell 1986). It is the colour and hardness of compression wood that has given this tissue a variety of names, e.g. red wood, glossy wood and hard streak. Compression wood appears dark because it absorbs more light, due to the high lignin content, and scatters less light, due to thick tracheid walls. As a general rule, the intensity of the colour of stem compression wood increases with increasing severity. However, many exceptions have been reported, e.g. Yumoto *et al.* (1982) reported no difference in the colour of the compression wood in trees displaced at 45° and at 90° from the vertical. They also noticed that the depth of colour decreased in the course of time course after inclination and suggested that this was an adaptation of the tree to a new equilibrium position. From the consideration of colour differences and microscopical studies it is obvious that compression wood is developed in different degrees of severity (Yumoto *et al.* 1983).

The cell wall is comprised of three structural substances: cellulose, hemicelluloses and lignin (Koch *et al.* 1990). The framework is cellulose within microfibrils. In normal wood, the cell wall of a mature tracheid consists of an outer primary wall and a secondary wall comprised of three layers S1, S2 and S3 (Fig. 1). In the primary wall the cellulose microfibrils are randomly distributed but in the secondary wall varying alignments are found in both the S1 and the S3-layer. In the thickest layer of the secondary wall, the S2-layer, the microfibrils are aligned almost along the longitudinal axis of the tracheid. The alignment of the microfibrils in relation to the longitudinal axis of the tracheid is often referred to as the micofibril angle (MFA). In juvenile wood and especially in compression wood the MFA is large. To a large extent, it is the MFA that governs the longitudinal shrinkage in wood. Koch *et al.* (1990) reported angles of more than 45° in severe compression wood.

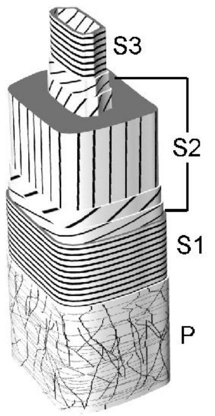

Fig. 1. Fibre model describing the micofibril angles in different layers of a mature late wood tracheid (Brändström 2002).

In cross sections, compression wood is characterised by thick cell walls and rounded outline of its tracheids, the profuse occurrence of spaces and the absence of the inner part of the secondary wall, the S3-layer (Ollinmaa 1959). The inner part of the secondary cell wall in severe compression wood is often highly lignified and is referred to as the S2 (L)-layer. In longitudinal sections, the secondary cell walls show abundant radial striations. Ollinmaa (1959) also found that in compression wood tracheids were shorter compared to those in normal wood. The radial striation is often referred to as helical cavities and the spaces are often referred to as intercellulars or intercellular spaces (Yumoto et al 1983).

The grading system of compression wood presented by Yumoto et al (1983), probably one of the most detailed systems, is based on various anatomical features. The grading system holds for compression wood tracheids in the middle of a growth ring. According to the authors, helical cavities, UV-absorption caused by the excessive lignification and the cell-wall thickness are considered to be primary properties of compression wood tracheids. Other properties such as the outline of the boundary between S1 and S2 (L), the outline of the bordered pits and the presence or absence of intercellular spaces and an S3 layer are less important.

The occurrence of the characteristic lignin distribution especially in the S2 (L) layer is probably the most essential feature of compression wood tracheids (Yumoto *et al.* 1983). This characteristic distribution is only found in compression wood and covers nearly full range of the severity of compression wood (Fig. 7). In severe compression wood the strong absorption in the S2 (L) layer is distributed almost evenly around the circumference of the tracheids (Yoshizawa *et al.* 1999). When the severity decreases the absorption decreases. The decrease is more apparent in the S1 and the inner part of the S2 layer. As the degree further lowers strong UV-absorption becomes concentrated near cell corners.

Formation of compression wood

Immediately after a conifer tree is displaced from its normal vertical position it will try to regain this vertical position by forming compression wood on the lower side of the displaced portion of the tree (Westing 1965). The recovery is often rapid, beginning with the upper part of the stem resulting in overcorrection (Cremer 1998). In vertically growing trees the outer layers of the stem are in tension while the centre is in compression. Leaning conifers are subject to considerable compressive stress along both the lower and upper periphery of the stem. The compression on the lower side is partly caused by the weight of the tree but more important is the active pressure exerted by the longitudinally expanding compression wood. Compression wood has two functions for the tree, to give static support and to exert dynamic pressure. The high flexibility of compression wood protects the tree from fracture and the high elasticity facilitates recovery (Timell 1986).

Previously it was suggested that compression wood formation was triggered by gravitational stimulus (Archer & Wilson 1973). This theory has been questioned by for example Kwon (2002), who conducted studies in a space shuttle and found that compression wood was formed even at microgravity. Yumoto *et al.* (1982) found that branches that were bent upwards formed compression wood on the upper side. The expanding mechanism of compression wood has been explained as an effect of excessive lignin swelling due to high micofibril angles in the S2-layers (Boyd 1973, Donaldsson 2001). According to another theory, the microfibrils of the S2-layer act as helical springs that during compression exert a compressive stress that either push the stem upright or stabilises it (Bamber 2001). Gindl (2002) found evidence for the fact that the increased lignin content in compression wood leads to increasing compressive strength. According to Burgert *et al.* (2003) the special quality of compression wood is not related to an exceptionally high compressive strength but to the capacity for generating compressive stresses. They state that the optimised generation of compressive stresses demands a high flexibility of each compression wood tracheid.

Juvenile stability

The juvenile stability of trees clearly impacts the future development of stem form (Moss 1971). Mechanical instability may result in leaning stem (Burdett 1979) and development of basal sweep when small trees strive to regain a vertical position by forming compression wood (Larson 1965; Archer & Wilson 1973; Yoshizawa *et al.* 1986; Timell 1986; Cremer 1998). Compression wood in the area surrounding the pith appears in most conifer trees (Du Toit 1963; Low 1964; Timell 1986). Moreover, small trees are especially susceptible to environmental forces that cause formation of compression wood during juvenile growth (Zobel & Sprague 1998).

Trees with pronounced basal sweep often develop a sinuously shaped stem due to overcorrection (Mork 1928; Low 1964; Cremer 1998; Spicer *et al.* 2000). Downes *et al.* (1994) suggest that the cause of sinuosity is biomechanical, with longer, more slender internodes being more susceptible to stem sinuosity than shorter, wider internodes. Spicer *et al.* (2000) found that the frequency but not the size of pith deviations was related to internode length. They suggested that leader damage was not a major cause of sinuous growth. There are different reasons for mechanical instability in trees, but root deformations (Håkansson & Lindström 1989; Lindström 1998) and environmental factors such as wind, snow and soil type are the most important ones (Low 1964; Moss 1971; Robertson 1990; Goulet 1995; Cameron & Dunham 1999).

It is probable that wind is one of the major causes for the formation of compression wood (Low 1964; Larson 1965; Nicholls 1982; Robertson 1990; Robertson 1991). According to Larson (1965), the requirements for sway induced compression wood formation are not just only a minimum amount of sway but also a minimum duration of sway. Factors such as wind force, snow load and gravitational unbalance affects the bending of a tree (Skatter & Kucera 1997). When trees are subjected to wind forces, bending deformation occurs when there is symmetry in the plane. If the tree has a crook in this plane, if the crown is unevenly distributed in this plane, or even if the roots are not symmetric in this plane, the tree will also be twisted by the wind. This twisting movement is also caused by the inclination of tracheids in the tangential direction, thus forming a helix around the stem axis, a phenomenon called spiral grain (Skatter & Kucera 1997).

