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Relation between Growth Characteristics and Warp of Sawed and Dried Timber.

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By
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Ana Artigas

ABSTRACT

The relationship between growth conditions and deformations in Norway Spruce trees grown in southern Sweden has been studied. The aim of this work was to clarify the relation between easily visible growth parameters and warp of sawed and dried timber.

The main effort of this thesis is to clarify the correlation between crook deformation observed at the forest (Forest Crook) and deformations (bow, crook and twist) after sawing and drying processes.

In the first part of the experimental work a measuring machine has been designed and built to measure bow and crook deformation after drying process. Twist deformation after drying is measured using a digital.

The study was carried out on trees belonging to two stands representing common stand types in phase of second precommercial thinning. Both stands contain different plots where different thinning methods were applied.

From the results it can be stated that a quite accurate prediction of the degree of warp can be made.

The degree of easily visible crook of still standing trees is a good predictor of the deformations after drying. However, with respect to bow deformation after sawing, no correlation can be stated.

With regard to the influence of the different silvicultural methods, the correlation among different plots when studying deformations after drying is not significant. This result agrees with the fact that all trees left in a specific stand may be considered as co-dominant trees.

Correlation between deformations shows that the relationship between different deformation modes is very little.

Finally, from the study of the influence of handling and sawing pattern, a relation between handling and bow deformation after sawing can be stated, but on the contrary, handling has no influence on bow and crook deformations after drying. Sawing pattern is found to affect twist deformation after drying.

ABSTRACTO

Las condiciones de crecimiento afectan claramente y en gran medida las propiedades físicas y mecánicas de la madera. Más concretamente, es bien sabido que los regímenes de silvicultura tienen gran influencia en las propiedades físicas de la madera y éstas, a su vez, son responsables del comportamiento de la madera usada como elemento estructural.

Así pues, la identificación de variables que puedan considerarse como determinantes en el comportamiento de la madera, conlleva un gran avance a la hora de definir, incluso antes de talado, el estándar de árbol cuya madera será, muy probablemente, idónea para uso estructural.

El principal objetivo de esta investigación es clarificar cuales son los factores de crecimiento fácilmente visibles que más notablemente influencian las propiedades físicas de la madera y que, por tanto, serán responsables de las propiedades mecánicas y el comportamiento de ésta dentro la estructura del edificio.

La especie Picea Abies, conocida comúnmente como Abeto Rojo, ha sido la madera seleccionada para la investigación por ser ésta la más valorada y utilizada por las empresas de construcción escandinavas. Los árboles han sido seleccionados aleatoriamente de entre todos los pertenecientes a dos áreas específicas cultivadas para el desarrollo de esta investigación.

Esta investigación consta de varias fases experimentales.

Durante la primera fase de la investigación ha consistido en el diseño y construcción de una mesa llamada “de medidas”, construida en madera y acero y en la que han sido acoplados *dial transducers*. para medir la deformación de *bow* y *crook* en cada uno de los 290 maderos seleccionados.

En la segunda parte de la investigación, los árboles seleccionados, han sido clasificados con relación al grado del aquí denominado *Forest Crook*. Esta unidad de medida se determina a simple vista a partir de la deformación observada en el bosque y teniendo en cuenta la situación y orientación del *crook* observado en el bosque.

También dentro de la segunda parte de la investigación, se han registrado las cantidades de *bow* después del proceso de aserrado, así como el contenido de humedad en cada uno de los maderos.

Después del proceso de secado en horno, todos los tablones son una vez más medidos. La cantidad de *bow* y *crook* ha sido medida en los extremos de los maderos y en el centro y, para la primera de las deformaciones la dirección de la deformación (hacia el tallo del tronco o en sentido opuesto) ha sido considerada. De esta forma se obtiene una aproximación simple de la geometría final de cada tablón y del patrón de deformación más frecuente. Por último, se ha registrado el grado de torsión utilizando un pie de rey y de acuerdo con el modelo previamente establecido. Una vez más datos relativos al contenido de humedad en la madera han sido registrados: en uno de los extremos de cada tablón, en el centro, y diferenciando entre humedad en superficie y humedad en profundidad.

Los resultados obtenidos demuestran que la mesa diseñada para la medida del *bow* y *crook* resulta ser una espléndida herramienta para obtener medidas suficientemente precisas de estos tipos de deformación. Este resultado queda contrastado con los resultados obtenidos empíricamente.

Con respecto a la influencia de los regímenes de silvicultura, sorprendentemente, la madera utilizada durante esta investigación presenta escasa influencia en cuanto al proceso de cultivo. No se observan diferencias significativas entre maderos que provienen de diferentes áreas y por tanto entre maderas que atienden a diferentes técnicas de cultivo.

En cuanto a la predicción del grado de deformación después de los procesos de aserrado, secado y almacenaje, los resultados demuestran ser de gran interés para la industria: esta investigación concluye que la cantidad de deformación de *bow* y *crook* es altamente predecible aún partiendo solamente de datos sobre relacionados con el grado de *crook* en el árbol todavía no talado. Por otra parte, con respecto al grado de torsión, es esta la deformación que presenta una mayor correlación con el denominado *Forest Crook*.

El estudio de la orientación de la deformación demuestra que para el total de árboles testados, la deformación orientada hacia el tallo del árbol es significativamente menor que la deformación en dirección contraria.
Por otra parte, diferenciando entre los maderos que provienen del lado izquierdo del tronco y aquellos que provienen del lado derecho, puede concluirse que los diferentes tipos de tablones son significativamente diferentes en cuanto al grado de *bow* medido después del proceso de aserrado. El resultado verifica la influencia de la manipulación de los maderos durante el proceso de aserrado. Sin embargo, cuando las deformaciones se estudian después del proceso de secado, no existen diferencias significativas entre tablones de uno u otro lado del tronco del árbol. En cuanto a la torsión, esta demuestra estar altamente relacionada con el proceso de aserrado.

Para finalizar, el estudio concluye demostrando que, tal y como se esperaba, no existe correlación significativa entre los diferentes tipos de deformación, es decir, después del proceso de secado, no es posible determinar a partir de una de las deformaciones (*bow, crook* o torsión), alguna de las otras dos deformaciones con la precisión requerida.

1. INTRODUCTION

1.1. Background

Wood continues to be a most preferable material for a large number of products though other competitive materials are available. Furthermore, and with respect to construction field, wood lumber has demonstrated for many years to have high versatility by serving as a primary raw material.

Even though wood is an outstanding structural material, continuing research and deeper knowledge of its mechanical behaviour are necessary in order to permit wider and more efficient utilisation and to encourage more advanced structural uses.

A tree log, when sawn, yields lumber of varying quality, to enable users to buy the quality that suits their purposes best, lumber is graded into categories, each having an appropriate range in quality.

It is known existence of dependence between wood quality and silvicultural operations. (Perstorper et al., 1995). Deeper knowledge of this relationship may however simplify and provide a more accurate grading.

1.2. Scope of the Study.

The purpose of this report is to clarify whether it is possible to determine, from the easily visible degree of crook on still standing trees, bow deformation after sawing and deformations after drying.

Wood has many advantages in regard to its structural behaviour but as previously discussed also some disadvantages. Wood, in contrast to e.g. metals is heterogeneous and anisotropic, it exhibits different physical properties in different growth directions, i.e., axial, radial, and tangential directions. It is well known that growth conditions strongly affect the mechanical properties. (Dinwoodie, 1981). Soil quality, climatic variations, and nature of terrain, as well as silvicultural regimes have large influence on the grade yield and mechanical properties of wood. Consequently, if growth characteristics and silvicultural practices affect mechanical properties and these are, in turn, responsible of the structural behaviour of wood, to identify the main growth variables affecting mechanical features are of high interest.

1.3. Disposition of the Report

In Chapter 2. a global vision of softwoods, its structure, properties and behaviour is discussed.

A description of macrostructural and microstructural characteristics of softwoods, a general explanation of the physical and mechanical properties' species this report relates to, and which are the factors affecting the degree of warp are presented in following sections.

In Section 2.5. a deeper description of shrinkage and swelling is given in order to explain its relationship with warp (bow, crook and twist), which are the responsible factors and which the consequences of such deformations.

The explanations and some theories are based on recent literature and, in some cases, new studies conducted by other researchers.

Section 2.6. gives the conclusions derived from the literature review.

The experimental work is presented in Chapter 3.

In Section 3.1. measuring equipment and other instruments used during the experimental work are described in depth.

The Section 3.2. presents a detailed explanation of the material (wood) employed and selection and classification specimen process are reported.

In Section 3.3. a description of where and how the testing was accomplished is given.

Presentation and a thorough discussion of the test results are given in Chapter 4.

In Chapter 5 certain needed numerical calculations are presented.

A summary of the report and some concluding remarks are presented in Chapter 6.

2. SOFTWOOD. STRUCTURE, PROPERTIES AND BEHAVIOUR

2.1. General Remarks.

Norway spruce (Picea abies) is the species this investigation relates to. Since it is one of the most common species in Sweden, Norway spruce was chosen as the material for this investigation. However, taken into consideration that its internal structure, many of its mechanical properties, and its behaviour are similar for other softwoods, the results may therefore also be valid for the other conifers from the Swedish forests.

2.2. Structural Levels of Softwood.

2.2.1. Macroscopic Characteristics of Softwood.

Macroscopic characteristics are those features visible with the naked eye. Macroscopic appearance varies depending on the studied tree surfaces. In the following, characteristics found in the three main planes of wood, longitudinal, transversal and radial will be discussed.

2.2.1.1. Characteristics of a Transverse Surface.

A transverse plane or a cross section of a stem is normally circular. Three parts may be distinguished: *pith*, *wood* and *bark*. New wood and bark is produced in the *cambium* which is a tissue between them.

Pith is normally at the center of the stem. It may vary in size from very small and barely visible in certain species, to large and conspicuous in others. In softwood, pith is fairly uniform.

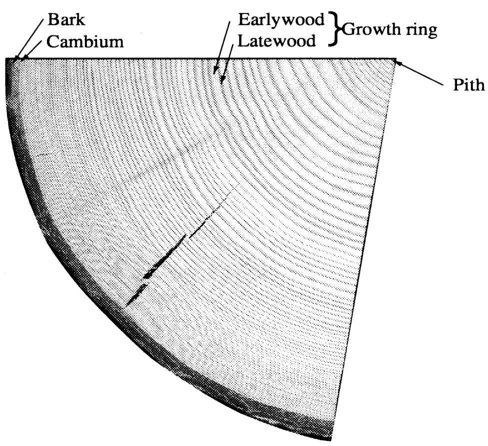

Figure 2.1: *Cross Section of a log.(From Persson, 1999)*

Wood is characterised by the presence of *growth rings* or *annual rings*, more or less conspicuous concentric layers that form an specific pattern as a result of the mechanism of tree growth that takes place by superposition of structurally different conoid layers. In most softwood species, growth rings can be easily distinguished from one to another because of differences between *earlywood* and *latewood*. See Figure 2.1. These tissues may differ in density, colour and other structural features, which reflect their cellular (microscopic) structure. In softwoods, earlywood and latewood differ in density and colour; latewood is darker in colour and has higher density.

Growth rings may be narrow or relatively wide. Differences exist within a tree, between trees and between species. In general, the width, as well as the pattern of variation of successive rings, are largely influenced by growth conditions; the availability of space both above and below ground is also important. In many species, the cross section of a stem does not have a uniform colour, but the inner portion is darker than the peripheral, these portions are called *heartwood* and *sapwood*, respectively.

The distinction between heartwood and sapwood is a functional one. As the diameter of the main stem (and the diameter of the branches and roots) increases with growth, the older growth rings gradually stop participating in the life process of the tree.

The sapwood alone take part in translocation and storage of food and the heartwood provides only mechanical support.

The relative amounts of heartwood and sapwood within a tree differ and depend on species, age and environment of growth. Heartwood starts forming in older growth rings near the pith; therefore, its diameter normally decreases from the bottom of the tree upward. This region is characterised of the absence of living cells and the richness of extractives. The later prevent the wood from the attack of fungi or insects. Softwoods contain approximately 8% extractives in the heartwood and about 3% in the sapwood.

An additional macroscopic feature of certain softwoods is the presence of *resin canals*. This normally also occurs in spruce. Resin canals are longitudinal oriented and form radical cavities within the tissue of the softwood. On the cross section of all woods appear also a kind of lines extending in the general direction from pith to bark which are called *rays.* In all softwoods the rays are more or less fine and sometimes difficult to distinguish, even with a hand lens. All rays do not start from the pith, they may start within any one growth ring but, once started, they usually continue toward the bark that will also enter.

The bark is surrounding the central cylinder of wood. The macroscopic appearance of this tissue differs according to species and age. In bark, growth layers are not macroscopically demarcated as the growth rings in wood are. However in older trees, two portions of bark may be recognised: *inner bark* (relatively light in colour, narrow and moist) and *outer bark* (dark, dry and corky). In a process that may be considered analogous to heartwood formation, the outer layers of the inner bark are gradually changing into outer bark and the outer layers of outer bark are gradually falling off.

2.2.1.2. Characteristics of Radial and Tangential Surfaces.

The surfaces that radial and tangential planes produce are characteristically different from each other, and from cross-sectional surfaces. A radial surface is produced when sectioning a stem through its pith. Various features like pith, growth rings, earlywood and latewood, heartwood and sapwood, inner and outer bark, appear as vertical strips. Resin canals appears as fine longitudinal lines of different colour and the rays are oriented crosswise.

By sectioning wood in a tangent to the growth rings, a distinctly different picture is presented. The tangential surface has a more or less wavy appearance, depending on the contrast between earlywood and latewood. The pith is not shown but all others macroscopic features may be represented according to the level of sectioning in relation to the pith. The rays, cut transversally, appear as longitudinal lines of varying length and width.

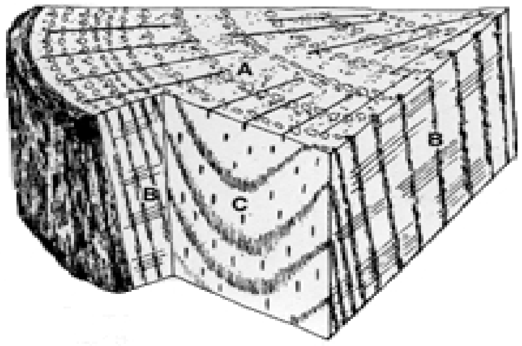

Figure 2.2: *Schematic representation of a sector of wood showing (A) transverse, (B) radial, and (C) tangential surfaces. (From Tsoumis, 1991).*

2.2.2. Microscopic Characteristics of Softwood.

Wood is composed of units called *cells*. Cells can only be identified on a microscopic level.

2.2.2.1. Description of the Wood Cell.

Cells are connected together in various ways to form the wood. Cells of softwoods species differ in appearance from the cells of hardwoods species. Softwoods, as Norway spruce, are composed of two types of cells called *tracheids* and *parenchyma cells*. Tracheids formed during the early growth season, when fluid transport from the root to the needles is high, form the earlywood part of the ring and they are low of density. In the later part of the growth season the tree builds latewood, which has tracheids with thick walls.

In the radial direction there are wood rays organised into bands of cells. The rays extend radially from the pith to the bark, serving mainly to provide food storage in the trunk. Ray cells consist primarily of thin walled parenchyma cells that are shorter and wider than tracheids. Parenchyma cells are also found in resin ducts, which are large sparsely distributed cavities distributed mainly in the longitudinal direction and surrounded by parenchyma cells. Due to their distribution, resin ducts have little influence on the mechanical properties of wood.

Pit pores are found almost entirely in the radial oriented cell walls between the lumens of adjacent cells. These allow liquid to flow between the cells and from the cells to the rays. Since they occur frequently, the pores may weaken the radially oriented cell walls and decrease the radial stiffness of the wood. (Persson, 1997).

2.2.2.2. Structure and Chemical Composition of the Cell Wall.

The cell wall consists of a *primary wall* (P) and of a *secondary wall.* The later is composed of three layers designated as *outer* (S_1), *middle* (S_2) and *inner* (S_3) layer. When present, a layer known as *warty layer* (W) is attached to the S_3 layer. This layer appears to be granular and very thin, and forms during the final stages of cell wall development. The *middle lamella* is not considered as a cell layer, it is the surrounding "glue" that holds individual cells. See Figure 2.3.

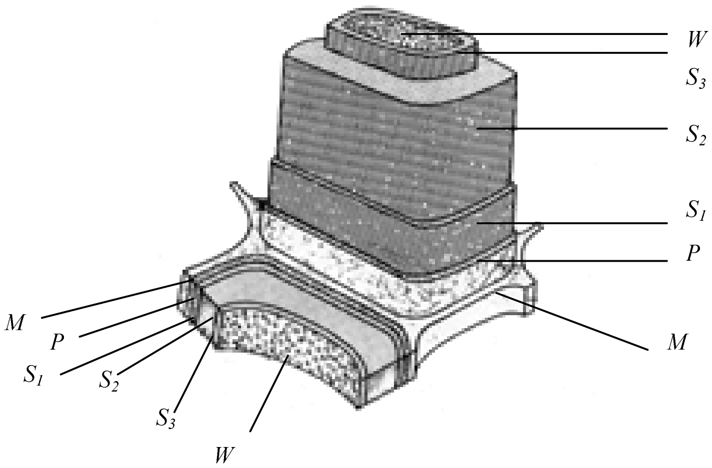

Figure 2.3: *Schematic representation of cell wall layers in a tracheid or fiber with respective orientation of microfibrils (*M*, middle lamellae;* P*, primary wall;* S_1, S_2, S_3*, layers of the secondary wall;* W*, warty layer). (From Tsoumis, 1991).*

The layers of the walls consists of cellulosic chains placed in a matrix formed by *hemicellulose* and *lignin* that forms units called *microfibrils*.

In softwood the proportions of those are approximately, 40-45% of cellulose; 25-35% of lignin and 20% of hemicellulose in percent of the oven-dry weight of wood.