Compression wood in relation to external geometry

It is well known that leaning trees or those that have a pronounced curvature such as sweep, crook or sinuosity, often contain compression wood. Cross sections from these trees tend to be elliptical with eccentric pith (Mork 1928; Larson 1965; Barger & Ffolliott 1976; Nicholls 1982; Robertson 1991). The relationship between external geometry of stems and the distribution of compression wood have been discussed by e.g. Low (1964) and Koch *et al.* (1990) among others. However, even straight, vertical trees with circular boles can contain large amounts of compression wood (Low 1964).

It seems that there is little or no correlation between displacement and the amount of mild or moderate compression wood present in moderately leaning or slightly curved stems. Nicholls (1982) found eccentricity to be a better indicator of compression wood than the angle of lean for straight but leaning trees. Frequently, such compression wood can be found in straight vertical stems (Shelbourne 1966; Timell 1986). It is generally agreed that stem curvature is a characteristic that can be inherited (Kärki & Tigerstedt 1985; Timell 1986; Giertych 1991), and that stem form is closely correlated with provenance (Moss 1971; Ståhl *et al.* 1990). It is also suggested that crook is more strongly heritable than sweep and lean, the latter two often being caused by environmental factors such as wind or snow (Timell 1986).

Several authors have tried to classify trees and logs according to their curvature (Low 1964; Dyson 1969; Gjerdrum *et al.* 2001). Dyson’s (1969) scheme contained five major classes: trees with sinuosity, bow, sweep, bends and forks. Bends and especially forks are examples of expressed curvatures that seldom reach sawmills today. Low (1964) included straight and straight but leaning in his scheme. However, in his studies he did not find any trees representing these two classes. Gjerdrum *et al.* (2001) used 6 classes to describe the curvature of logs; straight, end sweep, long sweep, angular crook, cross crook and multiple sweeps. The curvature that Dyson (1969) describes as bow is equivalent to what Low (1964) describes as J-shaped and Gjerdrum *et al.* (2001) describes as long sweep.

Log grading

For more than 20 years, most Swedish sawmills have used optical shadow scanners for automatic log scaling (Jäppinen & Nylinder 1997). Since the introduction of more sophisticated 3D-laser scanners in the middle of the nineties, more and more sawmills have started using this new technique (Staland *et al.* 2002). Data from 3D-laser scanners describe the spatial co-ordinates of the log surface at high resolution. They can be used for calculations of geometric variables, such as unevenness, taper, ovality and straightness (Lundgren 2000).

Both Lundgren (2000) and Gjerdrum *et al.* (2001) used variables obtained from 3D-data for development of log models based on straightness. To model straightness the curvature of the log centroid was used. Some of the variables that Lundgren (2000) used for the log model describing straightness were sweep (bow height), angle (abruptness of bend), snake (sum of angular deviation) and no-sweep (number of bends). According to Gjerdrum *et al.* (2001), logs with sharp curvatures that are prone to contain compression wood can easily be detected.

Most compression wood was confirmed in butt logs with end or long sweep and in logs with a high value of the variable MRD (maximum radial deviation). MRD is highly correlated to the intrinsic parameter bow height ($R^2 = 0.49$).

Besides from shadow scanners and 3D-scanners there are other techniques available for measuring and grading logs such as X-rays, gamma-radiation, nuclear magnetic resonance and microwaves. Some of these techniques have been successfully used to depict the compression wood content in dry wood. However, neither of these methods seems to be capable of identifying compression wood in logs, mostly due to the high water content (Öhman 2001).

One problem in using external geometry as a tool for grading of logs containing compression wood is that trees tend to become straighter as they grow older due to the concealment by radial growth (Little & Mergen 1966; Cremer 1998; Lindström & Rune 1999). Therefore, logs that appear straight can still contain large amounts of compression wood. By using information obtained from log ends such as compression wood content and/or pith position the detection of these logs could probably be improved.

Compression wood content in log ends is regularly considered during grading of saw logs in Sweden (Anon. 1999). According to Low (1965), the correlation between compression wood content in the log end and the total volume of compression wood within the stem was weak, because of the relatively low compression wood content in the butt section. However, both Mork (1928) and Koch *et al.* (1990) found a high incidence of compression wood in the butt section. Öhman (2001) found that secondary features, such as magnitude of log sweep, ovality and amount of visible compression wood in log ends, could be used for achieving a rough indication of the amount of compression wood within logs However, these features did not explain the variation in compression wood content in sawn timber.

Compression wood in sawn timber

The distribution of compression wood affects the longitudinal stress and strain distribution within the stem. Changes in stress and strain distribution, which occur during sawing, will affect deformations of green sawn timber (Archer 1987). Such effects have been reported by Öhman (2001) and Timell (1986). Öhman (2001) found that a convex shaped board was a very strong indicator of the presence of compression wood. He also found that size of convex bow was correlated to the compression wood content.

Deformations such as twist spring and bow all affect the quality of sawn timber negatively. Twist is caused by large annual ring curvature in combination with spiral grain angle (Ormarsson 1999; Johansson 2002). According to Kliger (2001) and Forsberg & Warensjö (2001), grain angle on log surface is a good predictor of twist in sawn timber. Twist is probably not correlated to compression wood content (Johansson 2002; Öhman 2001) even though Perstorper *et al.* (1995) found a negative correlation indicating a decrease in bow for pieces containing compression wood. According to Ormarsson (1999), deformations that occur during drying are highly dependent on the position of the board within the log. A board that is sawn at a greater distance from the pith will have a relatively small curvature of the growth rings, leading to less internal constraints and larger bow. Bow deformations are sensitive to the position of the pith. Spiral grain and the shrinkage parameter also have a substantial influence on bow deformations. Hallock (1965) found more bow and spring in butt log timber compared to upper log material, while the opposite was found for twist.

According to computer simulations by Ormarsson (1999), the presence of compression wood and the position of the pith have a strong influence on deformations such as bow and crook. The boards with the largest gradients in the longitudinal shrinkage will have the largest bow and crook deformations. Bow and spring are mainly caused by the release of residual stresses during sawing and by the large variation in longitudinal shrinkage in wood (Johansson 2002; Pang 2002). Examples of wood types with high longitudinal shrinkage are compression wood, juvenile wood and wood surrounding knots. Correlations between compression wood and deformations such as bow and spring have been reported by Timell (1986), Beard *et al.* (1993), Perstorper *et al.* (1995), Warensjö & Lundgren (1998) and Öhman (2001). External constraint greatly impacts board deformation during the drying process. However, when the external loading is removed deformations will occur due to the internal stresses present (Ormarsson 1999).

Nyström (1999) tested different methods for non-destructive detection of compression wood in sawn timber. According to his results, RGB-colour scanning and tracheid effect scanning were methods that could be used for detection in green conditions, while methods like spectral imaging, X-ray scanning and tracheid effect scanning were more suitable for detection in dried wood.

From the literature it is clear that there are many studies dealing with compression wood. However, in order to obtain better classification results for sawlogs, the relation between external geometry of logs and compression wood content needs further study. Moreover, in order to obtain a better understanding of the factors affecting deformations and especially the role of compression wood, further studies on sawn timber need to be conducted.

Objectives

The overall objectives of this thesis were to describe the 3-dimensional distribution of compression wood in trees, logs and sawn timber in relation to external geometry of trees and logs and deformations in sawn wood.

In studies I-III, the main objective was to study the relationship between external geometry and the distribution of compression wood in stems and logs at different ages. In study I, young container grown Scots pine trees were studied with emphasis on basal sweep, pith eccentricity and root deformations. In study II, the straightening process of 22-year old containerised Scots pine trees were studied.
In study III, the possibility of using external geometry data from a 3D-scanner and information obtained from log ends for modelling of the distribution of compression wood in Norway spruce logs, were evaluated.