As seen, cellulose is the component that appears in more quantity. Cellulose contributes to the large strength of wood in axial tension since microfibrils and cellulose chains are arranged parallel to tree length in the S_2 layer. Wood is a crystalline polymer even though cellulose chains run through both crystalline and amorphous regions. The degree of crystallinity varies therefore, however in general, it is high, between 67-90%. Crystallinity varies from pith outward and between earlywood and latewood.

Lignin is the cell-wall component that differentiates wood from other cellulosic materials produced by nature. It may be associated with the amorphous phase of cellulose and is found within the cell wall, but the large quantity is found in the middle lamella. Lignin and hemicellulose have high shear strength and, therefore, contribute to the high stiffness and integrity of wood. They bind the cells together and support the cellulosic framework giving elasticity and compressive strength. If removing lignin and hemicelluloses, the strength of wood in wet condition decreases drastically. (Dinwoodie, 1981).

Table 2.1: *Thickness and volumetric fractions of the chemical constituents of the cell wall layers. (From Fengel. 1969, Tsoumis. 1991).*

Cell Wall layer	*Chemical Contents, %*			*Thickness, μm*	
	Cellulose	*Hemicellulose*	*Lignin*	*Earlywood*	*Latewood*
P	20	15	65	0.23	0.34
S_1	35	30	35	0.12	0.35
S_2	50	27	23	1.77	3.68
S_3	45	35	20	0.10	0.15
M	20	15	65	0.5	0.5

Hemicellulose has a low degree of crystallinity and therefore, it has a low stiffness and, in contrast to cellulose and lignin, high moisture absorption capacity.

The arrangement of microfibrils is not homogeneous within a cell wall. In order to differentiate between primary and secondary walls, and also to distinguish the component layers in the latter, differences in microfibril orientation has often been used.

The primary wall is made up of a loose and random weaving of cellulosic microfibrils intermixed with lignin and closely packed. The primary layer is rarely visible because it is very thin and can be hard to distinguished from the S_1 layer.

The secondary wall has microfibrils with different distribution depending on the layer studied. In the outer layer (S_1), the closest to the primary wall, microfibrils form spirals and lies in a few lamellae that are arranged in an alternating left-handed and right-handed helical pattern. In each lamellae the helical angle is oriented in a direction 50º to 70º from the longitudinal cell axis.

In the middle layer (S_2), which is composed of several lamellae, the cellulosic microfibrils are generally quite parallel to cell axis, usually not exceeding an angle of about 30º. It is the thickest of the three layers that conform the secondary wall (from 3 to 15 times thicker, in earlywood to latewood, than the S_1 and S_3 layers combined) therefore, it has the greatest impact on how the cell will perform in strength, shrinking and swelling tests. Deviations of the microfibrils from lineament to cell axis increase axial shrinkage and swelling and decrease the strength of wood in the axial direction.

The S_3 layer is usually thinner than the S_1, lamellate (containing up to 6 lamellae) and the angle of the microfibrils varies from about 50º to 90º forming also flat spirals. Within the S_3 layer the microfibrils are arranged with a low inclination but not in a strict order.

Table 2.2: *Microfibril angle of the cell wall layers. (Dinwoodie. 1981, Tsoumis. 1991).*

Cell Wall Layer	**Microfibril angle, φ**	
	Earlywood	*Latewood*
P	Random	Random
S_1	50-70	50-70
S_2	10-30	0-30
S_3	50-90	50-90

2.3. Properties of Softwoods Affecting the Dimensional Changes.

Geometric performance (warp) is correlated to many factors, some known and some not known. Depending on growth characteristics, and different wood properties, softwood will suffer different distortions (bow, crook, twist, and cup), on three different directions (tangential, longitudinal and radial) and with different degree depending e.g. on the cross section location in the log.

2.3.1. General Remarks.

The log sampling and sawing pattern proposed Perstorper et al. (1995a) is a good reference to understand the different prone-warp depending on the radial and longitudinal situation.

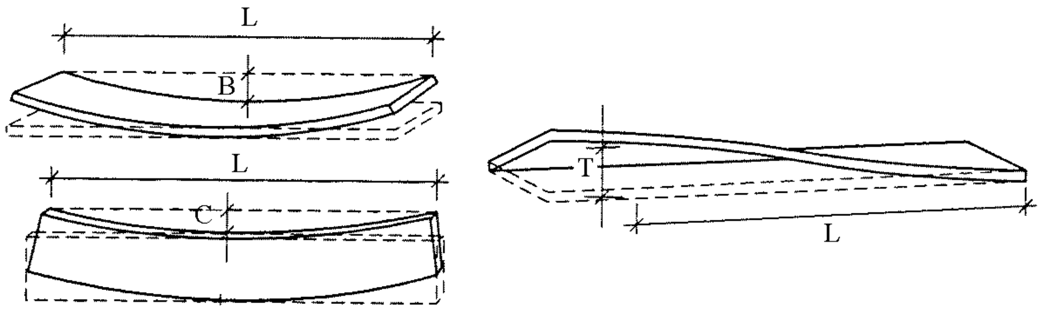

Figure 2.4: *Types of warping studied throughout this investigation. B: Bow; C: Crook; T: Twist.*

As shown in Figure 2.5., the material is cut from different radial and longitudinal positions in trees from two relatively fast-grown stands (a large diameter stand and a thinning stand).

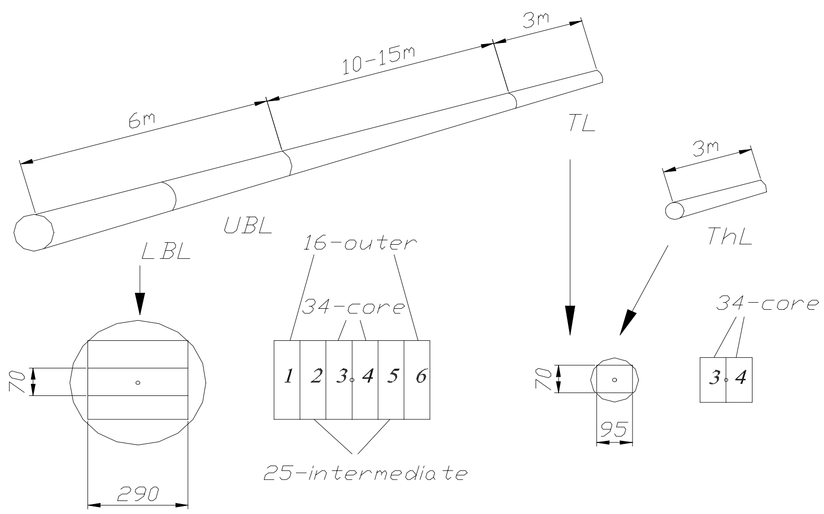

Figure 2.5: Log sampling and sawing pattern proposed by Perstorper. (Perstorper et al., 1995a).

Two sets of logs are taken from the butt end (LBL, UBL) and one set near the top (TL) of the trees from the large diameter stand. A fourth set of logs is obtained from the bottom part of the thinning trees (ThL) from a stand containing juvenile wood with only minor heartwood formation.
Six studs are cut from the butt log boards representing three stud groups with respect to radial location: 16 (outer), 25 (intermediate) and 34 (core).

2.3.2. Growth Characteristics.

Certain growth characteristics have an effect on the degree of warp in structural timber. The following variables have been recorded as parameters affecting the degree of warp.

2.3.2.1. Reaction Wood in Softwoods.

Reaction wood may occur in both hardwoods and softwoods, and is known *as tension wood* and *compression wood*, respectively.

Compression wood can be understood as abnormal wood formed in softwood tree stems and branches that have grown out of the vertical position. As a rule, compression wood is formed in softwoods on the underside of leaning stems.

Compression wood is relatively to visually identify. A stem cross section, containing significant quantity of compression wood is darker in tone than the surrounding normal wood and it has a reddish-brown colour that makes it conspicuous. The degree of severity in which this abnormal wood is present may be different, when it is pronounced, growth rings seem to be composed entirely of latewood, however, when the degree of intensity is slight, the recognition of this abnormality may be macroscopically difficult.

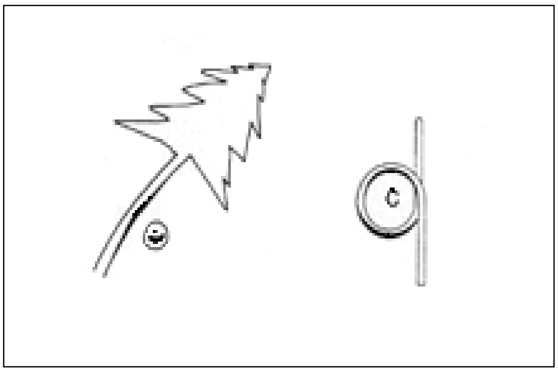

Figure 2.6: *Position of compression wood in trees displaced from the vertical. The position of compression wood is shown with black bands. (From Tsoumis, 1991).*

Microscopically, typical for compression wood is that in a cross-section, the shape of tracheids is circular, and as a result of this they are not tightly connected leaving intercellular spaces among them. Figure 2.7.(A). The structure of compression wood differs also from normal since the tracheids lack the inner layer (S_3) Figure 2.7.(B). of the secondary wall and the outer layer (S_1) is usually thicker than normal. Furthermore, in the middle layer (S_2), tracheids are arranged in flat spirals with an angle range from 40 to 60%. The cell walls of compression wood are thick, even though when the part where it is present is earlywood.

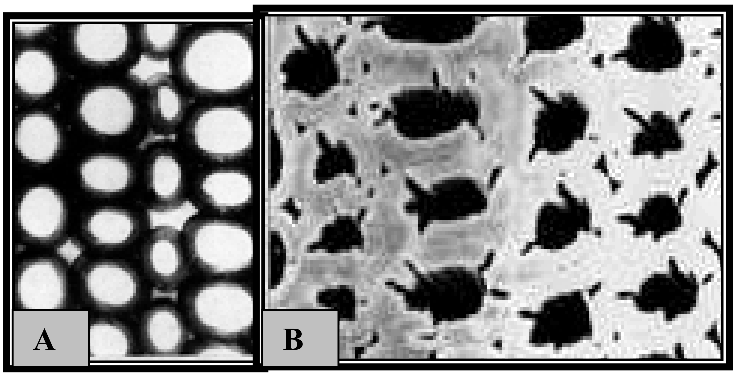

Figure 2.7: *Compression wood. (A) Compression wood in a light microscope with characteristic rounded tracheids and intercellular spaces (spruce, 350x). (B) Photograph showing the lack of the S_3 layer of the secondary wall. (From Tsoumis, 1991).*

With respect to physical and mechanical properties, compression wood contains less cellulose and more lignin than normal wood. An excess of lignin is deposited between the S_1 and the S_2 layers, this higher content of lignin decreases the tensile strength with almost 10% (Cockrell and Knudson, 1973). The compression strength is higher than in normal wood, however, small percentage of compression wood can reduce the *Picea abies* wood bending strength resulting in a bending failure that tends to be more brittle and without compression failure development.

It has been found that compression wood has relatively low stiffness, bending strength, and toughness for its weight. The MOE is lower and the density is higher, about 40% than in normal wood. This is explained by the thicker walls of tracheids, but in contrary to normal wood for which most strength properties increase rapidly when decreasing the moisture held in cell walls and also increasing strength when increasing density, these relationships do not apply to compression wood. Density will, therefore, be a poor indicator of strength when compression wood is present.

With respect to the relationship between the compression wood and the log position, a study carried out by Beard et al. (1993) found that the amount of compression wood affected bow and crook, and the amount of wane affected crook. Perstorper et al. (1995a) concluded that compression wood is much more common in top logs studs (75%), than in butt log core studs (35%), nonetheless the top logs have less crook compared with the butt log core studs. This is explained by the fact that the butt log material reacts much more to the presence of compression wood than the top logs do. Compression wood in the butt log core is mainly associated with the inclination of the young stem due to, for example, wind or snow, while in the top log the much large branches are the responsible. The compression wood formed beneath the heavy branches in the top log is less voluminous and consequently, creates a lesser degree of crook changes.

Furthermore, studs with easily visible compression wood have less twist but larger bow and crook as shown in Figure 2.8.

The lesser twist of studs with compression wood might be related to the smaller tangential shrinkage of compression wood fibres, which is an important variable influencing twist. The much higher longitudinal shrinkage of compression wood will result in curved distortions during drying.

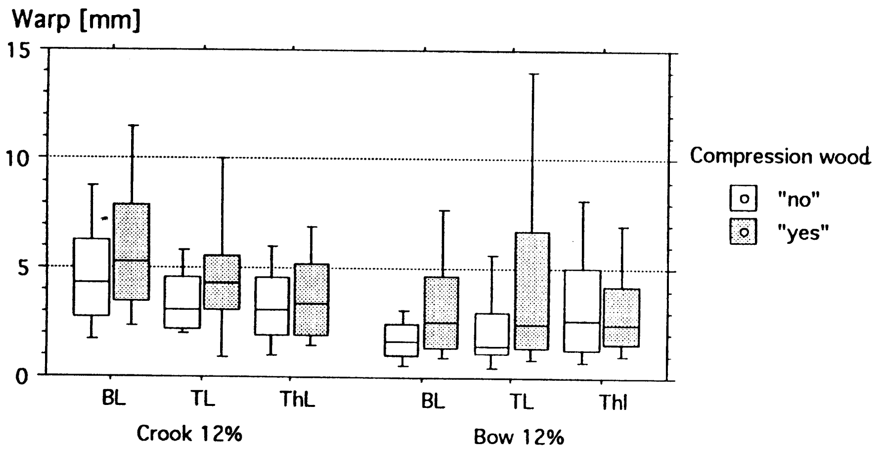

Figure 2.8: *Influence of presence of compression wood on crook and bow at 12% MC for different stud groups. The markers in each box represent the 10th, 25th, 50th, 75th and 90th percentile. (From Perstorper et al., 1995b).*

2.3.2.2. <u>Grain Angle.</u>

Grain angle in wood refers to the angle between fiber direction and the board edge.

Although spiral grain does not produce any figure effect, it has important technical repercussions: the strength is lower and the degree of twist on drying increases as the degree of spirality of the grain increases. Although there are exceptions, spiralling in softwoods often begin at a left angle, and then straighten out with time and growth and eventually slope more and more to the right as the tree matures.

With regard to Norway spruce, no consistent radial trend in grain angle is found (Danborg, 1990; Perstorper et al., 1995a). It seems that the left helix spirality is often present just in juvenile wood, therefore, fast grown timber having more content of juvenile wood than slow grown timber with same dimensions tends to have higher twist.

2.3.2.3. <u>Heartwood Formation.</u>

As explained in Section 2.2.1.1, the young outer region of a tree stem, called sapwood, conducts the upward sap's flow from the root to the crown. When the wall cells grow old, they stop functioning physiologically, this inner part of the bole is known as heartwood.

With relation to the warp-prone, studies carried out by Hillis (1984) and Panshin and de Zeeuw (1980) demonstrate that extractives present in heartwood may stabilise the warp-prone juvenile wood core. According to this hypothesis, studs close to pith in large diameter butt logs should be less prone to warp for a given moisture content than studs from small diameter thinning logs.

In the study carried out by Persterson et al. (1995a) the thinning material (ThL) represents juvenile wood with a little part of heartwood formation while the core studs of the butt log represent juvenile wood with heartwood formation. In this study the thinning studs and the core studs of the butt log (BL-34) are statistically identical with respect to twist, which contradicts the hypothesis that heartwood formation prevents excessive warp of warp-prone juvenile wood.

With respect to crook no stabilising effect of heartwood is found and the evaluation of the influence of heartwood formation on bow shows that timber from the thinning stand does not differ significantly from any of the other stud groups. This result is in good agreement with the conclusion that, for twist and crook heartwood formation, it seems not to diminish warp of pith in Norway spruce timber.

2.4. Other Factors Affecting the Degree of Warp.

As shown in Section 2.3., some growth features highly influence the deformations (warp) wood can suffer, however, different factors that are not related to the growth process may also be responsible of the degree of warp.

2.4.1. Density.

Density is the mass contained in a unit volume of material. Since shrinkage, and other properties such as stiffness and strength, is influenced by density of wood, it is an important property.

Density is influenced by moisture, structure, extractives and chemical composition. Wood is hygroscopic, therefore it can attract and retain moisture. Adsorption of moisture increases both weight and volume of wood, whereas losing moisture weight and volume reduces.

They are different options of defining the density of wood but a common measure is the oven-dry weight of wood divided by its volume in green condition.

Increasing moisture content will increase density of wood as shown in the next table.

Table 2.4: *Effect of moisture on the density of wood. Column 1: Oven-dry density; Columns 2-6: Density at respective MC. (From Tsoumis 1991).*

	r_0	Moisture content, % 10	20	30	50	100	Maximum MC %	Maximum swelling %
		Density, (g/ cm^3)						
Species	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Spruce	0.41	0.432	0.451	0.469	0.541	0.722	207	13.06
Pine, Scots	0.49	0.515	0.537	0.558	0.643	0.858	167	14.2

Density is also dependent on the cell structure because it varies in relation with the amount of cell walls and cell cavities present in a certain volume.

In regard to the influence on ring width, in softwoods the correlation is low between ring width and density. (Tsoumis, 1991). However, rings of the same width do not have the same influence on density. Density depends on position in the tree i.e. juvenile, mature or overmature wood, on the existence of compression wood, and variations of cellular structure.

Density will also vary with latewood formation. The latewood cells have thicker walls and small cavities in comparison to earlywood, this results in a higher density of latewood, from 0.55 to 0.87 g/ cm^3, than for earlywood, where the density ranges from 0.31 to 0.36 g/ cm^3 in spruce. Hence the density of softwood increases with increasing latewood proportion. Figure 2.9.