The main objectives of studies IV and V were to examine the impact of the compression wood distribution on deformations of sawn wood. Moreover, in study IV the impact of grain angle and spiral grain on deformations was studied. In study V, the impact of the annual ring curvature and distance to pith on deformations was evaluated.

Materials and methods

Origin of the material

An overview of the material used is all five studies are shown in Table 1. Study I, II and IV are based on field experiments established with container-grown Scots pine seedlings within the area surrounding Garpenberg in central Sweden (lat. 60°15´N, long. 16°15´E). For study III a Norway spruce thinning stand located 10 km SE of Uppsala (lat. 59°51´N, long. 17°38´E), was chosen. The stand was chosen because of the rather high incidence of non-straight stems.

In study V, butt-logs of Norway spruce, containing compression wood, were sampled at the log yard of a sawmill located in southern Sweden (lat. 57°32´N, long. 13°21´E). All logs came from the normal wood procurement area of the sawmill. The age of the trees and the logs in the five studies ranged from 6 years (I) to 90 years (V).

Table 1. *Species, age, number of trees, logs, discs, studs/battens and cross sections from the sawn timber used in the five studies. (Orig.).*

	Article/study				
	I	II	III	IV	V
Species	Pinus sylvestris	Pinus sylvestris	Picea abies	Pinus sylvestris	Picea abies
Age (Years)	6	22	~60	22	~90
Trees (no.)	36	16	11	56	-
Logs (no.)	-	-	22	56	90
Simulated logs (no.)	-	30	130	-	-
Discs (no.)	257	176	188	-	90
Studs/Battens (no.)	-	-	-	102	360
Board cross sections	-	-	-	408	720

Measurement of external geometry

The external geometry of the material in study I – IV was assessed in the field on standing trees as well as in the laboratory (I) or with industrial log scanning equipment on logs (II, III and IV). The external geometry of the material in study V was never assessed. Root morphology measurements were only carried out in study I exclusively.

Degree of basal sweep was measured in studies I, II and IV using a digital protractor (Lucas Anglestar, model DP 45, USA). The largest angle was assessed within 30 cm above ground for the young trees (I) and within 50 cm above ground for the older trees (II and IV). The 22-year-old sample trees used in studies II and IV had been assigned for stem straightness at two earlier occasions, in 1986 and 1997. In order to analyse the development of stem straightness in study II, the sample trees were divided into four categories based on their history of basal curvature: 1, trees with straight stem base in 1986 and straight stem base in 1997; 2, trees with straight stem base in 1986 and basal sweep in 1997; 3, trees with basal sweep in 1986 and basal sweep in 1997; and 4, trees with basal sweep in 1986 and straight stem base in 1997.

The maximum bow height and lean were measured on standing trees in studies II, III and IV using a cord, a plummet and a calliper. Diameter and distance from the centroid of the stem to the vertically hanging cord was measured at 2 dm intervals ranging from 0.1 m to 2.5 m height. The bow height data obtained from field measurements were also used to control bow height data obtained from the 3D-scanner.

In study I, the external geometry of the 6-year-old sample trees was measured in three dimensions using a right-angled "measuring frame" (Fig. 2). Each stem was positioned with the maximum bow upward in the frame. Horizontal and vertical distances from the measuring frame to the centroid of the stem were measured at given length intervals along the stem.

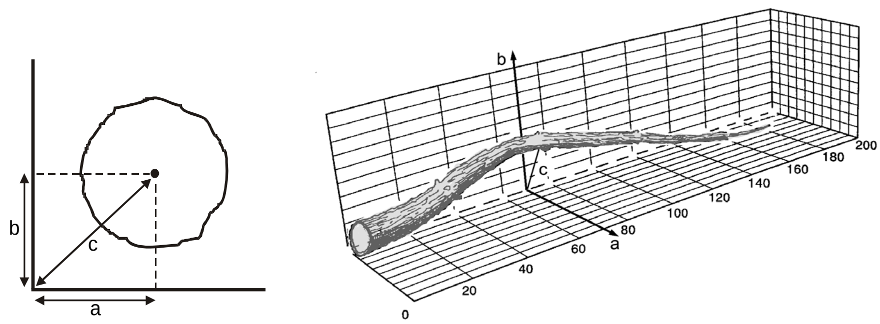

Fig. 2. Measurement of bow height in laboratory measuring frame. Horizontal (a) and vertical (b) distance from the walls of the measuring frame to the centroid of the stem and the calculated hypotenuse (c) of the bow-height.

3D scanning and cross cutting of logs

The sample logs in studies II, III and IV were transported to a sawmill where a Rema log 3D-scanner was used to collect data describing the spatial coordinates of the external geometry of logs. The scanner consists of three measurement heads, each containing 16-measurement units. Thus it can provide a maximum of 48 co-ordinates around the log circumference at each point of measurement (Gjerdrum *et al.* 2001). The resolution of the obtained log profile depends mainly on the speed of the conveyor (Lundgren 2000).

Before being fed through the log scanner, each log in study III was rotated on the conveyor, positioning the log with the colour marking (northern azimuth) upwards. This was done in order to facilitate the combination of log data sets into stem data sets with the software VIRTUAL MILL 1.0. During the scanning, raw data was checked for possible errors.

Prior to cross cutting, the western azimuth and the position of each disc were marked on the mantle surface of stems and logs in studies I-III. To prevent discs from containing branch-induced compression wood, discs were always positioned above branch whorls. The distance from butt end to the marked position was measured and recorded. In total, 257 discs in study I, 176 discs in study II and 188 discs in study III were cut from the sampled trees. The distance between the sampled discs ranged between 5 cm and 10 cm in study I, between 55 cm and 60 cm in study II and between 20 cm and 107 cm in study III. From each of the 621 discs, 2.5 mm thin cross sections were sawn using a circular saw.

Image analysis

In order to improve the visual appearance of compression wood, the thin cross sections were placed on a light box. The procedure is based on observations that compression wood is opaque to transmitted light while normal wood is translucent. The method is useful for detection of mild grades of compression wood as well as for ascertaining the presence of compression wood within large areas of normal wood (Pillow 1941). According to Andersson and Walter (1995), mild compression wood appears light orange to red in colour, while severe compression wood appears dark brown to black when exposed to transmitted light.

Images were registered with a digital camera (JVC 3-CCD KY-F55). For the analysis of compression wood content, the computer software "Compression wood analysis 1.0" was used. The software is especially designed for analysis of compression wood content in images of cross sections of wood viewed in transmitted light. During the analysis, the operator marks typical areas of normal wood, mild and severe compression wood, based on the colour appearance of the wood (Fig. 3). The software uses supervised multivariate classification for dividing the discs into the different wood types. The software also automatically extracts shape parameters that can be used for calculation of geometric variables such as out-of-roundness and pith eccentricity. Out-of-roundness expresses, in percentages, the deviation from a perfect circular shape of the diameter and pith eccentricity expresses the deviation of the pith from the geometric centre of the wood disc. The software also extracts the position (x, y) of the gravity of the different wood types.