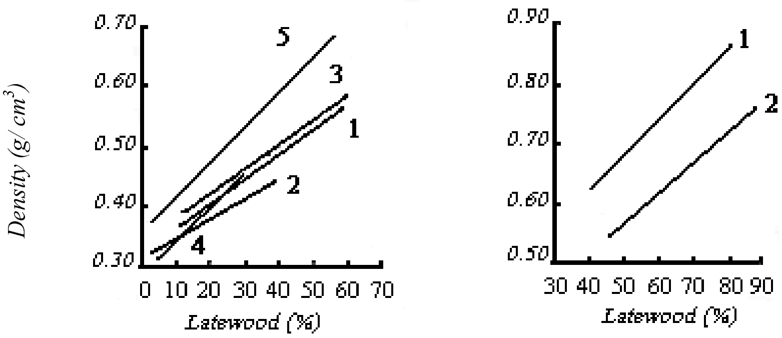

Figure 2.9: *Relationship between density and proportion of latewood: 1, European larch; 2, Scots pine; 3, Hybrid fir; 4, Norway spruce; 5, Douglas fir. (From Tsoumis, 1991).*

Density is not the principal factor affecting the warp on wood though. As seen in Table 2.4., even though there is a small but significant correlation between bow and density (coefficient of correlation R=0.2), this is rather an effect of the compression wood properties.

2.4.2. Moisture Content.

Wood is hygroscopic i.e. it is in equilibrium with the ambient climate, and it changes in both weight and volume with loss or gain of moisture content. Therefore, for any combination of relative humidity and temperature of the atmosphere there is corresponding moisture content of the timber.

Usually the moisture content of timber is expressed in terms of its oven-dry weight by the equation:

$$\mu = 100 \cdot \frac{W_m - W_0}{W_0}$$

Where $W_{m.}$ is the weight of wet timber, W_0 is the weight of timber after oven drying at 105 ^{0} C and μ is the moisture content *(%)*.
The moisture content is determined by weighing a wood specimen twice: the first time the purpose is to register the mass of the specimen when wet, and the second after drying to register the mass for the dry specimen.

Knowing the difference between the two weights, the formula above determinates the relation between the water and wood.

The range of moisture content can be from 0% when sawn timber is completely dry and as high as 160% (depending on the species) when timber is green.

The green timber is often not perfectly straight since internal stresses in the log are released while sawn into boards. (Nilsson, 1993; Perstorper et al., 1995a). However, the final distortion of timber occurs during drying while the anisotropy and inhomogenity of timber create warp, as explained later in following section.

The warp of Norway spruces exposed to moisture cycling, is affected by the different degrees of MC at which the trees are exposed. (Perstorper et al., 1995b). When measuring warp at an equilibrium moisture content of approximately 12%, then change the ambient conditions, in order to create an equilibrium moisture content of about 18% and, finally drying the timber to 12% MC, it is easy to notice that twist, crook and bow are influenced differently as a function of climate history.

As can be seen on Table 2.5. In the first step from 12% MC to 18% MC the median values for twist, crook and bow are reduced with 1.5 mm, 0.7 mm and 0.3 mm respectively, thus twist is more affected than bow and crook.

In the second step back to 12% MC, the studs nearly return to their original shape with respect to twist. However, for crook and bow the studs become more curved than in the initial stage: bow is 50% larger after the last step compared with the initial value at 12% MC while crook is 11% higher.

Table 2.5: *Median values of warp in mm for different stud groups at different moisture content stages.(From Perstorper et al. 1995b).*

Stud group	*Twist*			*Crook*			*Bow*		
	12%	*18%*	*12%*	*12%*	*18%*	*12%*	*12%*	*18%*	*12%*
All	3.7	2.2	3.6	4.2	3.5	4.6	2.0	1.7	3.0
BL-16	1.4	1.5	1.1	4.3	3.5	4.7	2.1	1.7	2.6
BL-25	2.3	1.1	2.1	4.2	3.7	5.6	1.7	1.3	2.4
BL-34	6.8	3.7	6.5	5.6	4.9	6.5	2.0	2.0	3.1
TL-34	6.6	3.3	7.5	3.9	3.3	4.1	2.2	2.3	4.1
ThL-34	5.6	3.2	6.5	3.1	2.8	3.1	2.5	1.9	3.9

Therefore, the conclusion is that warp at different moisture levels and the changes in warp between moisture levels is highly correlated for twist and bow, however it is less significant for crook deformation.

2.4.3. Drying Process.

Lumber logs usually contains considerable quantities of water immediately after its fell in the forest. Therefore wood should be dried properly so to give the material practical use in structures. Such drying has important advantages in comparison to raw wood:

a) Dried timber is lighter, since drying reduces weight.
b) When subjected to normal climate conditions, raw timber will dry and suffer large deformations (shrinkage), which will make wood unsuitable for structural use.

c) By drying timber, wood is protected from attack by stain and decay fungi since dried wood does not contain water enough for fungi to root.
d) Satisfactory painting, finishing, and preservative treatments require dry wood.
e) Drying results in higher stiffness and increasing strength.

Water content of sawn timber has, therefore, to be reduced considerably in order to produce suitable timber for practical purposes and construction use. For a mean log of Norway spruce the moisture content has to be reduced from approximately 85% to 16-10% the latter depending on final use. (Svensson, 1997).

When drying wood, two different transport water stages can be recognised. In the first transport stage, free water is removed and later, during the second stage, the bounded water begins to dry. Bound water is inside the cell walls and, when removed, wood material will contract. A piece of wood is always seeking towards moisture equilibrium with ambient climate. Convective air-drying is based on this principle, but under conditions of convective air-drying, wood close to a surface reaches the equilibrium before the material placed further away from a surface. In the first stage, drying of free water do not increase internal stresses. In the second stage (bound water is dried), moisture distribution is not uniform. Since shrinkage is proportional to the moisture content below the fiber saturation point, material closer to the surface wants to deform more than material further away from the surface resulting in internal stresses. Early in the drying process, restrained shrinkage on the surface induces tensile stresses, which can lead to surface cracking (Svensson, 1997).

Wood anisotropy and inhomogenity creates unequal shrinkage in the three axial directions: along the grain (longitudinal), edge grain (radial) and flat grain (tangential). In normal wood longitudinal shrinkage is quite small (less than 0.4%) but radial and tangential shrinkage is appreciable (on average 4% and 8%, respectively). Later in the drying process it is likely the reverse situation, that is compression on the surface and tension across the grain in the interior fibres. When these reversed stresses are large enough, surface cracks may close and become hard to detect.

Much effort has been made by sawmills to reduce the negative effects of drying. Mainly done by trial and error, material wood has been studied and its knowledge has been used to improve drying process of sawn timber.

Wood may be dried open-air or in a kiln. *Air-drying* is usually done in the open air, whereas *kiln-drying* is done in a close space and temperature, relative humidity, and air circulation are controlled in order to create an artificial climate. Kiln-drying is much faster, and moisture may be reduced to almost any level, independent of local out door climate. However, some basic aspects have to be kept into consideration in both, air-drying and kiln-drying methods, to avoid undesirable results and defects.

Suitable yard and proper piling of lumber are required when using air-drying method. Lumber has to be placed in piles properly constructed and arranged, (size of piles affects the rate of drying). The foundations of piles and the stickers used for separating rows of boards have also to be chosen carefully to avoid warp. Boards of unequal length may cause problems, because protruding ends warp if not supported.

When kiln-drying method is used, two kiln types, *compartment* and *progressive*, can be chosen, even though modifications may result in new kiln types.

Drying conditions are more severe in a kiln in comparison to air-drying, and therefore, deviations from proper piling and drying schedule will cause greater degradation of lumber.

2.4.4. Sawing Method.

Lumber is a wood product made by lenghtwise sawing of logs that is manufactured in varying dimensions and used in structures and other uses.

Three basic types of sawing machines, differing in constructional details, are used to produced lumber: frame saw, band saw, and circular saw. The latest has been the one used during this investigation. A circular saw is a disk that has teeth on its periphery and rotates on an axle. The advantage of a circular sawn, in comparison to other saw types, is the possibility of turning the log after each saw cut, which may contribute to a better quantitative and qualitative utilisation of wood. By quarter-sawn sawing, lumber shrinks and swell less in width, warps less, and wears more evenly. However, flat-sawn lumber shrinks and swells less in thickness, but lumber of large width has a tendency to warp.

Sawing parallel to bark or pith may also affect the quality of lumber, depending on taper and juvenile wood. Sawing parallel to pith will result in a more uniform distribution of grain deviation due to taper, whereas in sawing through the pith the central lumber boards will present just one side having juvenile wood. (Lumber including grain deviations and juvenile wood tends to warp).

2.5. Shrinkage and Swelling.

2.5.1. General Remarks.

Dimensional changes occur in wood when the moisture of wood varies below the fiber saturation point. The result of the dimensional variation is either an increase or reduction of the wood volume called *swelling* and *shrinkage*, respectively.

The swelling or shrinkage of wood, for a specific change of moisture content, is different in different directions of tree growth, therefore, wood is considered anisotropic with regard to shrinkage and swelling. Furthermore, the dimensional change is smallest in the longitudinal direction, much greater in the radial direction (from pith to bark), and still greater in a direction tangential to growth rings.

2.5.2. Factors Responsible of Shrinkage and Swelling.

Shrinkage and swelling in softwoods are affected by many factors. Most important is of course moisture, but also density, anatomical structure, extractives, chemical composition and mechanical stress influence shrinkage and swelling.

The degree of shrinkage and swelling depends on the amount of moisture that is lost or gained by wood when its moisture fluctuates below the fiber saturation point.

When the density is higher, the magnitude of shrinkage and swelling become also higher. Such reaction is due to the larger amount of wood substance, (a greater cell wall thickness) in woods of higher density, and to the exterior change of cell dimensions. Otherwise, when moisture is lost or gained the size of the cell cavity remains practically invariable; the relationship between shrinkage or swelling and density is directly related to the relationship between moisture and shrinkage or swelling in cell walls. Density affects the coefficient of anisotropy of shrinkage or swelling. Such coefficient (ratio of tangential to radial shrinkage or swelling) decreases when increasing density, and coefficient of shrinkage anisotropy increases with increasing moisture content of softwood.

Table 2.6: *Variation of density and shrinkage for a given air-dry density (12-15%MC) in Norway spruce.*

Density (g/ cm^3)	Shrinkage, %			
	Axial	*Radial*	*Tangential*	*Volume*
0.32-0.55	0.1-0.5	1.4-6.1	4.7-12.1	6.8-16.5

A large extractive content results in a reduction of shrinkage or swelling. This reduction is proportional to the space occupied by the extractives in the cell walls.

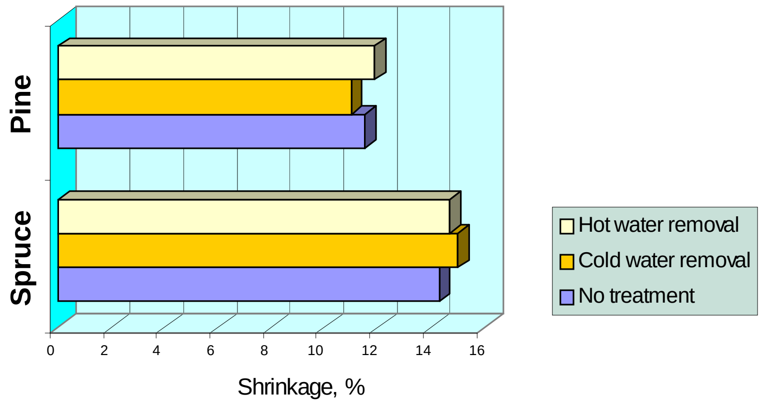

Figure 2.10: *Effect of extractive removal on volumetric shrinkage: Spruce; Pine. (From Nea, 1955; Tsoumis, 1991).*

The influence of the chemical composition of cell walls is small. Lignin posses a restraining effect on shrinkage and swelling, but it may also contribute to the greater shrinkage of high-density woods, because lignin content is reduced with increasing density. Softwoods shrink less than hardwoods, at an equal wood density, because of the higher lignin content.

2.5.3. Shrinkage and Swelling. Its Anisotropy.

As discussed previously, the shrinkage and swelling of wood varies depending on the direction of growth; this fact is attributed mainly to cell wall structure.

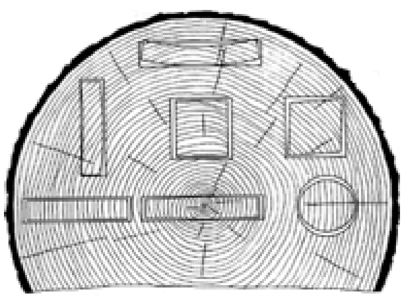

Figure 2.11: *Distortions, change of shape and warping due to radial and tangential shrinkage, of various cross sections cut from different locations in a log.*

The primary wall (P) of a cell wall is very thin, and the secondary wall is composed of three layers (S_1, S_2, S_3) with different orientation of microfibrils. When moisture is absorbed, the middle layer S_2 tends to swell proportionally to the number of microfibrils, thus to its thickness, but the outer and inner layers (S_1 and S_3) exercise a restraining effect due to the different orientation of the microfibrils. The small longitudinal shrinkage is due to the orientation of microfibrils in the middle layer. If these were perfectly parallel, longitudinal shrinkage would not exit, but small deviations from parallelism cause a small longitudinal shrinkage. When the deviations are larger, like in compression wood or juvenile wood, shrinkage and swelling are greater.

With regard to the differences between radial and tangential shrinkage and swelling, they are in part attributed to the presence of rays, which, because of their radial orientation, exercise a restraining effect to the radial shrinkage and swelling. This restraining effect is attributed to the direction of microfibrils in the walls of their parenchyma cells, mainly parallel to cell length.

Another factor considered to produce anisotropy in softwoods is the different density between earlywood and latewood. Latewood shrinks and swells more due to its higher density. Since latewood is dominant causes the attached earlywood to follow the same tendency. The tangential arrangement of the growth rings produces a greater tangential shrinkage.

In conclusion, it may be stated that a combination of different factors produce differences between radial, tangential and longitudinal shrinkage and swelling, which may, within others defects, produce warping.

2.6. Conclusions.

As a conclusion the following aspects can be drawn from the evaluation of the different literature studied:

- Twist and crook tend to be maximum near the pith. However, twist decreases much more rapidly with the distance from the pith compared with crook. Crook of core studs is larger in the butt log than in the top log, while twist and bow of core studs does not vary longitudinally.
- Heartwood formation in the butt log juvenile core does not diminish prone-warp. Crook is in fact larger for the butt log core studs than for thinning studs.
- The warp at different moisture levels and the changes in warp between moisture levels are highly correlated for twist and bow. However the correlation between the degree of crook and crook change between moisture levels is less significant.
- Twist is highly correlated to the distance from the pith. The ratio of grain angle to pith distance is a good parameter for twist prediction.
- Presence of compression wood increases bow and crook significantly, while ring width, density and knot area ratio do not substantially contribute to explain warp variation.
- Adequate sawing and drying methods may reduce the warp-prone.

3. EXPERIMENTAL WORK

3.1. Measuring Equipment.

A measuring table designed during the first part of the experimental work of this master project basically composes the measuring equipment. However, other measuring instruments have also been used in order to do different readings of the boards. A digital gauge slide was necessary, first at the sawmill, for measuring the degree of bow on the boards after sawing process, and lately, at the laboratory in order to measure the twist on every board after drying process and a short period of storage (3 days). A moisture meter was used to measure moisture content in the selected boards.

3.1.1. Designed Tool.

The tool designed during the first part of the experimental work was used in order to measure bow and crook after the drying process in a kiln. The tool was designed and constructed at the Division of Structural Engineering laboratory. See Figure 3.1.

It was important to design a portable tool, even not having high accuracy, with the accuracy necessary in order to do the measurements in a range expected.

The table with the dimensions 3000mm x 600mm x 946mm is made of wood (mainly plywood) and steel parts, the main structure, three supports built in order to hold the measuring instruments, and three metallic guides set in the plywood.

The main structure of the table is a metallic frame composed by metallic pipes 40mm of diameter that, are detachable. That characteristic helps the table to be light and portable. Its legs are welded with the upper part of the metallic frame. The frame is employed in order to hold the secondary structure of the plywood. For the secondary structure the main piece of wood is a joint of three pieces of plywood with different thickness (16mm), (22mm), (34mm).

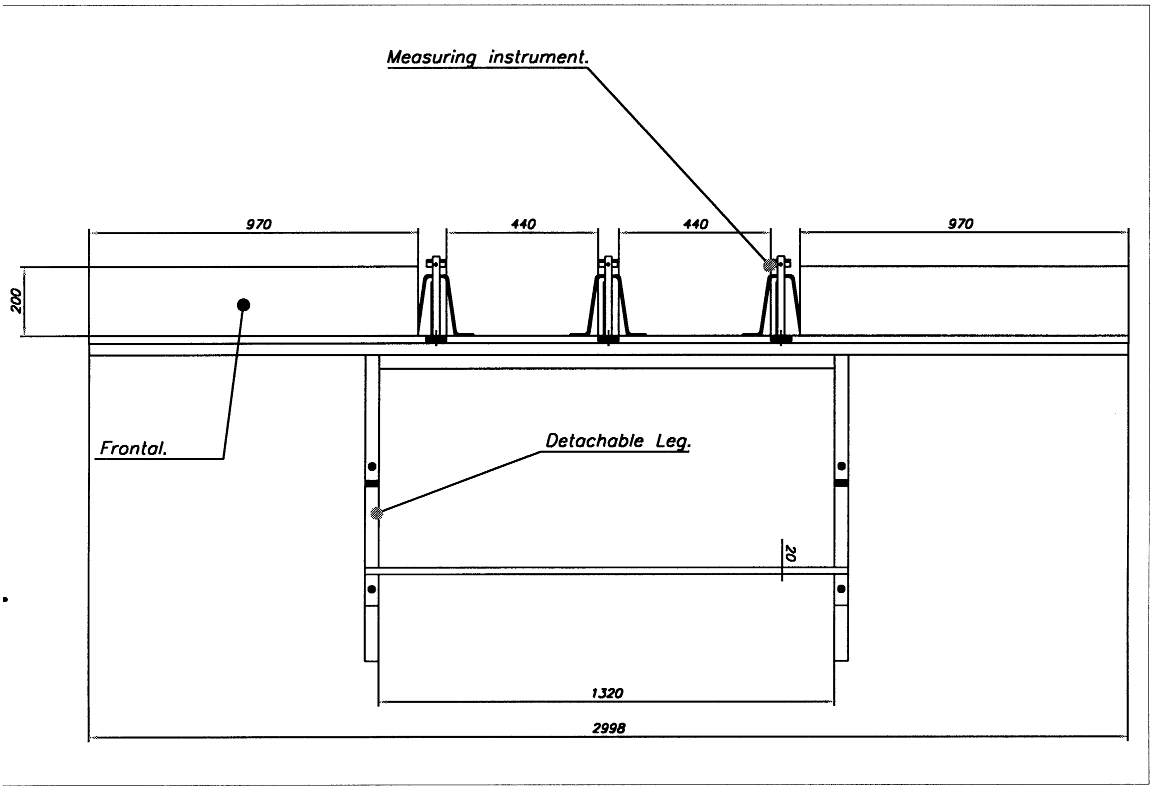

Figure 3.1: *Designed table to measure bow and crook deformations after Drying.*

The top plywood 16mm depth has the same thickness as the metallic guides, these later mounted. See Figure 3.1. These guides are screwed on the second plywood and these, on their turn, are screwed on the metallic frame.

Two pieces of wood (frontal panel) measuring 970mm x 200mm x 4mm are glued and screwed on six wood triangles. The frontal panel acts as a top where the boards drag along the plywood plates. For holding the measuring instruments three metallic supports were also designed.

Deformations (bow and crook) were measured with the measuring instruments, dial transducers. One transducer is centred and the other two are spaced on both sides 970 mm. The transducers do not give the highest accuracy but they were chosen because the reading they give is accurate enough for this investigation.

3.1.2. Gauge Slide.

Bow after sawing, and twist after drying process have been measured by using a digital gauge slide. With the gauge slide measures between the marks drawn during the marking process were obtained.

3.1.3. Moisture Meter.

There are two types of moisture meters based on electric resistance to passage of direct current and based on dielectric properties of wood in a high-frequency electrical field. This type of moisture meters includes two meters: a) electric capacitance, which is based on the relationship between dielectric constant and moisture content of wood and b) power loss of high frequency current.

With using an electric meter some advantages are: take fast measurement of moisture, measurement that is as well non-destructive, it is a light and portable instrument and its cost is reasonable. On the other hand, however, they are some disadvantages; measurements are affected by various factors, such as density of wood, temperature of wood, atmospheric conditions, etc. By proper use moisture meters may give an accuracy of ±1-2% in comparison to weighing and drying. Basically, the factors affecting the electric properties of wood are the basic factors affecting the accuracy of electric moisture meters.

The moisture meter used through out this investigation is a resistance moisture meter. By using this type of moisture meter, we have the advantage that it is more accurate because electrical resistance is very sensitive to moisture and it is less affected by the density of wood.

Figure 3.3: *Resistance moisture meter used during the investigation.*

Grain direction is also important for resistance meters, especially for moisture contents higher than 20%; the electric current should flow parallel to grain. (Tsoumis, 1991). Unequal distribution of moisture can not be measured with resistance meters, since they measure the maximum moisture content at the contact points of the electrodes, and the region of maximum moisture is also the path of minimum electrical resistance.

In order to have readings that are close to the average moisture content, the electrodes of resistance meters should enter to a depth of 1/4 - 1/5 of boards' thickness. (Tsoumis ,1991).

3.2. Material.

3.2.1. General Remarks.

The most common conifers in Sweden are Scotts pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*), however, this research relates only to spruce. Spruce is the most important conifer for providing structural timber in Sweden and 70% of Swedish are forests of spruce.

Norway spruce is one of the most important species on the European Continent. Depending on the country this tree is called Epicea commun, Faux sapin, Pesse (French), Fichte, Rottane, Weissfichte (German), Gewnow spar, Fijndsr, Kerstspar (Dutch), Picea comune, Abeto rosso (Italian), Abeto rojo (Spanish), Gran (Swedish), Kuusi (Finish), Jolka, Jalyna (Russian), etc.

Norway spruce has a rather extensive range in Europe, growing from Scandinavia to the Balkans and the Alps. It is a cool climate species and is found at elevations of 1000 to 2300 meters. In the centre of Europe it appears as mountain tree while in the north, in the Scandinavian countries, Russia and north of Poland it is a plane tree.

The species is adapted to cool temperature climates. Growth is best in full sunlight inn deep, rich, moist soils.

Visually it is a high tree. In Europe, Norway spruce grows from 40 to 65 meters in height, but in United States is seldom more than 40 meters tall.

It has cylindrical straight trunk and diameter may reach as much as 70 cm on older trees. The species has a reddish bark, giving it the nickname of “red fir”. Its dark green needles and drooping branchlets readily identify it. Trees have dark green crown with a triangular shape. Leaves (needles) are rectangular in section, 1.25–2.50 cm. long, and sharp or somewhat blunt at the tip. At the top of each needle is a twig-like projection, which remains after the needle is lost.

The wood is strong for its weight, but slightly resinous and is also importance in the manufacture of pulp and paper.

3.2.2. Stands and Plots Characteristics.

The material used in this investigation was manually sawn by using a chain saw from trees belonging to two different stands. Both stands are situated at Asa experimental forest, 37 Km north of Växjö. (57º08’ N 14º45’ E, alt.225 and 200 m). See Figure 3.4.

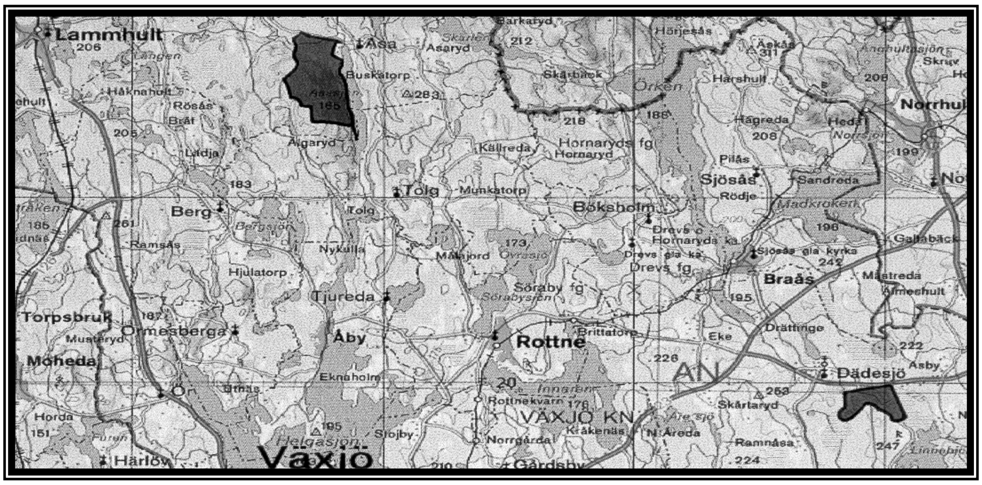

Figure 3.4: *Topographic map over the area of Asa Experimental forest.*

The experimental stands represent common stand types in phase of second commercial thinning. Factors considered for the selection were size, evenness, and successful regeneration.

The stands, called Tabergsvägen and Sandshagen respectively, contain spruce that were established trough planting after scarification process, by using four-year-old bareroot seedlings of local provenance.

Two thousand five hundred seedlings per ha. were originally planted in such stands. However, some special characteristics may differentiate each stand from each other.

Tabergsvägen Stand. (Spruce I)

Such stand was planted in 1956 and replanted lately in 1960 on areas were first plantation was not successful. There is not available information about precommercial thinning.

Table 3.1: *Site data of Tabergsvägen Stand. (From Klang 1999).*

Stand	**Inventory year**	**SI** *Dm*	**T** *Year*	**h_{dom}** *dm*	**D_g** *Cm*	**N** *st/ha*	**G** *m^2/ha*	**V** *m^3sk/ha*
Spruce I	1990	356	30/34	159/179	14.5	1878	31.1	235

Tabergsvägen stand also contains six different plots that are quadratic or rectangular having 0.1 ha area each one. A buffer strip 5 m long surrounds each plot. See Figure 3.5.

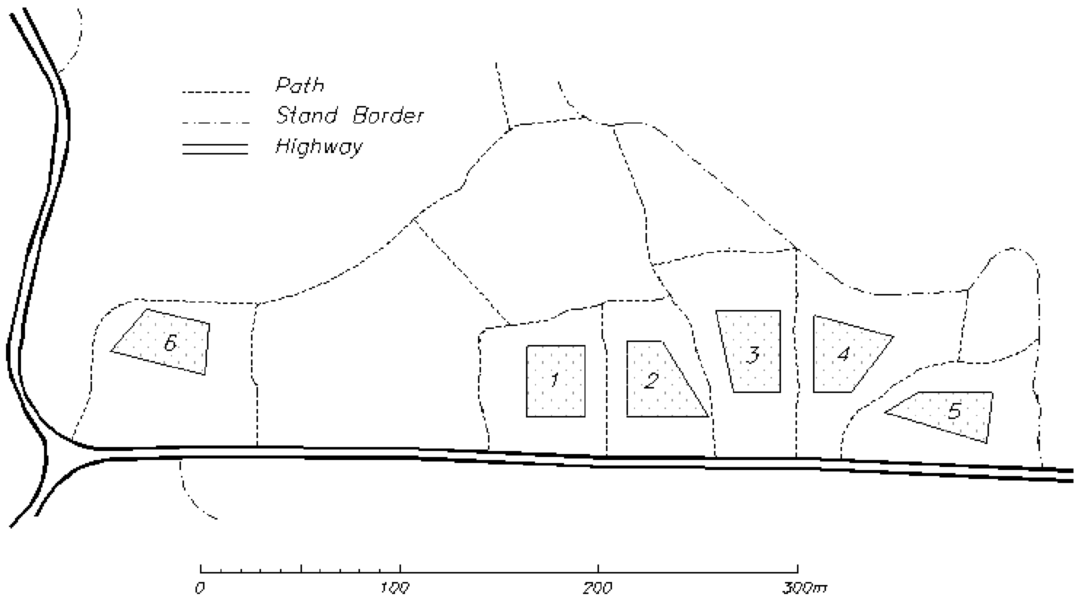

Figure 3.5: *Emplacement and plot distribution of Tabergsvägen Stand. 1. LÅG Plot, 2.ORÖRD Plot, 3. SLU Plot, 4. HÖG Plot, 5. FUL Plot, 6. FIN Plot. (From Klang 1999).*

Every plot differs from each other because of the thinning method that was applied on it. The plots called FIN, FUL, HÖG, and LÅG were used through out the investigation without taking into consideration the buffer zones. Extra trees from the stands were also used and are called SPEC trees.

These plots have been classified as follows:

- FIN Plot: The name may be translated like *NICE Plot*. The trees considered splendid specimens (for example, straight trees with thin branches) were left in the forest plot, and the bad trees e.g., trees crooked were removed from such plot when the thinning was done.
- FUL Plot: Which translates as *UGLY Plot*. When thinning method was applied on it, high quality trees were removed in favour of low quality trees.
- HOG Plot: A thinning from above was applied on it, large trees were removed from the plot in favour of small trees. It may be translated like *HIGH Plot*.
- LÅG Plot: Its name may be translated to *LOW Plot*. Thinning from below was applied, i.e. small trees were eliminated in favour of large trees when thinning method was done.
- SPEC Plot: Is not exactly a plot, in fact they are extra trees with severe crook collected outside the other plots to get more severe crooked trees as samples, since trees with severe crook inside the plots were too few.

Sandshagen Stand. (Spruce II)

The stand was planted in 1961 and precommercial thinning was made in it in 1971 to remove broad-leaved trees.

Figure 3.6: *Emplacement and plot distribution of Sandshagen Stand. 1. OGALLRAD Plot, 2. SLU Plot, 3. FIN Plot, 4. HÖG Plot, 5. FUL Plot, 6. LÅG Plot. (From Klang 1999).*

Table 3.2: *Site data of Sandshagen Stand. (From Klang 1999).*

Stand	**Inventory year**	**SI** *Dm*	**T** *year*	$\mathbf{h_{dom}}$ *dm*	$\mathbf{D_g}$ *Cm*	**N** *st/ha*	**G** m^2/ha	**V** m^3sk/ha
Spruce II	1991	390	29	174	14.2	2438	38.9	317

The stand contains six different plots where six different thinning methods have been applied. Moreover, all plots are quadratic or rectangular and their area is 0.1 ha each plot. A 5 m long buffer strip surrounds every plot. See Figure 3.6.

In the current study, FIN, FUL, HOG and LÅG have been classified as done in Tabergsvägen stand, and a new plot called SLU has been introduced. In SLU Plot thinning was done without considering either size or quality of the trees. The buffer zones were also excluded here. Extra trees from the plot called SPEC were also collected from this stand.

3.2.3. Process to Obtain the Tested Boards.

3.2.3.1. Sawing Process.

Sawing was done with a circular saw and in a so-called cant-sawing pattern, as shown in Figure 3.7. Sawing was parallel to pith and symmetric according to the position of taper. Each board had a parallel ending and the final dimensions obtained were 3200 mm x 90 mm x 50 mm.

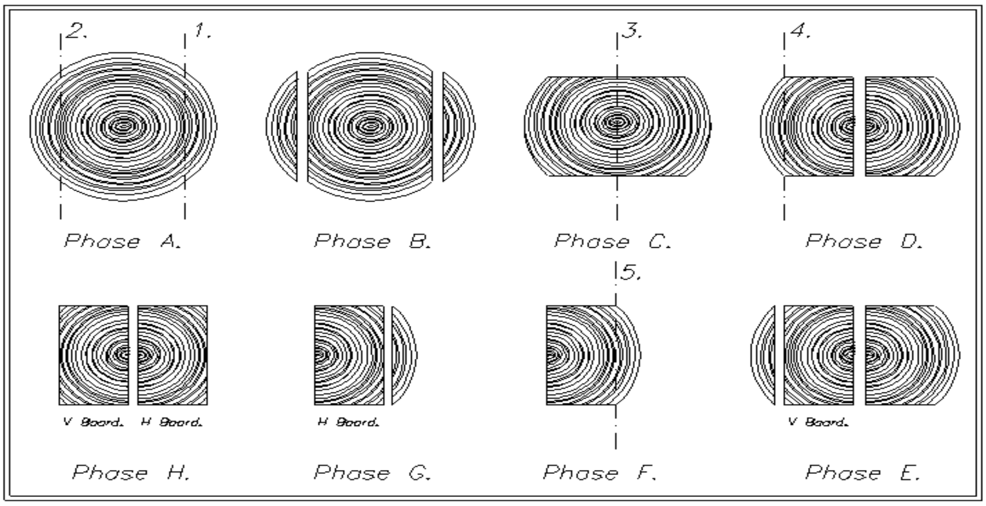

Figure 3.7: *Sawing pattern.*

Sawing step by step was done as follows. See Figure 3.7.

A first longitudinal cut *(Phase A. (1.))* was sawn after placing the log in a way that circular saw was exactly 45 mm from pith situation and on the base of the log. The log was arranged on the sawing bench having the forest crook facing upward. A second longitudinal cut was sawn parallel to the first, 45 mm on the opposite side of the pith. *(Phase A. (2.))*. Then pieces of bark were remove *(Phase B.)* and one cut along the pith done. *(Phase C.)*. Pith position on the base of the log acted as a reference.

It is important to mention that while *Phase C.* was carried out, the piece of wood placed on the right side of every log was not carefully handled and fell down each time the cut along the pith was sawn. When this "right piece of wood" fell down, stresses inside wood were probably released.

A cut on the piece of wood classified as V *(left)* was later done 50 mm far from pith position *(Phase D.)* and finally V board obtained. *(Phase E.)*. Following the same pattern, a longitudinal cut 50 mm far from pith position and parallel to the cut along the pith *(Phase F.)* was then done on the piece of wood classified as H *(Right)* and remaining bark removed. *(Phase G.)*.

3.2.3.2. Pattern to Classify Tested Boards.

All boards were classified following a model previously established.

First, at the forest, stand, plot and number of tree were marked on every board. See Figure 3.8. Later, at the sawmill, after *Phase D* of sawing process, pieces of wood were marked with stand name, plot name, number of tree and also left (V) or right (H) side of the tree.

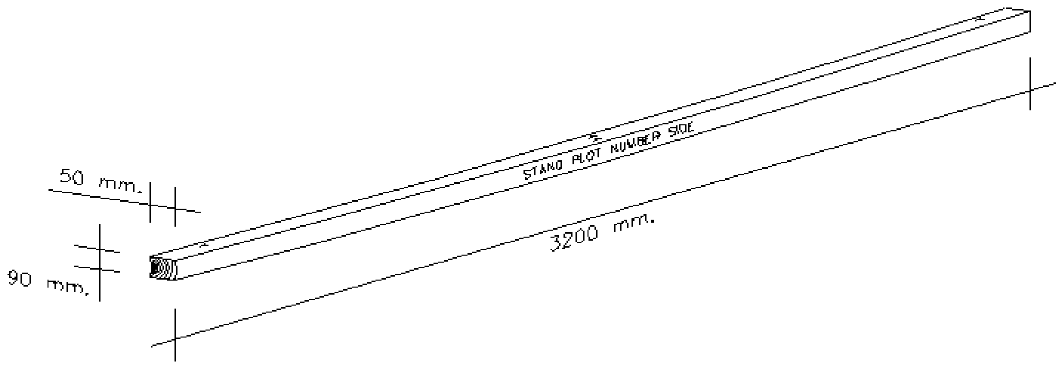

Figure 3.8: *Final dimensions and classification of a tested board.*

3.3. Testing Procedure.

3.3.1. Recorded Data at the Forest.

At the forest, every tree was classified by using a card, stapled on the bark, where stand, plot, and tree number were registered.