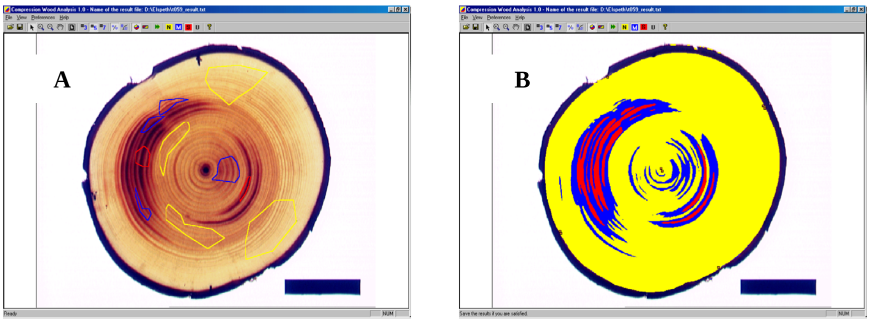

Fig. 3. Classification of compression wood using the image analysis software,
A. The operator marks typical areas of normal wood (yellow), mild compression wood (blue) and severe compression wood (red), based on the colour appearance of the wood.
B. Classification result presented by the software.

In order to test the result from the image analysis method a small verification study was conducted within study III. For this study, six sample discs from two Norway spruce trees, one fairly straight and one with a severe basal sweep, were chosen.

X-ray microdensitometry measurements were conducted along radii of the sample discs, using a flatbeam wood scanner (Woodtrax) (Bergsten *et al.* 2001). Data from the scanner were analysed using the WINDENDRO software (Instruments Régent Inc., Québec, Canada).

Fig. 4. Sample disc of Norway spruce containing large amounts of severe compression wood. Marked are the small sample areas used for microscopy analysis. The x-ray micro-densitometry scanning was conducted along the same radii.

Fluorescence microscopy, using the auto fluorescence of lignin was conducted on sections of small wood blocks of 10 x 10 x 20 mm (W x B x H) that represented different wood types (Fig. 4). Features typical for compression wood tracheids such as roundness, cell wall thickness, intercellular spaces and lignin distribution within the cell wall were used to distinguish between normal wood, mild and severe compression wood. The classification was based on the scheme for compression wood tracheids by Yumoto *et al.* (1983).

Analyses of external stem and log geometry

In studies II, III and IV, the software VIRTUAL MILL 1.0 (Dianthus, Boden, Sweden) was used for the analysis of external log and stem geometry data. The software makes it possible to visualise and combine 3D log data sets into whole tree data sets as well as virtually simulate crosscuts. The only limitation of the method is that the starting point and the end point of each simulated log have to be based on the position of the analysed discs (Fig. 5). By moving the position of the crosscut along the stems, it was possible to simulate logs and log sections with known external geometry and compression wood content. In study II, 30 log sections and, in study III, 130 4-metre logs were simulated.

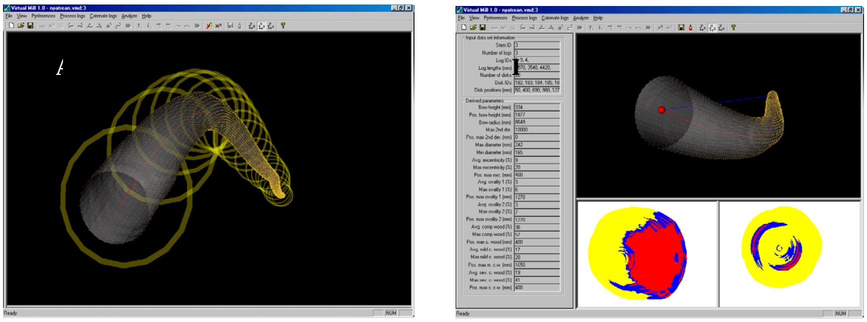

Fig. 5. Screen dumps from the software Virtual Mill. A: Log profile data have been combined into a stem profile. B: The result from the simulated crosscutting of a stem. Geometry and compression wood data are presented.

In studies I, II and III, for each disc and stem section, mild and severe compression wood content, pith eccentricity and out-of-roundness were calculated. These values were calculated from the data obtained from the image analysis software. In study III, the size of bow height and bow radius was automatically extracted from the raw data obtained from the 3D-scanner. Since the size of bow height is dependent on the log length all values were divided with the actual length. The variable bow radius, used in study III, describes how the log curves and the value represent the radius of a circle with the same curvature as the log. As a consequence, straight logs have very high values of bow radius and crooked logs have rather low values. Due to this, all values were transformed into a logarithmic scale.

Processing of saw logs

Before processing the sawlogs of study IV, the diagonal grain angle on the mantle surface was assessed at breast height. Measurements were conducted with a scribe on debarked areas according to a method described by Shelly *et al.* (1979). The sawlogs were square sawn into two main yields of the dimension 32 x 75 mm in study IV, and into four main yields of the dimension 38 x 155 mm in study V.

The 102 studs in study IV and the 360 battens in study V were dried in kilns at conventional temperature (~65°C). In study IV, the studs were hanging freely from the ceiling of the kiln, allowing them to deform without any influence of outer restraint. In study V, the battens were positioned in packages positioned close to the ceiling of the kiln. Due to the large number of battens the influence of outer restraint on the material varied. In study IV, the target moisture content (MC) was first 18%. After measurements of deformations the drying continued towards a new target moisture content of 12%. The target moisture content in study V was 12%. After drying, the battens in study V were conditioned for two weeks.

At green conditions (IV & V), at 18% MC (IV) and at 12% MC (IV & V), bow, spring and twist were measured using a 3-m-long right-angled aluminium profile and a mm-graded wedge. When measuring spring and bow the studs and battens were positioned with the largest deviation upwards in the profile. Twist was measured by fixing one end of the batten to the profile and measuring the greatest deviation in the opposite end corner (Fig. 6).

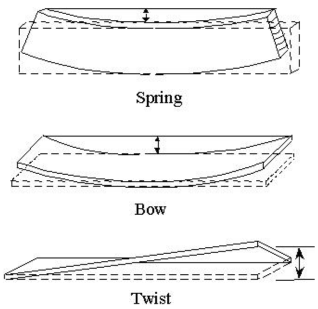

Fig. 6. The principle of measuring twist, spring and bow (modified from Johansson 2002).

In study IV, grain angle measurements were conducted. Lines were drawn with a scribe on tangential faces of studs and the distance from the scribed lines to the edge of the studs was measured at every 5 cm along a 10 cm length interval. These measurements were conducted close to the butt end, close to the top end and in the middle section of the stud.

In order to map the 3-dimensional distribution of compression wood, each stud in study IV was crosscut into 3 sections with a length of 80 cm. From butt and top ends and between the 80 cm sections, 2.5 mm thin cross sections were sawn. In study V, thin cross sections were sawn from butt and top ends of the battens. The compression content of the cross-sections were analysed using the image analysis software, see earlier section. In study IV, the compression wood content was also measured on the wide faces of the studs. Moreover, measurements of deformations were conducted on the short sections from the studs in study IV.

In study IV, the 3-dimensional distribution of compression wood within short sections and studs was calculated by multiplying the X- and Y-coordinates for the gravity of the compression wood areas with the relative compression wood areas of the cross sections. In study V, the distribution of compression wood was estimated for all cross sections. If the compression wood content was distributed towards the flat faces of the batten, a bow was expected, and if it was distributed towards edge faces, spring was expected. The direction was multiplied with the amount of weighted compression wood content per cross section. The total crack length was measured on the pith side and the tangential side of the wide faces. In study V, the annual ring curvature and the distance to the pith was also assessed for all cross sections.

Statistical analyses

Due to the relatively limited quantity of the material used in studies I-IV, these should be regarded as case studies. This makes it difficult to facilitate a good generalisation of the results. However the results are valid for the studied stands.

In studies I and II, Spearman rank correlation coefficients (r_s) were used to measure the association between the variables compression wood content, out-of-roundness, pith eccentricity and maximum bow height (Bluman 1997). In studies III, IV and V, Pearson moment correlations were used to test correlation between single variables. Best subsets regression was then used to generate regression models using the maximum R^2 criterion by first examining all one-predictor regression models and then selecting the two models giving the largest R^2. The best subsets regression procedure can be used to select a group of likely models for further analysis (Anon. 1998).