The following variables were recorded for each log: Klang (1999).

- Diameter at breast (dbh).
- Tree class (dominant, codominant, intermediate or suppressed).
- Diameter and status (living, dying or dead) of the thickest branch below 2 m height.
- Number of branches in the tree closest to breast height (diameter larger than 3 mm), and the average intercept between the three whorls.
- Stem crookedness.
- Stem lean (weak or strong lean depending on the deviation from the base of the tree).
- Occurrence of spike knots, sharp bends, breaks and cracks.

Even though not all these variables have been used during this investigation, stem crookedness and tree class have been data of great interest.

On the other hand, the trees in the plots were classified in four categories: straight (1), slightly crooked (2), crooked with impact on saw-yield (3), and severely crooked (4) (not valid for sawing).

Before cutting down the trees, forest crook and north direction were marked on all selected trees. The part of a tree having an obvious crook, that is to say crook visible with the naked eye, was marked with a vertical line about 30-50 cm long, from the but of the tree upwards and by using a blue spray. North direction was marked likewise but using red spray.

The felling process was done with chain saws and cutting every trunk 3.20 m long from the base of the tree. Moreover, two slices 5 cm thick were cut from the base and from the top of every log. Those slices will be used on future investigations.

One hundred and fifty-six trees were cut down from SA and TA stands in all, and later transported to a sawmill placed in Gårdsby. See Figure 3.4. See also Appendix I.

3.3.2. Test Procedure at the Sawmill.

At the sawmill tests were carried out following an specific pattern.

Just before sawing, forest crook (blue spray) and north direction (red spray) were marked again at the base of every log and recorded on a graph as shown on Figure 3.9. See Appendix VI.

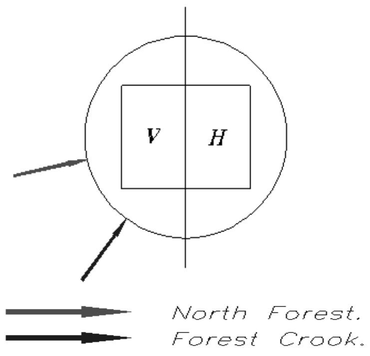

Figure 3.9: *Pattern used for marking forest crook and north forest on the base of the log. Example of Marked Tree.*

One hundred and fifty-six trees cut down from the stands, and one hundred and sixty-eight boards were measured at the sawmill.

After marking every board and obtain boards V *(left)* and H *(right)*), some notations as inner bark existence *(IB)*; fungus; frost crack; presence of some remaining bark *(VK)*; irregular length; and damages were registered. On the other hand, the boards considered no valid were eliminated from the investigation. Eleven boards were rejected. Factors such as to much fungus, to much crook, a lot of bark, or length shorter than 3 m, were taken into consideration for the elimination.

Bow deformation was measured as well. In order to start the first phase of sawing *(Phase A)*, the log was placed so that the circular saw made a first longitudinal cut parallel to pith and 45 mm far from its position on the base of the log. However, it should be taken into consideration that on boards containing obvious crook the lineament between the pith and the lengthways cut was not exact in some regions of the board. Bow deformation may therefore not showing a true growth stress situation for the whole length of the board.

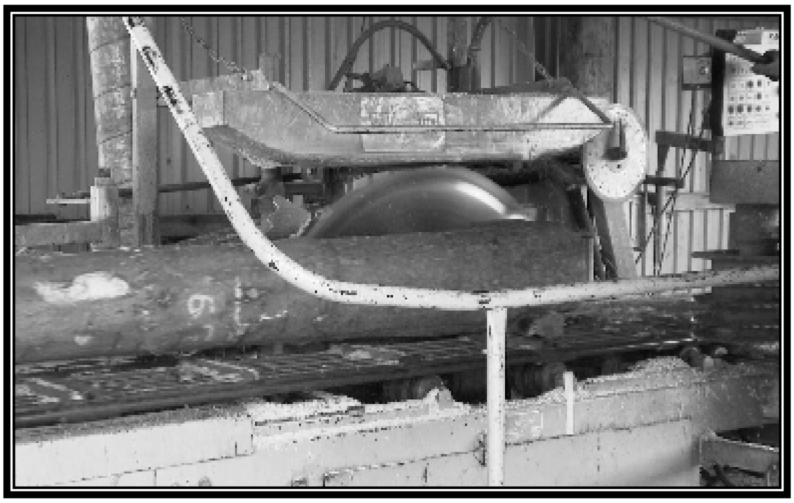

Figure 3.10: *First phase of sawing process. Longitudinal cut along the pith.*

Two marks that coincided with the pith position were done at both extremes of every board, 20 mm far from the edges, and a third mark done in the middle of the boards. With the digital gauge slide, the difference between the *middle mark* done previously and the new middle of the boards was measured and, by this, bow deformations on boards V and H obtained. The measurements were done in order to know the internal stresses of wood.

Moreover, the direction of the deformation was recorded distinguishing between deformation toward the pith (*i*: in) or outward the pith (*o*: out).

Figure 3.11: *Classification and marking of boards to measure bow deformation.*

Figure 3.12: *Measuring bow deformation.*

Moisture content was also measured on some chosen boards by using a resistance meter. Moisture content was measured in the middle and at both board ends.

Lumber was piled for storaging at the end of all process. Piles incorporate appropriate foundations and stickers for separating different rows of boards in order to avoid development of fungi.

Figure 3.13: *Piling of lumber at the sawmill.*

At the end of all the process, which took three days, boards were transported to a kiln were the lumber was dried.

All measurements and remarks recorded at the sawmill are reported in Appendix II.

3.3.3. Measurements after Drying Process.

After drying the lumber was transported to the laboratory of the Division of Structural Engineering where series of measurements were done in order to document the deformations present after drying process.

After drying the lumber in a kiln, all boards were again placed on piles and some measurements done.

The measuring machine designed during the first part of the experimental work was used for reading crook and bow deformations and, crook deformation was done first. The board was placed on the table and slid over the metallic guides set on the table. When the ends of the board were tight against the frontal panel of the table, instruments for measuring were correctly placed and measurement accomplished.

Bow deformation was there after measured. The method followed was the same but, for this case, boards were placed in a different situation according to Figure 2.4.

Twist was measure by using the digital gauge slide and holding one of the extremes of the board with a carpenter's clamp while the measuring was done on the other extreme.

Seven measures (three measures of crook, three measures of bow, and one measure of twist) were obtained from the boards that had previously been measured at the sawmill after sawing process. Moreover, three measures (one measure of crook, one of bow and twist deformation), were carried out on the boards that were just sawn but not measured at the sawmill. See Appendix III and Appendix V.

Measures were done in the middle and about 970mm from each end of the boards. When just one measure was necessary and, since the middle board is the region where crook and bow deformations are likely to be the largest, the transducer with a dial indicator placed in the middle of the table was the one used. Orientation of the bow deformation was also recorded making a distinction between deformation toward and outward the pith.

In order to have the accuracy expected, the equipment was calibrated every 20th boards. See Appendix IV.

Moisture content was also measured on the first *(f)* and the last *(e)* board of each calibrated group. Moisture content was measured in the middle and at one of the extremes of the board selected. Furthermore, two different readings were done; moisture content was done on the surface and deeper on the board for reporting that a moisture content gradient still existed.

4. TEST RESULTS

4.1. Forest Crook.

Previous investigations refer to the importance of the orientation of the tree when determining the location and the degree of compression wood, e.i. when determining the degree of growth stresses. It is known that the main factors that promote the growth towards certain directions are the prevailing wind and light conditions. (Alhasani, 1999b).

On tested trees coming from the same territory, those factors should have approximately the same effect, therefore cause a similar type of growth stresses.

However it is not easy to establish the amount of deviation that can be observed in a specific stand due to variations on these factors, according to the results of this research, 61 trees on 138 tested trees show some degree of forest crook deformation. See Appendix I.

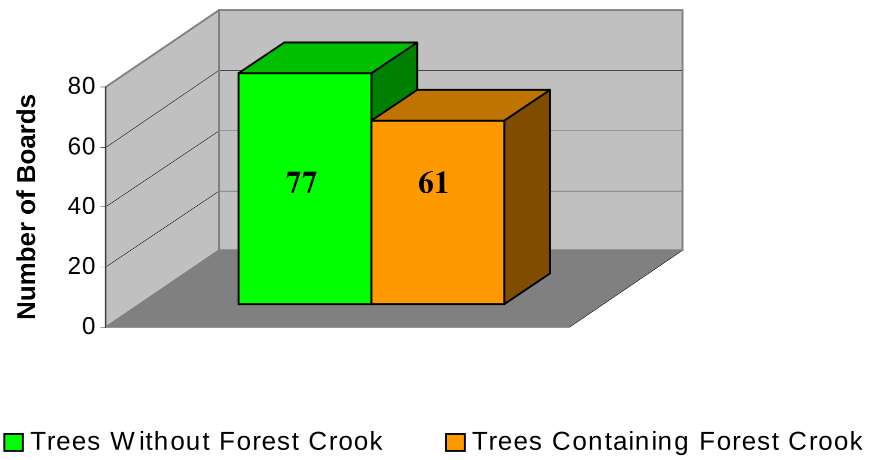

Figure 4.1: *Number of tested trees and number of trees showing Forest Crook deformation.*

4.1.1. Location of Forest Crook.

Figure 4.2. shows the pattern used for establishing the location of Forest Crook with respect to the location of North orientation in the forest. See Appendix VI.

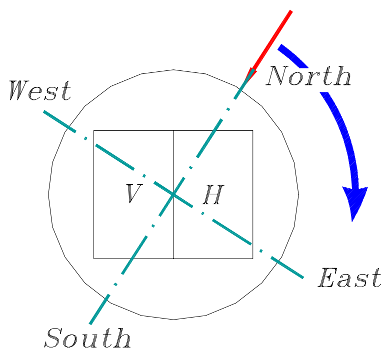

Figure 4.2: *Situation of the Forest Crook taking as a reference the North Orientation in the forest.*

Northern orientation has been considered to be always placed 0 degrees on the circumference. From this, the position of the Forest Crook is located with respect to North.

Thirty-four samples, as shown in Figure 4.3., exhibit a main formation of Forest Crook, thus compression wood, in the N-E to S-W orientation, however twenty-seven samples show different tendencies.

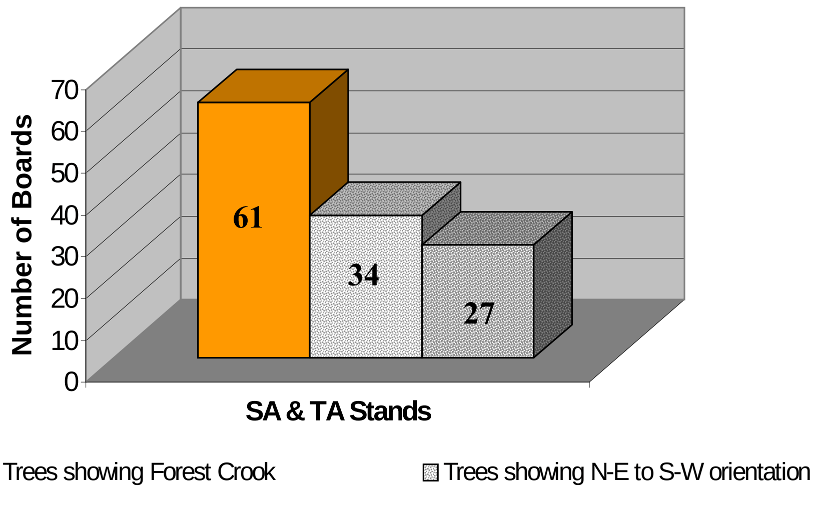

Figure 4.3: *Orientation of growth stresses. Amount of trees showing Forest Crook, number of those that show N-E to S-W orientation and number of trees showing N-W to S-E orientation.*

The trees showing N-E to S-W orientation can not be regarded as a whole group since some of the trees (44%) exhibit compression wood located in the N-E, while others (11%) show compression wood in the S-W. See Figure 4.4.

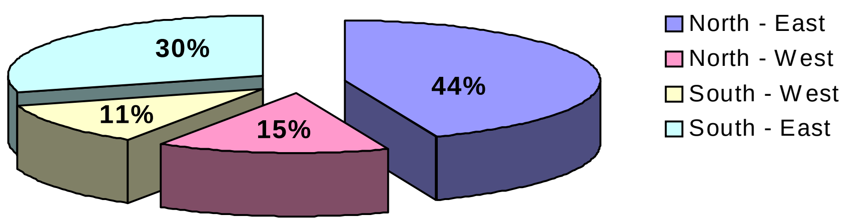

Figure 4.4: *Exact location of compression wood referred to the position of the North Forest.*

From the obtained results, small correlation can be found between the location of compression wood in a tree and the orientation. It is obvious that the surrounding of the tree determines the degree of forest crook as well as wind and light.

4.2. Growth Stresses.

It is well known that the relief of growth stresses when sawing, leads to the deformation of the sawn timber. Depending on sawing pattern species tree sawn timber exhibited deformations such as bow, crook, twist and cup (Alhasani 1999) In boards with large dimensions some growth stresses may remain in timber after sawing. The study of growth stresses throughout this research is based on the measurement of bow after sawing. Measurements were accomplished on the production line just after the sawing on boards still in green condition. Their dimensions change is therefore a consequence of the stresses developed within the standing tree.

4.2.1. Correlation between Forest Crook and Bow after Sawing.

The purpose for the correlation between forest crook and bow after sawing is to clarify if is possible to determine, from the measurement of forest crook, de degree of bow on still green boards.

The statistic test used for calculating the correlation is the so called χ^2 - Test. This test calculates the total difference that exits between the found results (in this section, deformations after sawing) and the results that theoretically should exit between two variables if they were not associated.

The degree of crook deformation of each tree was recorded on standing trees and these trees were classified in three categories: *0 Forest Crook* which corresponds to the trees which can be considered as straight, *1 Forest Crook* corresponding to the trees which contain certain crook deformation and finally *2 Forest Crook* which corresponds to trees containing an evident severe crook deformation.

Since just three values of Forest Crook were taken into consideration, it is not possible to establish a linear correlation between Forest Crook and all bow deformation values after sawing. Therefore, values of those deformations were also classified in three "Assigned Categories".

Forest Crook was considered to be the "theoretical variable" that had to be compared with "real values" i.e. deformations after sawing in order to clarify if, from the crook at the forest, it is possible to predict the degree of deformation after sawing.

Results of bow measurements after sawing are also classified in three categories *(0 Assigned Category, 1 Assigned Category, 2 Assigned Category)* which correspond to the boards containing lower, a medium, and higher deformation respectively.

The sort criterion is as following: On the whole graph of the stands SA & TA (See Figure 4.5.) the first point of diversion is determined. This point corresponds to an obvious change of slope among the overall deformation's data arranged from lower to higher deformation. The boards with larger deformation than the "division point" board, are the *2 Assigned Category*. The remaining boards were equally divided into *0 Assigned Category* and *1 Assigned Category*. *0 Assigned Category* contains boards with smallest deformation. Hence, 1 Assigned Category contains boards with deformations between *0* and *2 Assigned Category*. This type classification of boards was established for the whole group of boards, SA-Boards and TA-Boards as well.

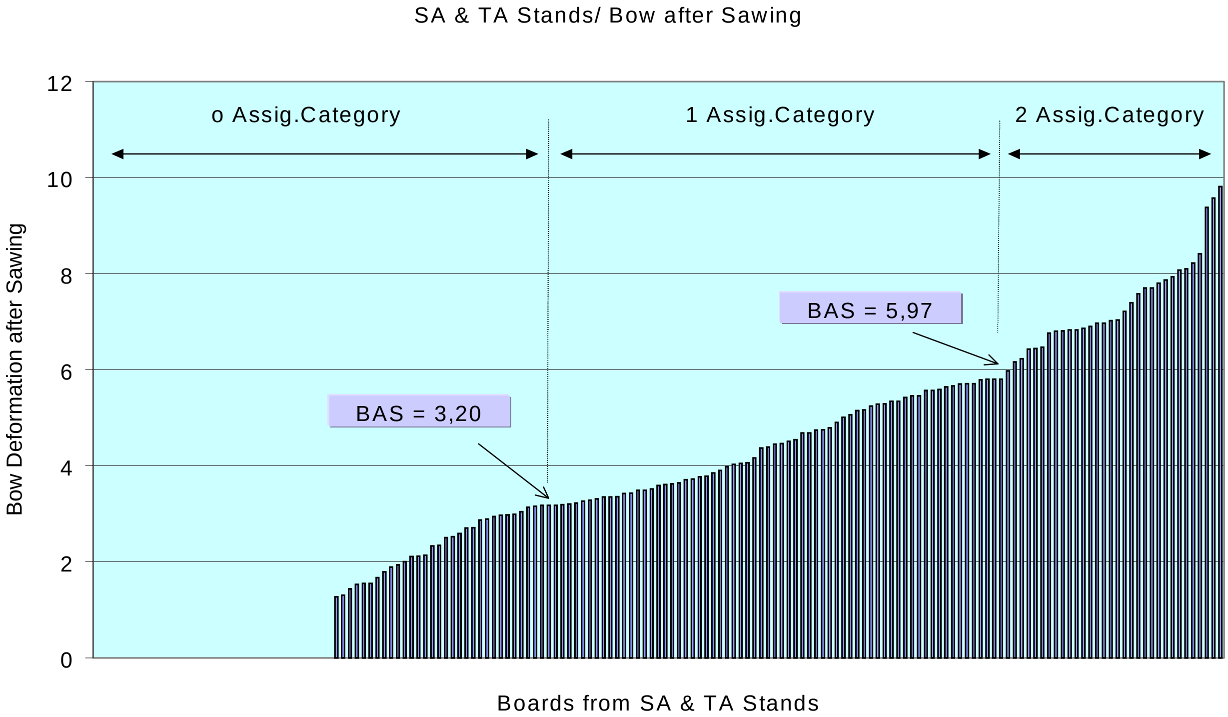

Figure 4.5: *Bow after Sawing vs. Forest Crook. Sort Criterion.*

Finally, the obtained data has been compared with the "hypothetical" data obtained at the forest (*Forest Crook*). The correlation obtained for each group and each kind of deformation is recorded in Table 4.1.

No distinction among the different plots was considered while classifying Forest Crook and measurements of bow, crook and twist deformations after drying, thereby, it is necessary to make a distinction between the different kind of plots used during the investigation.

There is, of course, other ways to determine the intervals for every assigned category. This sort criterion is just the one has been proposed to carry out this investigation.

Table 4.2: *χ^2 – Test. Correlation and number of boards contained in each Hypothetical and Assigned (Real) Category according to bow deformation after sawing.*

BOW AFTER SAWING (BAS)																	
SA & TA Stands						SA Stand						TA Stand					
Category						Category						Category					
Theoretical			Real			Theoretical			Real			Theoretical			Real		
0	1	2	0	1	2	0	1	2	0	1	2	0	1	2	0	1	2
72	18	15	60	37	68	46	6	47	55	34	10	69	42	32	65	52	22
$\chi^2 = 22,70888$						$\chi^2 = 161,555198$						$\chi^2 = 33,824175$					
Significance Level 95%; $\chi_t^2 = 9,488$																	
There's no Correlation						There's no Correlation						There's no Correlation					

Table 4.2. shows that there is no correlation between Forest Crook and bow after sawing. T

4.2.2. Orientation of the Deformation on Tested Boards.

Table 4.2., shows that difference between towards pith orientation (*i*) and outwards pith orientation (*o*) is significant. From the data it can be observed that the average of towards pith orientation ($\bar{i}$= 4,73688 mm.) is much higher than the average of outward pith orientation ($\bar{o}$= 3,3936364 mm.). In addition, by applying Z-Test, it can be stated that the difference between such pair of data is not a consequence of the chance, not even for 5% of the cases.

Table 4.2: *SA & TA area. Orientation of the deformation. Correlation between towards pith orientation and outwards pith orientation.*

			Std.Dev	*Average [mm]*	*n*
BAS	SA & TA Stands	***i* Orientation**	2,02466172	4,73688	125
		***o* Orientation**	1,09243076	3,3936364	11
		|Z|	3,57360161		
		95% (1,645)	Orientation is significantly different.		

In conclusion, towards pith orientation seams to be noticeable higher than outwards pith orientation and, furthermore, since 125 of the tested samples (92%) undergo towards pith orientation whereas just 11 boards experiment outwards pith orientation, the former appears to be more frequent than outwards pith orientation.

4.2.3. H Boards vs. V Boards. Study of Bow Deformation after Sawing.

In this section, the Z-Test has been applied in order to study whether the difference between the averages of bow deformation after sawing is significantly different or not.

Boards from the right side of the log (h Boards) and boards from the left side of the log (v Boards) are considered as different samples and as expected, it exits a difference between the average of the deformation. See Appendix II.iv. and Table 4.3.

Table 4.3: *Z-Test. Bow after Sawing. Comparison between values from H Boards and V Boards.*

			h Side	**v Side**
BOW AFTER SAWING (BAS)	SA & TA Stands	*Std.Dev*	2,39175626	2,7036035
		Average [mm]	3,3190698	4,1271765
		N	86	85
		|*Z*|	2,069273176	
		95% (1,645)	*Sides are significantly different.*	

The Z-Test results show that the difference between the averages of each sample of boards should be considered as a significant. It is found a noticeable difference between averages and as a result it can not be explained as a consequence of the chance.

As discussed in Section 3.2.4.1., boards are expected to show different deformation depending on their origin. See Figure 4.6. During *Phase C*. the piece of wood placed on the right side (h Side) of every log was not carefully handled. As a result, different values of deformation can be observed in both categories (h Side, v Side) of boards. Boards from left side show an average deformation ($v\overline{BAS}$ = 4,1271765 mm.) higher than boards coming from right side ($h\overline{BAS}$ = 3,3190698 mm.) and, besides, standard deviation appears to be somehow bigger on V boards (*Std. Dev* = 2,7036) that on H boards (*Std. Dev* = 2,3917). Hence, growth stresses were, indeed, released as a result of the "wrong", but unavoidable, handling of boards at the sawmill.

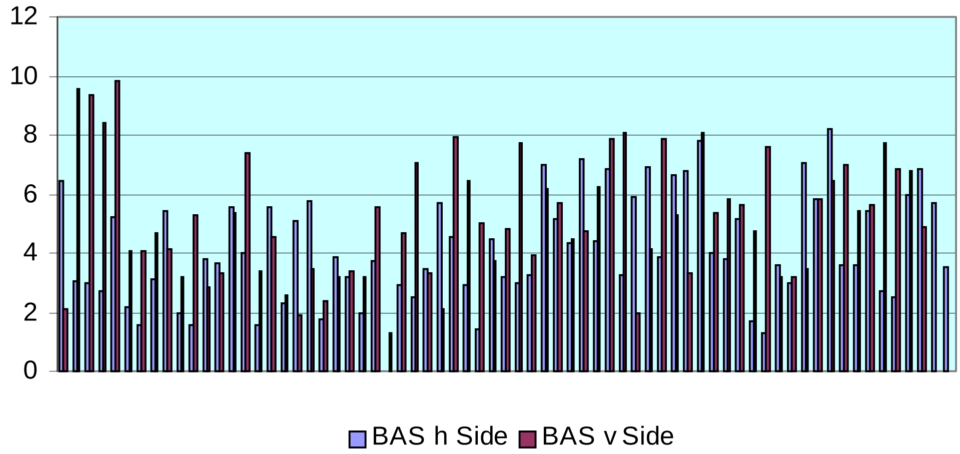

Figure 4.6: *Bow after Sawing. Comparison between values from H Boards and V Boards taking into account orientation of the deformation.*

4.2.4. Influence of Silvicultural Practices on Bow after Sawing.

Previous studies have already demonstrate that the competition between neighbouring trees in combination with other environmental factors create the incentive for the trees to reorient. (Alhasani, 1999b). As a result it could be said that foresters are able to influence the magnitude of growth stresses and the defects that spring from these by providing the trees with the best growth opportunities, thus, for example, supporting some determinate trees eliminating others at the same time. However, it is difficult to recognise the right method.

From the actual knowledge, no specific method may be considered to be the suitable. Growth stresses are different depending on the tree's characteristics, and those cause different defects depending on the size of the tree.

In forest containing even sized trees, these compete with each other to gain the best light. Such competition results in changes that create new situations with new stimulus for reorientation. On the contrary, if the forest contains tress having different sizes, the smaller trees live under the protection of those much taller and, as a consequence, the environment is stable and no stimuli for the trees to reorient themselves are created. (Alhasani, 1999b).

Kubler (1987) recommended that in order to control the growth stresses, it is necessary to keep constant those factors that influence the position of the stem, and avoid the incentives for reorientation, try to obtain vertical stems but, on the order hand, let the leaning steams to lean. Other works concerned with the silvicultural practices found that growth stresses decreased with increasing the dominance of the tree in eucalyptus in Australia. However, another study reported that dominant trees showed high growth trees, which might be because these trees were subjected to strong winds, stimulating the development of high stresses. (Atanakovic, 1976).

The Simple Analysis of Variance (F-test) is used for determining the influence of the plot where the board comes from with respect to its deformation.

The F-test calculates the variation existing among some groups (plots) with respect to a determined variable (bow after sawing).

Table 4.4: *F-Test. Application on SA Stand, TA Stand and SA & TA Area. Correlation between different plots when studying Bow Deformation after Sawing Process.*

BOW AFTER SAWING							
	SA Stand	**FiN**	**FUL**	**HÖG**	**LÅG**	**SLU**	**SPEC**
Std. Dev.	2,5089502	3,6038640	1,82538013	1,6690347	2,2839549	2,32742287	2,48397564
Average [mm]	3,0551613	3,4044444	3,3413043	2,9963636	3,59	2,2416667	2,515
Maximum [mm]	9,81	9,81	7,39	6,81	5,57	7,03	7,93
Minimum [mm]	0	0	0	0	0	0	0
N	99	18	23	22	4	12	20
Fisher = 0,58503501							
	TA Stand	**FiN**	**FUL**	**HÖG**	**LÅG**	**SLU**	**SPEC**
Std. Dev.	2,35414974	2,1784990	3,26719585	2,27045582	0,99059326		2,22353524
Average [mm]	4,7311111	5,1054167	5,6075	3,8740909	6,565		4,6772222
Maximum [mm]	8,22	8,1	7,87	8,07	8,22		7,7
Minimum [mm]	0	0	0	0	5,8		0
N	72	24	4	22	4		18
Fisher = 1,66602431							
	SA & TA	**FiN**	**FUL**	**HÖG**	**LÅG**	**SLU**	**SPEC**
Std. Dev.	2,58014724	2,9977823	2,58841311	2,05746319	2,30467324	2,32742287	2,59902854
Average [mm]	3,7864848	4,3764286	3,677037	3,4352273	5,0775	2,2416667	3,5392105
Maximum [mm]	9,81	9,81	7,87	8,07	8,22	7,03	7,93
Minimum [mm]	0	0	0	0	0	0	0
N	171	42	27	44	8	12	38
Fisher = 1,96773717							

Table 4.4. summarises the study of the differences among plots respecting to the bow after sawing. From this, it can be stated that it does not appear an appreciable difference among each kind of plot. Bow after sawing is almost equal independently the plot where the board comes from.

4.3. Study of the Deformations after Drying Process.

After completing measurements of the growth deformations as detailed in Section 3.3.2., shrinkage was determined for the tested boards. See Section 3.3.3. The aim is to determinate the magnitude at which the growth stresses influence the form stability of the final product after considering timber seasoning.

Through this chapter, the study of deformations after drying process is based on measuring the variation of length between green and dried boards.

4.3.1. Influence of Silvicultural Practices.

From the calculations obtained on this thesis (Appendix V.i.) it can be observed that the averages of different samples are different, therefore now the main question is to solve whether those are significant or, on the contrary, their differences should be considered as a result of the chance. The distribution called Fisher's F gives a simple answer to confirm or deny the correlation.

A review of Table 4.5., Table 4.6. and Table 4.7. shows that the correlation among different plots when studying deformations after drying process is not significant. It can, therefore, be stated that, with respect to bow, crook or twist deformation after drying process, different thinning methods has no influence.

As discussed in Section 3.2.3., when thinning method was applied in FIN, FUL, LÅG and HÖG plots, trees were removed by taking into consideration either quality or size of tree. Since every thinning method had a common feature: all trees left in its corresponding plot exhibited equal characteristics (determined with respect to visible classification), thus no trees can be considered as dominant and therefore have stimuli to reorient themselves. This could be the reason that no difference has been found between the different plots studied.

Table 4.5: *F-Test. Application on SA Stand, TA Stand and SA & TA Area. Correlation between different plots when Studying Bow Deformation After Drying Process.*

BOW							
	SA Stand	FiN	FUL	HÖG	LÅG	SLU	SPEC
Std. Dev.	3,4684812	4,1544944	3,5829307	3,3434816	2,3100505	2,4697793	2,7304538
Average [mm]	4,5635374	5,8884354	4,781	4,2638235	4,4416667	3,2114286	4,0414706
Maximum [mm]	19,35	18,095	19,35	14,745	9,035	8,295	9,26
Minimum [mm]	0,11	0,11	0,115	0,185	0,905	0,145	0,17
n	147	31	35	34	9	21	17
Fisher = 1,7251508							

	TA Stand	FiN	FUL	HÖG	LÅG	SLU	SPEC
Std. Dev.	2,6507349	3,0140342	2,0922485	2,5301581	1,769463		2,9504206
Average [mm]	2,4996897	3,2023529	3,3628947	2,7328049	3,1363889		2,7281875
Maximum [mm]	16,48	16,48	8,055	11,105	6,37		9,1
Minimum [mm]	0,03	0,03	0,525	0,07	0,35		0,05
n	145	51	19	41	18		16
Fisher = 0,3084321							
	SA & TA	**FiN**	**FUL**	**HÖG**	**LÅG**	**SLU**	**SPEC**
Std. Dev.	3,1832904	3,7237638	3,2277343	3,0246074	2,0602723	2,4697793	2,909967
Average [mm]	3,8020753	4,2162805	4,282037	3,4268667	3,5714815	3,2114286	3,4047273
Maximum [mm]	19,35	18,095	19,35	14,745	9,035	8,295	9,26
Minimum [mm]	0,03	0,03	0,115	0,07	0,35	0,145	0,05
n	292	82	54	75	27	21	33
Fisher = 1,0038332							

Table 4.6: *F-Test. Application on SA Stand, TA Stand and SA & TA Area. Correlation between different plots when Studying Crook Deformation After Drying Process.*

CROOK							
	SA Stand	**FiN**	**FUL**	**HÖG**	**LÅG**	**SLU**	**SPEC**
Std. Dev.	2,38728	2,61183651	2,25976	2,65643	2,3320081	1,69084	1,53426
Average [mm]	3,17849	3,2879032	3,31132	4,03882	2,2472222	2,64333	2,14676
Maximum [mm]	10,735	10,44	9,405	10,735	8,095	6,78	5,175
Minimum [mm]	0,015	0,05	0,015	0,085	0,065	0,375	0,03
N	146	31	34	34	9	21	17
Fisher = 2,1000369							
	TA Stand	**FiN**	**FUL**	**HÖG**	**LÅG**	**SLU**	**SPEC**
Std. Dev.	2,02891	1,97660776	2,63792	1,24801	1,4107782		2,91084
Average [mm]	2,51777	2,4257692	2,93868	2,09415	2,5408333		3,28111
Maximum [mm]	12,555	8,195	12,555	5,725	4,61		10,74
Minimum [mm]	0,06	0,06	0,175	0,09	0,17		0,3
N	148	52	19	41	18		18
Fisher = 1,3179913							
	SA & TA	**FiN**	**FUL**	**HÖG**	**LÅG**	**SLU**	**SPEC**
Std. Dev.	2,20637	2,27365984	2,40882	2,2333	1,7772942	1,69084	2,41295
Average [mm]	2,84588	2,7477711	3,17774	2,97573	2,442963	2,64333	2,73014
Maximum [mm]	12,555	10,44	12,555	10,735	8,095	6,78	10,74
Minimum [mm]	0,015	0,05	0,015	0,085	0,065	0,375	0,03
N	294	83	53	75	27	21	35
Fisher = 0,5371797							

Table 4.7: *F-Test. Application on SA Stand, TA Stand and SA & TA Area. Correlation between different plots when Studying Twist Deformation After Drying Process.*

TWIST							
	SA Stand	FiN	FUL	HÖG	LÅG	SLU	SPEC
Std. Dev.	8,9751235	7,2758985	6,8304865	14,700228	4,2880785	4,5943424	5,0729767
Average [mm]	11,842517	12,756774	12,042857	12,164118	8,3722222	10,667143	12,408824
Maximum [mm]	93,3	29,86	33,33	93,3	16,12	22,65	23,33
Minimum [mm]	0	0	1,11	2,49	2,57	4,88	4,35
N	147	31	35	34	9	21	17
Fisher = 0,41978406							
	TA Stand	FiN	FUL	HÖG	LÅG	SLU	SPEC
Std. Dev.	6,0499386	3,8628441	4,0480626	8,3445642	5,1130617		6,3016778
Average [mm]	9,7216779	8,6117308	8,84	11,590952	8,69		10,528889
Maximum [mm]	38,67	17,8	18,59	38,67	20,84		26,32
Minimum [mm]	0	3,84	0	0	0		5,15
N	149	52	19	42	18		18
Fisher = 1,77656303							
	SA & TA	FiN	FUL	HÖG	LÅG	SLU	SPEC
Std. Dev.	7,7170755	8,0881244	7,8869814	8,1512627	5,768383	4,5943424	6,0127075
Average [mm]	10,774932	10,15988	10,915926	11,847368	8,5840741	10,667143	11,442
Maximum [mm]	93,3	29,86	33,33	93,3	20,84	22,65	26,32
Minimum [mm]	0	0	0	0	0	4,88	4,35
N	296	83	54	76	27	21	35
Fisher = 0,88622852							

4.3.2. Correlation between Forest Crook and Deformations after Drying Process.

The purpose for studying the correlation between crook, bow and twist vs. forest crook is, of course, to clarify the possibility to determine, from the measurement of the forest crook, the degree of crook, bow and twist after drying process.

From the classification of the degree of crook on standing trees, i.e., *0 Forest Crook, 1 Forest Crook and 2 Forest Crook,* results of bow after sawing measurements were classified in three assigned categories*, 0 Assigned Category, 1 Assigned Category* and *2 Assigned Category*, corresponding to the boards containing lower, a medium, and larger deformation respectively.

The statistic test used for calculating the correlation is the so called χ^2 - Test. See Section 4.2.1.

The degree of crook deformation of each tree was recorded on standing trees and these trees were classified in three categories: *0 Forest Crook* which corresponds to the trees which can be considered as straight, *1 Forest Crook* corresponding to the trees which contain certain crook deformation and finally *2 Forest Crook* which corresponds to trees containing an evident severe crook deformation.

As discussed in Section 4.2.1., since just three values of Forest Crook were taken into consideration, it is not possible to establish a linear correlation between Forest Crook and all deformation values i.e. twist, bow, and crook after sawing and after drying. Therefore, values of those deformations were also classified in three “Assigned Categories”.

Forest Crook was considered to be the “theoretical variable” that had to be compared with “real values” i.e. deformations after sawing and drying in order to clarify if, from the crook at the forest, it is possible to predict the degree of deformation after sawing and drying.