In study III, regression equations were calculated to model the compression wood content in logs. In studies IV and V regression equations were calculated to model the variables bow, spring, twist and compression wood content for studs and battens. All statistical analyses were carried out by Minitab, Release 12 (Anon., 1998).

Results and discussion

Validity of results from the image analysis

All studies within this thesis were based on measurements of compression wood content in cross sections of discs and boards using image analysis. The method used was semi-automated, and it was the operator who, for each disc, defined typical areas of the different wood types. This had to be done due to the large variation in colour for different discs and species, but this also makes the method more subjective. Since it was important that the method worked well, had a good repeatability and delivered accurate results, the result from the method was tested.

The repeatability of the image analysis technique was tested by Andersson & Walter (1995). The result from the comparison indicated a good repeatability for the total compression wood content (mild+severe), a rather good repeatability for the mild compression wood content and a poor repeatability for the severe compression wood content. According to Andersson & Walter (1995), the poor repeatability indicated that the operators had difficulties in discriminating between mild and severe compression wood. The poor repeatability of severe compression wood is a result of the relative amounts of the different compression wood types. If the discs used had contained more severe than mild compression wood, the repeatability would have been better for the severe compression wood content compared to the mild compression wood content. In order to obtain better repeatability, Andersson & Walter (1995) emphasised the importance of well-trained operators that use the same colour display throughout the whole investigation. In all studies conducted within this thesis the analysis was made by the same operator.

The small verification study conducted within study III confirmed the results from the image analysis. Within most annual rings containing compression wood, the compression wood features followed a gradient, from very thin walled tracheids in the early wood part to very round and thick walled tracheids in the late wood part. This was in accordance with the findings by Yumoto *et al.* (1983). The characteristic lignin distribution described in Yumoto *et al.* (1983) was apparent for all compression wood tracheids (Fig. 7). Moreover, the features roundness, cellwall thickness and intercellular spaces were relatively easy to discern. Helical cavities, one of the primary features of compression wood, were much more difficult to spot. However, they could be seen as scars in the inner part of the S2-layer.

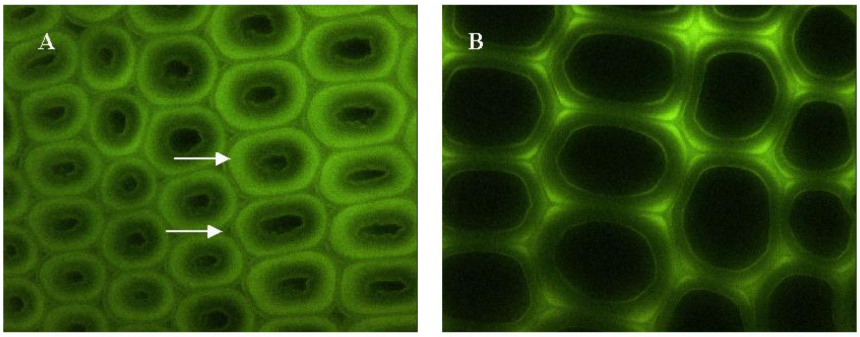

Fig. 7. A: Transverse section of severe compression wood. The outer part of the middle layer of the secondary cell wall (i.e. S2L) (upper arrow) appears bright due to the high lignin content. The tracheids have a rounded outline and helical cavities and intercellular spaces (lower arrow) are present. B: Transverse section of mild compression wood. The lignin distribution is concentrated near cell corners. Tracheids are slightly round. Intercellular spaces are not present.

In the very eccentric discs from the tree with a very large basal sweep, it was observed that there was a large variation in number of cell rows between corresponding sides for the same annual ring (Fig. 4). According to Yumoto *et al.* (1983) this is a result of the fact that compression wood tracheids starts forming earlier in the season. Yumoto *et al.* (1983) reported unchanged cell wall thickness when gravitational stimulation was strong. This can also be seen in the density profile in Fig. 8 for the very thick annual ring, where the variation in density is very small.

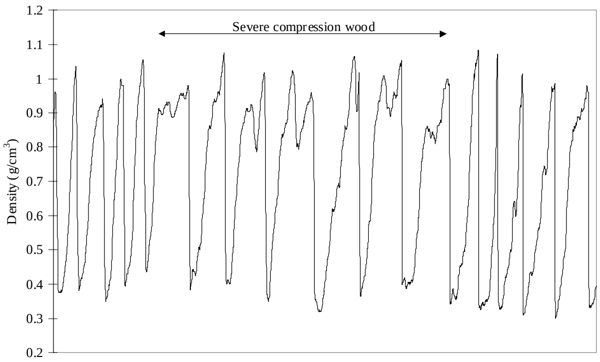

Fig 8. Density profile from X-ray microdensitometry measurements showing rings with severe compression wood. Observe the width, low peek and small variation in density for the first annual ring with severe compression wood. This is in accordance to findings by Yumoto *et al.* (1983).

According to Pillow (1941), the best contrast when using transmitted light is observed in species with white sapwood such as Norway spruce. In species with coloured heartwood such as Scots pine, the detection of compression is more difficult. In this thesis, both Norway spruce and Scots pine material were used. Differences in contrast were noted, but since most of the Scots pine material originated from relatively young trees, 6 to 22-years-old, they contained rather small amounts of heartwood. Consequently, the image analysis method worked well even for the Scots pine material.

One big problem in studying compression wood is the large variation in appearance. Compression wood appears in many grades from almost normal wood to very pronounced (severe) grades. Many authors have tried to classify the compression wood into several grades based on colour appearance or anatomical features. Pillow (1941) and Nichols (1982) used two grades of compression wood. Many authors have three grades (e.g. Low 1964; Shelbourne 1966; Harris 1977). Burdon (1975) used five grades and Yumoto *et al.* (1983) used six classes.

During the studies, using one more grade of compression wood was at times considered. This grade should then have been used for very mild grades of compression wood, by many authors referred to as slight compression wood (Low 1964; Shelbourne 1966). The slight compression wood was especially apparent in many of the discs from upper parts of the logs in study II. Since slight compression wood resembles normal wood to a great degree, it does probably not affect mechanical wood properties such as e.g. longitudinal shrinkage. Consequently, by classifying such wood as mild compression wood the correlations between compression wood content and deformations would be affected negatively. Another approach would have been classifying the slight compression wood as normal wood. By using more grades during analysis, the precision would be lowered due to difficulties in discriminating between the different grades. Best precision would have been obtained if only one grade of compression wood had been considered. One interesting finding is that Low (1964), who classified the compression wood into three grades during his analysis, used only one grade because of the difficulties of separating the areas when using a dot grid.

Compression wood in relation to external geometry

Although 20 of the 56 sampled trees in studies I and II had straight stem bases, compression wood was found in all stems and in almost all discs. Moreover, in study III, a majority of the discs contained various grades of compression wood. This was in accordance with Boone & Chudnoff (1972) and Koch *et al.* (1990) who found that virtually all stems contained compression wood. Compression wood formation was most pronounced in the basal part of the stems in all studies. With increased stem height, compression wood content and the severity of compression wood decreased. This was particularly apparent in studies I and II. Also Mork (1928), Burdon (1975), Nicholls (1982) and Koch *et al.* (1990) report similar results.

In study I, contrasting study II, the degree of basal sweep was significantly correlated to severe compression wood content. The lack of correlation in study II was probably an effect of the concealment of the juvenile basal sweep by eccentric radial growth. This was confirmed in the analysis of the temporal pith eccentricity, which showed that the pith eccentricity had decreased for trees that in 1986 had basal sweep, but were classified as straight in 1997. The analysis of temporal pith eccentricity also showed that the extent of pith eccentricity increases for those trees with basal curvature (Fig. 9).