Results of bow, crook and twist measurements after drying are also classified in three categories *(0 Assigned Category, 1 Assigned Category, 2 Assigned Category)* which correspond to the boards containing lower, a medium, and higher deformation respectively. The sort criterion is as following: On the whole graph of the stands SA & TA (See Figures 4.7., 4.8. and 4.9.) the first point of diversion is determine.

This point corresponds to an obvious change of slope among the overall deformation’s data arranged from lower to higher deformation. The boards with larger deformation than the “division point” board, are the *2 Assigned Category*. The remaining boards were equally divided into *0 Assigned Category* and *1 Assigned Category*. *0 Assigned Category* contains boards with smallest deformation. Hence, 1 Assigned Category contains boards with deformations between *0* and *2 Assigned Category*.

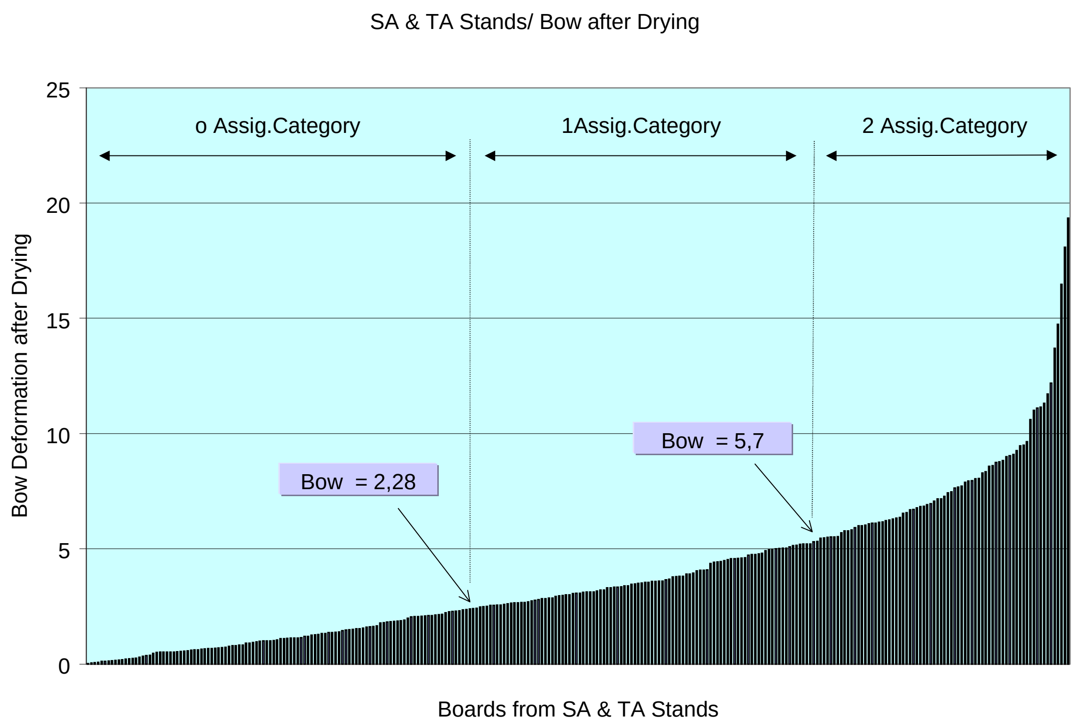

Figure4.7: *Bow after Drying vs. Forest Crook. Sort Criterion.*

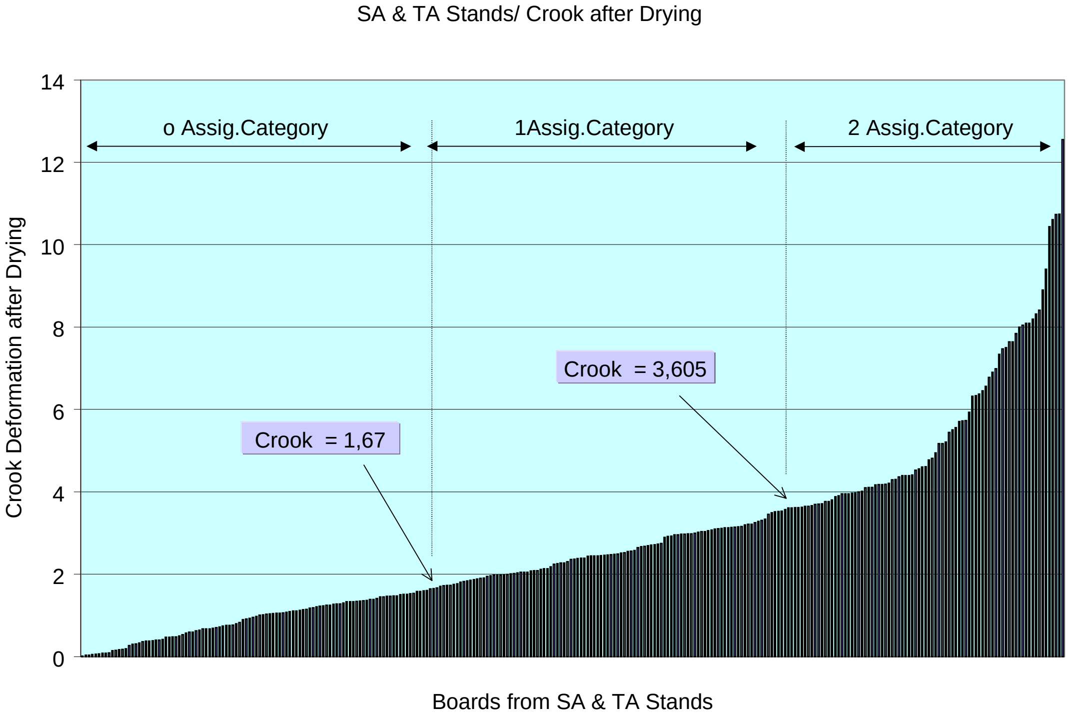

Figure 4.8: *Crook Deformation after Drying. Sort Criterion.*

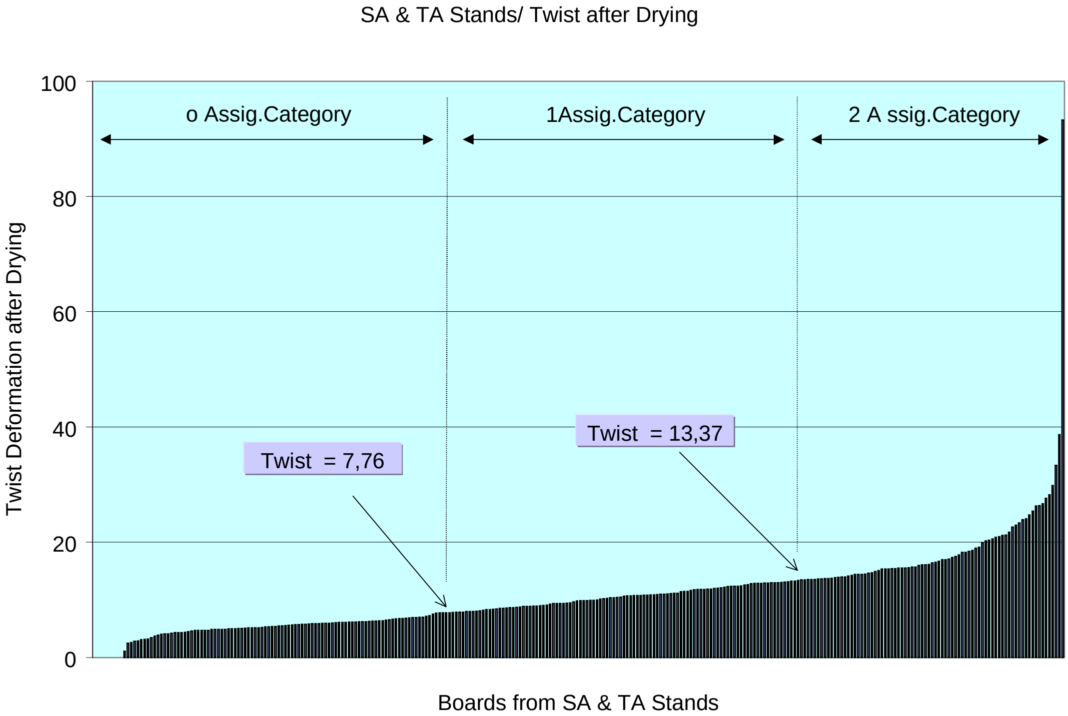

Figure 4.9: *Twist Deformation after Drying. Sort Criterion.*

This type classification of boards was established for the whole group of boards, SA-Boards and TA-Boards as well.

Finally, the obtained data has been compared with the "hypothetical" data obtained at the forest (*Forest Crook*). The correlation obtained for each group and each kind of deformation is recorded in Tables 4.8, 4.9, and 4.10.

4.3.2.1. Correlation between forest crook and bow deformation after drying process.

Table 4.8 and Figure 4.10. show the existence of a correlation between Forest Crook and bow after drying. The correlation has been studied to a 95% significance level, thus the expected results are not a consequence of the chance not even for 5% of the situations.

Table 4.8: χ^2 -Test. *Correlation and number of boards contained in each Hypothetical and Assigned (Real) Category according to bow deformation after drying process.*

BOW																	
SA & TA Stands						**SA Stand**						**TA Stand**					
Category						*Category*						*Category*					
Theoretical			*Real*			*Theoretical*			*Real*			*Theoretical*			*Real*		
0	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***
126	87	73	110	109	67	58	45	44	45	57	45	69	42	32	65	52	22
$\chi^2 = 8{,}0881151$						$\chi^2 = 6{,}1365204$						$\chi^2 = 5{,}7378364$					
Significance Level 95%; $\chi_t^2 = 9{,}488$																	
There's Correlation						*There's Correlation*						*There's Correlation*					

With regard to the study of the SA & TA areas separately studied, an evident correlation between Forest Crook an bow deformation after drying process can be established at SA Stand ($\chi^2 = 6{,}1365204$) and, in the same way, a correlation could be established at TA Stand ($\chi^2 = 5{,}7378364$).

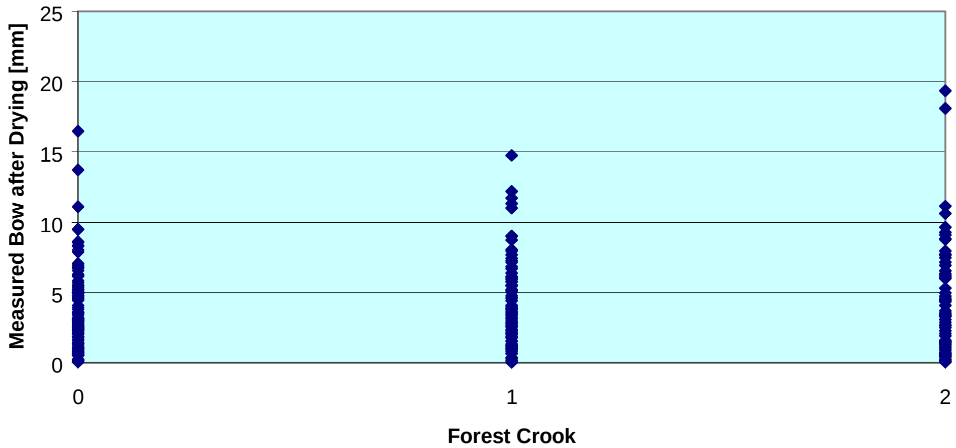

Figure 4.10: *SA & TA Stands. Forest Crook versus Bow after Drying Deformation.*

4.3.2.2. Correlation between forest crook and crook deformation after drying process.

In relation to the correlation between Forest Crook and crook deformation after drying process, Table 4.9. shows correlation between those deformations.

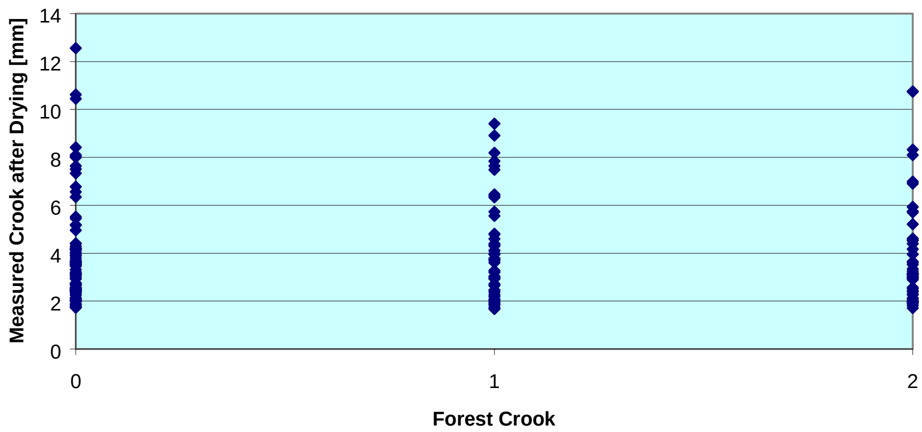

Figure 4.11: *SA & TA Stands. Forest Crook versus Crook after Drying Deformation*

When studying the results obtained from the stands SA & TA as a whole area (See also Figure 4.11.), a quite good correlation ($\chi^2 = 8{,}6224396$) may be established, therefore it can be stated that crook deformation increases with increasing crook deformation at the forest. SA Stand shows as well a high correlation ($\chi^2 = 4{,}9865665$) but, on the contrary, no correlation can be stated for boards from TA stand.

Table 4.9: χ^2 - Test. *Correlation and number of boards contained in each Hypothetical and Assigned (Real) Category according to crook deformation after drying process.*

CROOK																	
SA & TA Stands						SA Stand						TA Stand					
Category						Category						Category					
Theoretical			Real			Theoretical			Real			Theoretical			Real		
0	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***
130	87	77	106	105	83	61	46	45	51	46	55	69	41	32	55	61	26
$\chi^2 = 8{,}6224396$						$\chi^2 = 4{,}9865665$						$\chi^2 = 13{,}721677$					
Significance Level 95%; $\chi_t^2 = 9{,}488$																	
There's Correlation						*There's Correlation*						*There's no Correlation*					

4.3.2.3. Correlation between forest crook and twist deformation after drying process.

Table 4.10. shows that there is, indeed, an obvious high correlation between Forest Crook and twist deformation after drying.

Table 4.10: χ^2 - Test. *Correlation and number of boards contained in each Hypothetical and Assigned (Real) Category according to twist deformation after drying process.*

TWIST																	
SA & TA Stands						SA Stand						TA Stand					
Category						*Category*						*Category*					
Theoretical			*Real*			*Theoretical*			*Real*			*Theoretical*			*Real*		
0	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***	***0***	***1***	***2***
127	87	76	105	105	80	58	45	44	42	57	48	69	42	32	63	48	32
$\chi^2 = 7{,}7456879$						$\chi^2 = 7{,}9774295$						$\chi^2 = 1{,}378882$					
Significance Level 95%; $\chi_t^2 = 9{,}488$																	
There's Correlation						*There's Correlation*						*There's Correlation*					

The study of SA & TA area shows a larger correlation ($\chi^2 = 7{,}7456879$) between Forest Crook and twist than the correlation between Forest Crook and bow ($\chi^2 = 8{,}0881151$) or crook deformation ($\chi^2 = 8{,}6224396$) respectively.

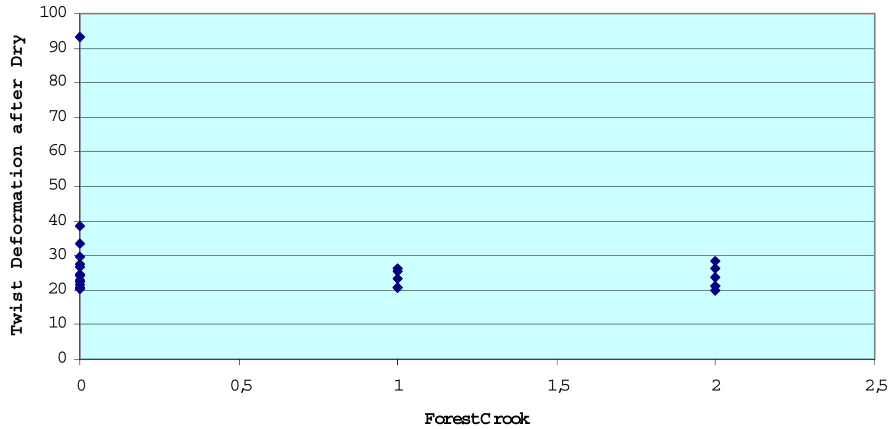

Figure 4.12: *SA & TA Stands. Forest Crook versus Twist after Drying Deformation.*

Furthermore, when results from the TA Stand are particularly studied the correlation between twist and Forest Crook increases considerably. Trees showing a high degree of Forest Crook also have higher twist deformation after drying.

4.3.3. Orientation of Bow Deformation after Drying Process.

From the data recorded in Appendix V.v. and the revision of Table 4.11. it can be concluded that the orientation of the deformation on all tested boards is significant when the overall samples are considered as a whole group, and within TA Stand. Nevertheless, no distinction between outward pith orientation and toward pith orientation can be stated when studying SA Stand as a separated group.

Table 4.11: *Orientation of the Deformation. Correlation between towards pith orientation and outwards pith orientation.*

BOW						
	SA & TA Stands		*SA Stand*		*TA Stand*	
	i **Orientation**	*o* **Orientation**	*i* **Orientation**	*o* **Orientation**	*i* **Orientation**	*o* **Orientation**
Std. Dev	2,65641069	3,144245	2,99301223	3,4151213	2,28020804	2,9343418
Average [mm]	3,3127985	4,2226224	4,0737	4,8423973	2,5742647	3,5762857
N	134	143	66	73	68	70
|Z|	2,6070054		1,4140958		2,2435832	
95% (1,645)	*The orientation is significantly different.*		*The orientation is not significantly different.*		*The orientation is significantly different.*	

4.3.4. H Boards vs. V Boards. Study of the Deformations after Drying.

In order to study the difference between sides when measuring bow, crook and twist deformation, Z-test has been again applied. See Appendix V.vi.