The straightening process in study II was also confirmed by the assessment of basal sweep in 1986 and 1997, which showed that 89% of the stems had straight stem bases in 1997 compared to 60% in 1986. Measurements in 2001 showed that 96 % of the sample trees had developed straight stem bases.

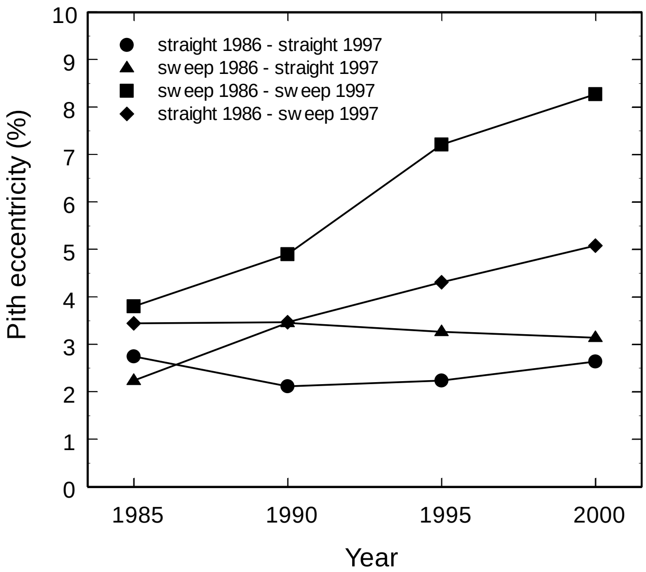

Fig. 9. Pith eccentricity expressed as mean values for wood discs taken from 0, 0.6 and 1.2 m heights representing growth intervals: 1982-1985, 1982-1990, 1982-1995 and 1982-2000, for Scots pine trees with straight stem base in both 1986 and 1997, straight stem base 1986 and basal sweep 1997, basal sweep both 1986 and 1997 respective basal sweep 1986 and straight stem base 1997. (From study II).

The size of the tree when it becomes displaced is crucial for the straightening process. In study I, most sample trees were displaced as early as during the first growing season. According to Little & Mergen (1966) and Cremer (1998) a small tree will be able to recover from a leaning position rather quickly. As a consequence, limited compression wood formation can be expected. An example of this quick recovery is shown in Fig. 10. However, a young established tree that is leaning more than 45° would never be able to conceal the basal sweep (Mason 1985). Consequently the basal part of the stem will continue to produce compression wood even though the upper part of the stem may have reached a stable vertical position, leading to overcorrection (Cremer 1998) and sinuosity (Spicer *et al.* 2000). A major source for compression wood formation during juvenile growth is the susceptibility of young trees to external forces such as wind and snow, which often cause formation of compression wood (Zobel & Sprague 1999).

In study II, the displacement occurred between the fourth and the eight growing season. Due to the size and weight of the tree the straightening process for these trees took longer time, resulting in more compression wood formation. Similarly, if a tree with a large diameter becomes inclined, the tree will never be able to conceal the basal part of the stem by eccentric growth. In this case the compression wood formation will continue, resulting in overcorrection. This was apparent in several of the trees of study III, especially one tree with a severe basal sweep. Also Low (1964) reported this phenomenon.

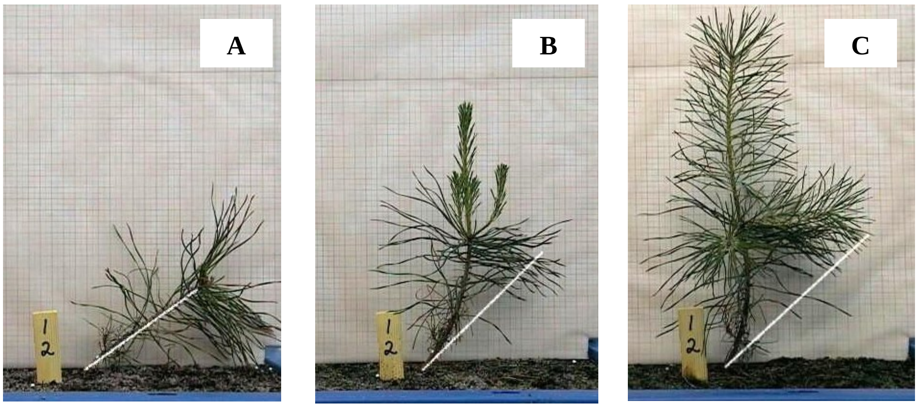

Fig. 10. Development of basal sweep. The seedling was planted in a box at an angle of 45° from the vertical and was grown for 30 days in a greenhouse. Image A=day 0, B=day 15 and C=30 days after planting. From Rune (2002).

In studies I and II, a spiral compression wood distribution pattern was found. This indicated that, previously the tree or stem segment had been leaning in several directions (Timell 1986). According to these findings, the spiral develops when the tree starts to lean in a direction that is offset from the direction of the basal sweep. When the formation of compression wood in the basal part continues the upper part slowly becomes displaced in a new direction. The direction of the spiral is probably caused by chance, since both clockwise and anti-clockwise directions were present. The large amounts of single-sided severe compression wood found in the basal discs of the trees with the most obvious spiral pattern indicated a pronounced basal sweep formation. The absence of spiral compression wood in basal discs indicated that the anchorage of the trees had been improved and that only upper parts of the stem had been moving.

In this thesis, the external geometry of the log was described by the variables bow height and out-of-roundness. Out-of-roundness describes the difference between the largest and the smallest diameter in relation to the mean diameter of the two directions. Bow height was only significantly correlated to compression wood content in study III. The reason for the non-existing correlation in study II was probably the limited bow height of the material. The majority of the cross sections in study II were almost circular even though they had an eccentric pith position.

Often, discs with an eccentric pith position are reported to have an elliptic or oval appearance (Timell 1986). In the present studies, pith eccentricity was significantly correlated to out-of–roundness in study I and to out-of-roundness in the basal 2.4 metre part of the logs in study II. However, if all discs in study II were included in the analyses, there was no significant correlation. In none of the three studies (I-III), correlations between out-of-roundness and compression wood content were found.

In study I, pith eccentricity was significantly correlated with basal sweep and maximum bow-height. In studies I, II and III, pith eccentricity was significantly correlated to compression wood content in discs. In study III pith eccentricity in log ends was significantly correlated to the compression wood content in logs (Table 2).

Table 2. *Spearman rank correlations for compression wood content in stems and logs in relation to variables obtained from log ends and external geometry measurements. ns=not significant*

Variables	Severe CW[1]-content			Total CW[1]-content		
	I[4]	II[5]	III[6]	I[4]	II[5]	III[6]
Basal sweep	0.66	ns	-	0.67[7]	ns	-
Bow height	ns	ns	0.23	ns	ns	0.26
Out-of-roundness[2]	ns	ns	ns	ns	ns	ns
Pith-eccentricity[3]	0.44	0.68	0.39	0.43[7]	0.68	0.31
Pith-eccentricity[3] in log ends	-	-	0.32	-	-	0.28
Severe CW[1]-content in log ends	-	0.94	0.89	-	0.89	0.71
Total CW[1]-content in log ends	-	0.87	0.67	-	0.87	0.73

[1] CW=compression wood
[2] Out of roundness = ((largest-smallest diameter)/((largest+smallest diameter)/2))*100
[3] Pith eccentricity = (pith deviation from geometric centre of disc/mean diameter)*100
[4] Study I, Scots pine, 6yr-old, stems~1.5m long, n=36
[5] Study II, Scots pine, 22yr-old, log length=4.2m, n=15
[6] Study III, Norway spruce, ~60yr old, simulated logs, lengths~4m, n=130
[7] Weighted compression wood (Severe CW+0.5*Mild CW) were evaluated instead of total CW

From the results of study II, it was evident that eccentric growth and compression wood formation played major roles in the development of stem straightness Young trees with basal sweep will also become more straight over time. Consequently, the straightness of a log is not a reliable measure of the compression wood content within the stem. In study III, most of the logs had some kind of curvature, indicating that the displacement appeared when the tree was larger. For these logs the bow-height was significantly correlated to compression wood content. Even though correlations were weak, this shows that curved logs are prone to contain compression wood.

Grading of saw logs containing compression wood

In Sweden, the compression wood content in log ends and the external geometry are regularly considered during ordinary log grading routines. For assessment of external geometry the parameter bow height is used. The bow height describes the maximum deviation between a straight line joining both log end centres and the centroid of the log (Fig. 11).

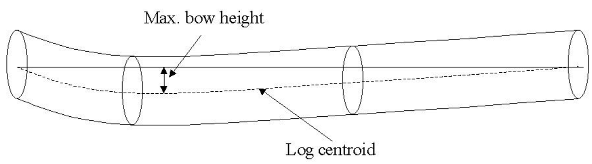

Fig. 11. Description of variable bow height

According to the national grading rules for saw logs in Sweden, logs should preferably be straight, but swept logs with a maximum bow height of 2 % are also allowed (Anon. 1999). For better grades (1-3), the limit for maximum bow height is 1%.

According to the findings in study III, the parameter bow height was significantly correlated to the amount of compression wood. This was especially apparent for the 22 original logs (R=0.61). However, in this case the correlation was dependent on one observation, the only log with a large bow height (>2%). Due to the large bow height, the log was considered to be an outlier and was excluded from the analysis. For the simulated 4-meter logs, the corresponding correlation coefficient was 0.25. This rather weak but significant correlation was a result of rather straight logs and significant amounts of compression wood. The weak correlation was in accordance to the findings by Öhman (2001), who stated that the magnitude of log sweep could be used for obtaining a rough indication of the amount of compression wood. However, if only curved logs were considered in study III the correlation was improved (R=0.45).

Apart from bow height, the smoothness of the curvature needs to be considered as well. Sharp curvatures indicate serious stem defects such as top failures (Gjerdrum *et al.* 2001). In response to the loss of the leader, the apical dominance is overtaken by a branch that bends upwards with the aid of pronounced compression wood formation on the lower side of the branch (Timell, 1986). Consequently, logs with sharp curvature mostly contain considerable amounts of severe compression wood within a limited length interval. However, logs with sharp curvatures are relatively easy to detect when using data from external geometry measurements (Gjerdrum *et al.* 2001). The position of the crosscut within a stem with a sharp curvature is important for the size of bow height. If the stem is crosscut in the middle of the most extended curvature, the point where the 2^{nd} derivate of the centroid has its highest value, the bow height will be limited, compared to that of the maximum deviation being positioned in the middle of the log length. However, in the first case the log ends will contain large amounts of compression wood.

Logs with smooth curvatures can also contain large amounts of compression wood. However, compared to logs with sharp curvatures, these logs can be accepted to a larger extent, since the compression wood content often is more evenly distributed within the stem. Examples of log types with smooth curvature are those with bow or sweep. By applying curve sawing it is possible to improve the volumetric yield as well as the quality of the sawn timber, due to less grain deviations (Gibson 1999). Smooth curvatures are better suited for curve sawing.

One problem when using external geometry as a tool for grading of logs containing compression wood is that trees tend to become straighter as they grow older due to the concealment by radial growth (Little & Mergen 1966; Cremer 1998; Lindström & Rune 1999). Therefore, logs that appear straight can still contain large amounts of compression wood. By using information obtained from log ends, such as compression wood content and/or pith position, the detection of these logs can most certainly be improved.

According to the findings of this thesis, the pith eccentricity of a disc was significantly correlated to the amount of compression wood within that particular disc. Due to this fact, it might be possible to use the position of the pith as a measure of the compression wood content. This parameter could be used on occasions when the compression wood content in log ends is difficult to discern. When freshly cut, compression wood normally appears rather clear, but as soon as the wood start to dry the compression wood begins to fade. During certain periods of the year the log ends are often covered with dirt, packed snow or ice, making the detection of compression wood even more difficult.

One important question to adress is the correspondence between compression wood content in log ends and the total compression wood content of the log. According to the findings in this thesis, the compression wood content obtained in log ends was a very good measure of the compression wood content of the log. This was especially apparent for severe compression wood content in the simulated logs of study III (R=0.89). If only logs from straight trees were considered the correlation was even better (R=0.97). A regression model for describing the compression wood in logs was calculated for the variables severe compression wood content and pith eccentricity. The model explained 77% of the variation. However, the variable severe compression wood content in log ends described 76% of the variation by itself. Based on these results, the compression wood content in log ends really should be considered during ordinary log grading.

Another important issue is the accuracy of the log scalers´ estimations of compression wood content. In a study by Warensjö & Lundgren (1998), the accuracy of the log scalers´ and the executive scalers´ estimations of compression wood were checked. Warensjö & Lundgren (1998) found that the executive scalers´ estimations corresponded rather well to the results obtained from the image analysis (R=0.80). However, there were rather large differences between the log scalers´ and the executive scalers´ estimations. In general, the log scalers´ overestimated the amounts of severe compression wood. If both mild and severe compression wood content from the image analysis were considered, there were no overestimations. However, these results were obtained under ideal conditions with clean log ends and with logs laying still at log yard. In reality, log ends are often dry or dirty and the log is moving on the conveyor, making it more difficult to estimate compression wood content.

However, if log ends were cut clean with a circular saw or sprinkled with water before grading, the optical contrast would be improved. This would make the task easier. This would also enable the use of cameras and image analysis techniques for automatic depiction and calculation of the compression wood content in the log ends. By combining information obtained from log ends with data obtained from the 3D-laser scanner the prediction could probably be improved. With new, more complex variables describing the curvature in a more accurate way the predictions could be even more reliable.

Based on the findings of this thesis along with the literature on compression wood, a grading scheme for logs that are prone to contain compression wood is proposed (Fig. 12.) Log features such as bow height, smoothness of external curvature, pith eccentricity and compression wood content in log ends are used in the grading scheme. However, the critical limits for the different variables are as yet only suggestions. Further research needs to be conducted in order to decide these limits more accurately.

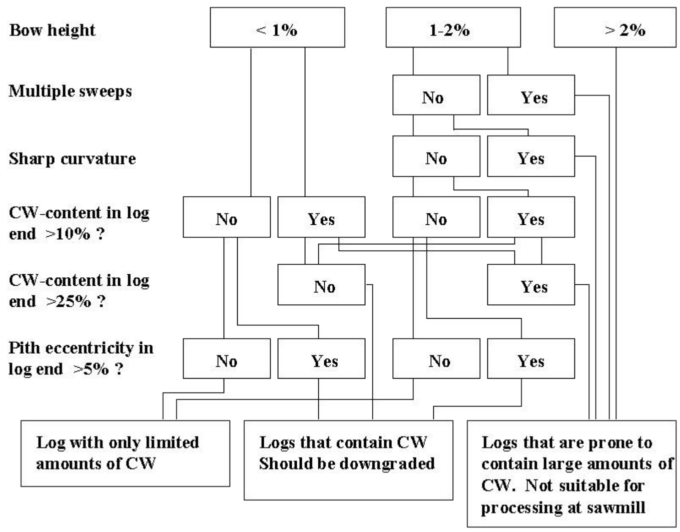

Fig. 12. Suggested grading scheme for identification of logs that are prone to contain compression wood.

Deformations in sawn wood

Deformations occurred in a majority of the studs and battens in both study IV and V. Even though the maximum size of bow, spring and twist at 12% MC were almost identical for the two studies, the mean values were three to four times larger in study IV compared with the values in study V (Table 3). There were many reasons for the high incidence of deformations in study IV, including the drying routine, the wood type, the distance to the pith and the relatively small dimension of the studs.

The studs in study IV were dried hanging freely in a cord from the ceiling of the compartment kiln. As a consequence, there were no constraints that could prevent the studs from deforming. Since the studs only consisted of juvenile wood and compression wood, both wood types with pronounced longitudinal shrinkage (Danborg 1994; Johansson 2002), and were positioned close to the pith, they were more prone to become deformed. The distance to the pith is important since the grain angle is known to be large close to the pith, largely influencing the magnitude of twist (Danborg 1994; Forsberg 1999; Johansson 2002). Consequently, most of the studs in study IV were severely twisted. In study V, the battens positioned close to the pith had significantly larger twist than battens positioned further away from the pith. In study IV, the spiral grain angle measured on the log surface, was strongly correlated to the size of twist. This was also in accordance with the findings by Kliger (2001) and Forsberg & Warensjö (2001).

Table 3. *Deformations at green condition and at 12% moisture content (MC) for studs and battens in studies IV and V.*

Variable	N	Min	Max	Mean	Stdev.
Deformations at green Condition					
- Bow (Study IV)	102	0	18.5	7.9	3.9
- Bow (Study V)	310	0	5.6	0.7	0.7
- Spring (Study IV)	102	0	9.0	2.2	1.9
- Spring (Study V)	310	0	1.2	0.2	0.2
Deformations at 12% MC					
- Bow (Study IV)	102	4	78	24.4	14.6
- Bow (Study V)	296	0	55	6.2	6.8
- Spring (Study IV)	102	2	45	12.4	9.3
- Spring (Study V)	296	0	34	5.3	4.5
- Twist (Study IV)	102	0	46	19.1	9.2
- Twist (Study V)	296	0	43	6.3	6.9

In study V, the lumber dimension was larger (38 x 155 mm), the battens were dried under constraint and half of them were positioned further away from the pith and consisted of mature wood. The small lumber dimension in study IV (32 x 75 mm) probably had an impact on the size of deformations (comp. Cown *et al.* 1996). Studs of a limited dimension are probably also more sensitive to the distribution of knots compared to larger dimensions, when being dried. In study IV, spring appeared occasionally when knots were positioned on the edge faces of the battens.

Another reason for the high incidence of deformations in study IV was probably related to the history of basal sweep. About half of the trees had basal sweep when their stem curvature was assessed in 1986. Consequently, many of the logs contained large amounts of compression wood in their basal sections. During processing of such logs grain deviations will appear. Grain deviations in combination with the pronounced longitudinal shrinkage in compression wood and juvenile wood will affect deformations such as bow and spring (Pang 2001; Johansson 2002).

The boards with the largest gradients in the longitudinal shrinkage will, according to Ormarsson (1999), experience the largest bow and crook deformations. The deformations that appeared directly after sawing in studies IV and V, green spring and green bow, were either caused by the release of residual stresses (Archer 1987; Öhman 2001) or curve sawing (Söderström & Cederholm 1988; Gibson 1999). Curve sawing probably caused most of the observed green bow in study IV, since the size of bow decreased during the drying process. However, in study V, the size of both green spring and green bow increased during drying. This might be related to the distribution of compression wood, since compression wood is known to induce compressive forces (Archer 1987). In study IV, the green spring also seemed to have reduced the size of twist since they were negatively correlated. However, in study V no such correlation was found.

All studs in study IV and a majority of the battens in study V contained compression wood. Correlations between compression wood and deformations such as bow and spring were reported by, e.g., Timell (1986), Perstorper *et al.* (1995), Warensjö & Lundgren (1998) and Öhman (2001). In both studies IV and V, bow and spring were significantly correlated to the compression wood content, especially the severe compression wood content. One reason for this is probably found in the more pronounced shrinkage in severe compression wood. In study V, the correlations for spring increased during drying while they decreased for bow.

In order to obtain a better description of the compression wood distribution in study IV, the positions of the compression wood content within cross sections were evaluated. For the short 80 cm sections, compression wood content located towards the flat faces (y-direction) was negatively correlated to size of bow, and compression wood content located towards the edge faces (x-direction) was significantly correlated to spring. However, when the spatial compression wood distribution for the entire stud was considered no correlations were found. Also, in study V, the spatial position of the compression wood content was significantly correlated to bow and spring.

Even though correlations were weak, the result from study IV and V indicated that the distribution of compression wood influenced the direction and size of bow and spring in sawn timber. The relatively weak correlations could be explained by the large variation in longitudinal shrinkage that, according to Johansson (2002) is the case for most pieces of wood. The long distance between the analysed cross sections, 80 cm in study IV and 400 cm in study V, has probably also affected the results. Even though the mapping of the compression wood distribution was satisfactory, other wood properties have most likely affected the longitudinal shrinkage.

In study V, the position of each batten within the log in relation to the position of the pith was evaluated. Bow increased with increasing distance from pith while the opposite was found for twist. Spring was large for those battens with annual rings distributed along the edge face. All these results supported the results of a simulation study by Ormarsson (1999).

Conclusions

The compression wood content in log ends is a good measure of the compression wood content, especially in straight stems. The compression wood content is often most pronounced near ground level and decreases further up along the stem. Young trees with basal sweep often contain large amounts of severe compression wood. When trees grow older the sweep, or the curvature of the stem, often becomes concealed by eccentric radial growth. Consequently, the straightness of a log is not a reliable measure of the compression wood content. However, the compression wood content and the position of the pith in log ends can be used for estimations of compression wood content. If information obtained from log ends is combined with information obtained from external geometry measurements, logs that are prone to contain compression wood can most likely be detected. In sawn timber, the compression wood content and its position affect bow and spring deformations both directly after sawing and after drying. However, the annual ring curvature seems to be more important when estimating deformations such as bow and spring after drying. Grain angle measured on tangential faces of the sawn timber and the spiral grain angle measured on the mantle surface of logs, under bark, have a large influence on twist deformations.

Further research

This thesis has focused on the distribution of compression wood in relation to the external geometry of stems, trees and sawn timber. Further results regarding these issues will be presented in 2004 within the EC-project “Compression wood in Conifers”. Within the project, results describing the distribution of compression wood within stands will also be presented. However, to solidify the empirical data further studies are needed. Because of the strong link between juvenile stability and compression wood formation, further research needs to focus on the occurrence of unstable trees in future forests and the incidence of compression wood in such trees. This is important since the forest industry still processes the yield from more or less naturally regenerated forests. What will happen when the unstable forests from the sixties and the seventies are ready for harvest? We already know that a lot of these unstable trees have developed basal sweep, and that this is highly associated with compression wood formation. However, it needs to be considered what the long-term effects of juvenile instability on wood quality and wood utilisation will be. What will the effects be on an industry that already is struggling? What effects will increasing amounts of compression wood have on mechanical wood processing? Moreover, further research dealing with the economic consequences of compression wood needs to be considered. Another important question is whether this will have an effect on the pulp and paper industry as well. If so, the future usage of wood containing compression wood needs to be considered.

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