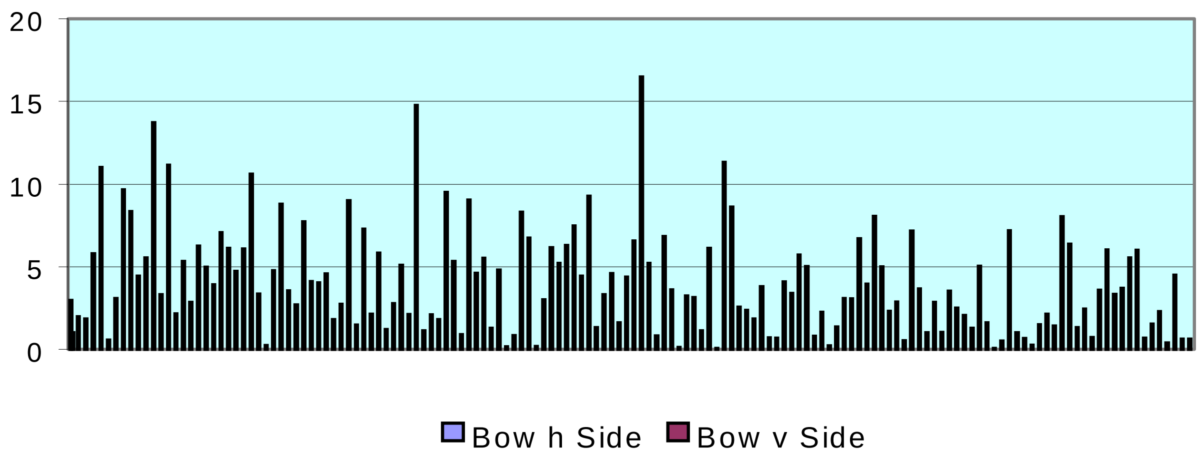

Figure 4.13: *SA & TA Stands. Bow Deformation. Comparison between values from H Boards and V Boards.*

In Tables 4.12. and 4.13., and Figures 4.13. and 4.14. it is shown that difference between sides is not noticeable for crook and bow deformations after drying. The improper handling of V Boards at the sawmill has no importance with respect to these deformations. Neither of the statistic groups, SA & TA group, SA Stand or TA Stand shows significant difference.

Table 4.12: *Bow Deformation after Drying Process. Comparison between values from H Boards and V Boards.*

BOW						
	SA & TA Stands		*SA Stand*		*TA Stand*	
	Side h	**Side v**	**Side h**	**Side v**	**Side h**	**Side v**
Std.Dev	3,13602792	3,2051006	3,17223413	3,7346809	2,88174598	2,3553509
Average [mm]	3,8027	3,2040845	4,8550658	4,2514789	3,2559459	2,8024648
Maximum [mm]	16,48	19,35	14,745	19,35	16,48	11,905
Minimum [mm]	0,06	0,03	0,145	0,11	0,06	0,03
N	150	144	76	71	74	71
|Z|	1,61196072		1,05253387		1,03937622	
95% (1,645)	*Sides are not significantly different.*		*Sides are not significantly different.*		*Sides are not significantly different.*	

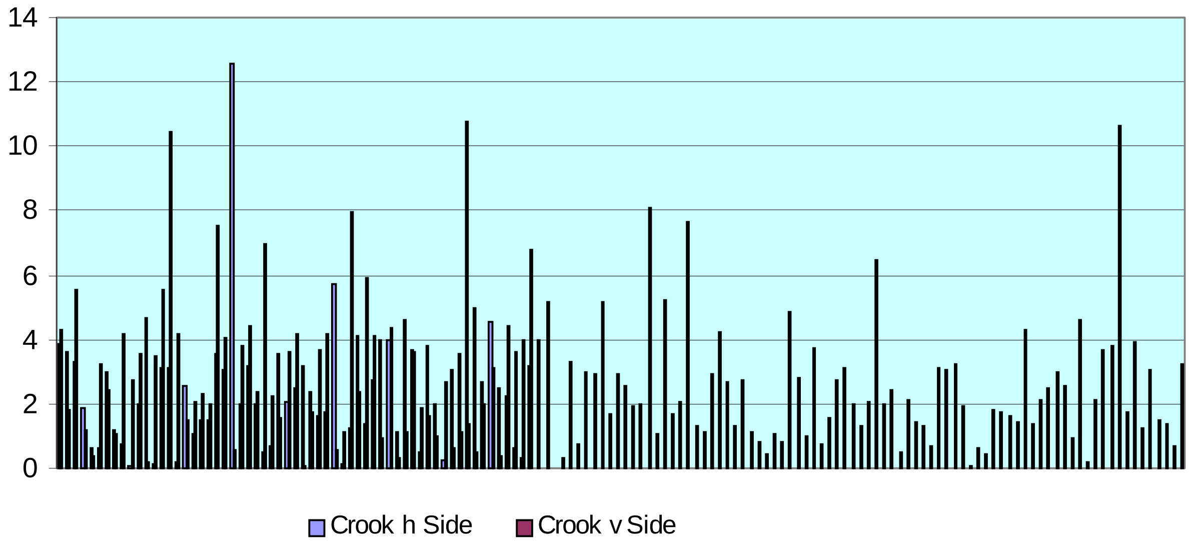

Figure 4.14: *SA & TA Stands. Crook Deformation. Comparison between values from H Boards and V Boards.*

Table 4.13: *Crook Deformation after Drying Process. Comparison between values from H Boards and V Boards.*

CROOK						
	SA & TA Stands		*SA Stand*		*TA Stand*	
	Side h	**Side v**	**Side h**	**Side v**	**Side h**	**Side v**
Std.Dev	2,44636824	1,9817148	2,60422764	2,0981488	2,20512399	1,8282146
Average [mm]	2,7331	2,3463542	3,4098026	2,9273571	2,6360811	2,3994595
Maximum [mm]	12,555	10,61	10,735	10,44	12,555	10,61
Minimum [mm]	0,015	0,03	0,015	0,03	0,06	0,09
N	150	144	76	70	74	74
|Z|	1,49223417		1,23693468		0,71061199	
95% (1,645)	*Sides are not significantly different.*		*Sides are not significantly different.*		*Sides are not significantly different.*	

In contrary to bow and crook, twist after drying show large differences between H Boards and V Boards. See Table 4.14. In this case, differences should be explained as a consequence of the sawing since there is no relation between twist deformation and the rough handling of h Boards. See Section 3.3.2.

Table 4.14: *Twist Deformation after Drying Process. Comparison between values from H Boards and V Boards.*

TWIST						
	SA & TA Stands		*SA Stand*		TA Stand	
	Side h	**Side v**	**Side h**	**Side v**	**Side h**	**Side v**
Std.Dev	9,08631943	4,7760231	10,78747426	4,6922251	6,54624362	4,8255537
Average [mm]	13,227086	8,2213103	14,861316	8,6111268	11,571067	7,8472973
N	151	145	76	71	75	74
|Z|	5,965702837		4,60610225		3,955970534	
95% (1,645)	*Sides are significantly different.*		*Sides are significantly different.*		*Sides are significantly different.*	

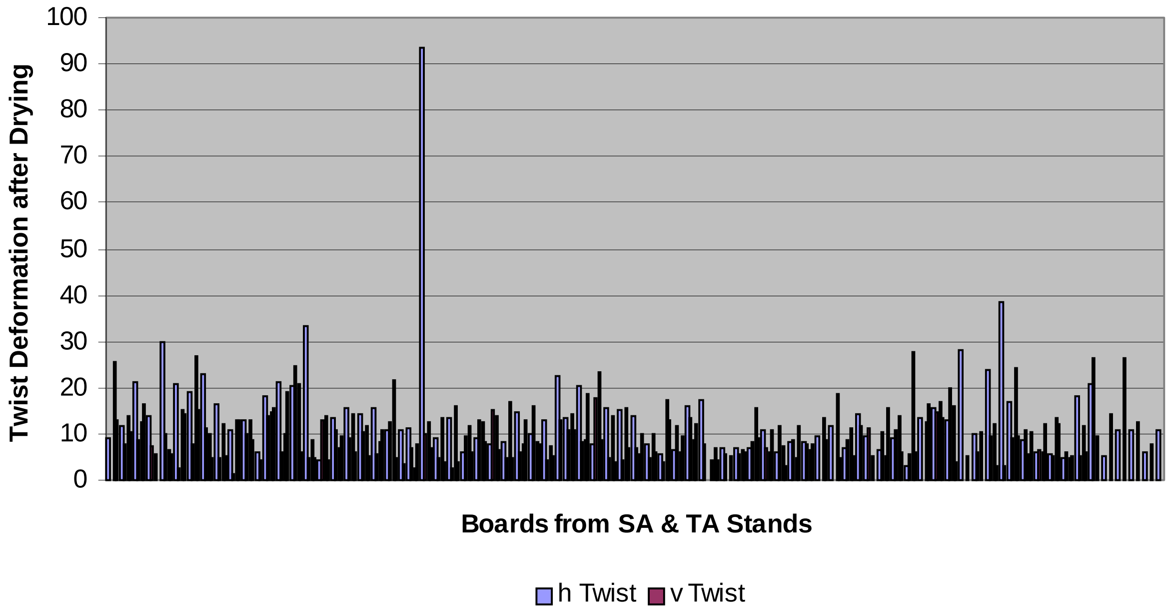

Figure 4.15: *SA & TA Stands. Twist Deformation. Comparison between values from H Boards and V Boards.*

4.3.5. Correlation between Bow, Twist and Crook Deformations.

In this work, Z variables have been used for comparing data distributions of twist, bow and crook after drying and establishing the correlation between different types of deformations. See Appendix V.ii.

Z variable is a typified variable that expresses non-dimensional variables. Z variables are independent from the units that have been used when doing the measurements and are also independent from the rank of each kind of deformation, like this the direct value (punctuation) from the distributions can be compared.

Table 4.15: *Correlation between deformations after drying process. Coefficient of correlation r. Study of Sandshagen and Tabergsvägen stands. Study by plots.*

	Correlation Twist - Crook	Correlation Twist – Bow	Correlation Crook – Bow
SA	0,166325975	0,31362209	0,064396
Fin	-0,074376126	0,017614635	-0,045307
Ful	0,242826985	0,276022456	0,235613
Hög	0,26684823	0,520684153	0,065374
Låg	0,159157707	0,603584991	0,163216
Slu	-0,101584804	0,26775451	-0,108122
Spec	0,29359704	0,447770932	0,040287

TA	-0,003948129	0,059350847	0,116542
Fin	-0,093587185	0,426852849	0,093189
Ful	0,07559373	0,173435572	-0,451936
Hög	0,085089915	-0,009119219	0,26132
Låg	-0,013679025	0,098570041	0,131025
Spec	0,001885813	-0,389282322	0,483157
SA & TA	0,123155198	0,24916826	0,115904

Table 4.15 shows the correlation found for twist, bow and crook deformations. The samples were studied taken into consideration the different plots where the boards come from. From the study of the calculations, it can be observed that most of the correlations are small which means that the relationship between the deformations is very little. However, for some plots like Hög, Låg and Spec plots from SA Stand, and Fin and Spec plots from TA Stand, the correlation between twist and bow, even classified as regular (values between 0,40-0,6), is larger. With regard to correlation between twist and bow deformations at Låg Plot from SA Stand, it could be classified as an intensive correlation, however, it should be mentioned that the number of samples from Låg Plot (9 tested boards) is not enough to stated that this high correlation really exists.

When crook and bow deformations are studied, it can be stated that it exits a considerable correlation between crook and bow in Ful and Spec plots from TA Stand. When studying the correlation between crook and bow deformations in Ful Plot, the correlation is considerable but negative ($r = -0,451936$) thus, when increasing crook, bow decreases.

In addition, when the samples are studied making no difference between plots or stands, which is considering all the tested boards as a group, the highest correlation appears when studying the correlation between twist and bow deformation after drying, even though that is not a very large one ($r = 0,249168$). The correlation between twist and crook and correlation between crook and bow, as shown on Table 4.15, are still lower and, even if they exist, they can not be considered as significant.

It should be also pointed out that no significant correlation has been found among the deformations of the trees coming from SLU Plot and the deformations of the trees coming from the remaining plots. From this, and knowing that thinning in SLU Plot was done with no special pattern, i.e. thinning without considering size or quality, the results lead up to say that thinning have no influence on the deformation after drying, however this result contradicts previous investigations that state the importance of the application of thinning methods.

4.3.6. Bow after Sawing vs. Deformations after Drying.

Table 4.16. shows the relationship between bow after sawing and deformations after drying. The results lead up to say that it exits a correlation between bow after sawing and bow after drying. The average bow after drying for all studied boards ($\overline{BAS} = 3{,}8477 mm.$) is slightly larger than the average bow after sawing ($\overline{BAS} = 3{,}6877 mm.$). See Appendix V.viii. On the contrary, when crook and twist deformations after drying are studied, Z-Test allows saying that no consistent tendency is found between the pair of data. No correlation between those deformations and bow after sawing can be stated.

Table 4.16: *SA & TA area. Orientation of the deformation. Correlation between towards pith orientation and outwards pith orientation.*

BAS vs. Deformations after Drying						
	BAS	**Bow**	**BAS**	**Crook**	**BAS**	**Twist**
Std. Dev	2,574638	3,103447	2,574638	2,320979	2,574638	6,17
Average [mm]	3,687785	3,847753	3,687785	2,900032	3,687785	10,9
Maximum [mm]	9,81	18,095	9,81	12,555	9,81	33,3
Minimum [mm]	0	0,05	0	0,03	0	0
N	158	158	158	158	158	158
|Z|	0,49866		2,856565		13,5456	
95% (1,645)	*Deformations are not significantly different.*		*Deformations are significantly different.*		*Deformations are significantly different.*	

4.3.6.1. Orientation of the deformation.

Respecting to the orientation of the deformation, it has already been explained in Chapter 2 that, since shrinkage is proportional to the moisture content below the fiber saturation point, wood closer to the surface tends to deform more than that one further away from the surface resulting in development of internal stresses. As a consequence, restrained shrinkage on the surface induces tensile stresses. However, later in the drying process it is likely the reverse situation, and therefore compression occurs on the surface while tension takes place across the grain in the interior fibres.

Figure 4.16. reports that among all the test samples, 110 boards show bow deformation towards pith, while outwards pith orientation undergoes on 12 tested boards. Nevertheless, after drying process was carried out, the number of boards showing towards pith orientation

is 62 and 60 boards exhibit outward pith orientation, thus reverse stresses took place during drying.

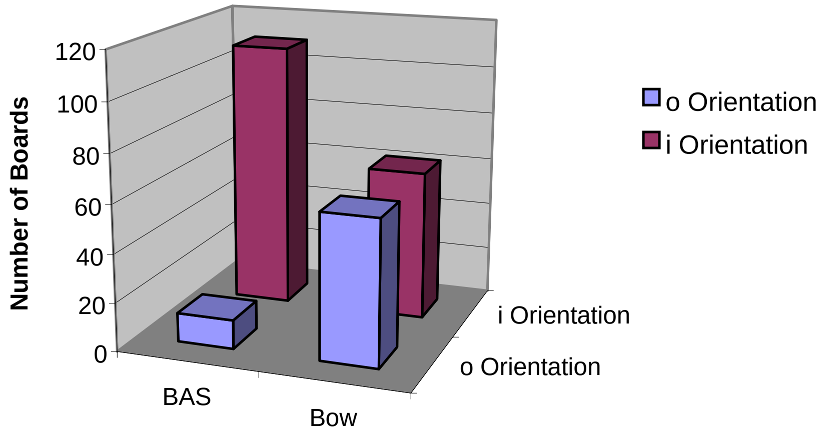

Figure 4.16: *Orientation of the Deformation. Bow after Sawing versus Bow after Drying Deformation.*

4.3.6.2. Bow after Sawing of Boards having o Orientation vs. Deformations after Drying.

Correlation between bow deformation after sawing on those boards having outward pith orientation and deformation of these boards after drying has also been studied.

Table 4.17. shows that, since deformations are not significantly different, there is a correlation between bow after sawing and bow and crook deformations after drying.

Table 4.17: *Bow Deformation after Sawing of Boards having o Orientation vs. Deformation after Drying.*

BAS of Boards having *o* Orientation vs. Deformations after Drying						
	BAS	**Bow**	**BAS**	**Crook**	**BAS**	**Twist**
Std. Dev	1,0924308	2,6321248	1,0924308	2,0153563	1,0924308	4,7198407
Average [mm]	3,3936364	4,2395455	3,3936364	3,1204545	3,3936364	11,766364
Maximum [mm]	5,71	9,495	5,71	6,565	5,71	20,8
Minimum [mm]	1,44	0,235	1,44	0,685	1,44	6,49
N	11	11	11	11	11	11
|Z|	0,98447		0,3952384		5,731971	
95% (1,645)	*Deformations are not significantly different.*		*Deformations are not significantly different.*		*Deformations are significantly different.*	

On the contrary, it can be observed that there is no correlation between bow after sawing and twist after drying.

4.4. Moisture Content after Drying Process.

As explained in Chapter 2, since dimensional changes occur in wood when the moisture of wood changes below the fiber saturation point. The degree of shrinkage and swelling depend on the amount of moisture that is lost or gained by wood when its moisture fluctuates below the fiber saturation point. The relation may be considered linear for radial and tangential directions and to volumetrics changes and applied to all growth directions and, therefore, to volumetric changes and in stepwise also linear in longitudinal direction.

An assessment of the influence of moisture content on dimensional changes of tested boards will be dealt with in this section.

Moisture content was measured in the middle *(Middle MC)* and at one of the extremes *(End MC)* of the ten selected boards. Moreover, two different readings were done; moisture content was done on the surface *(Shallow MC)* and deeper on the board *(Deep MC)* for reporting that a moisture content gradient still existed.

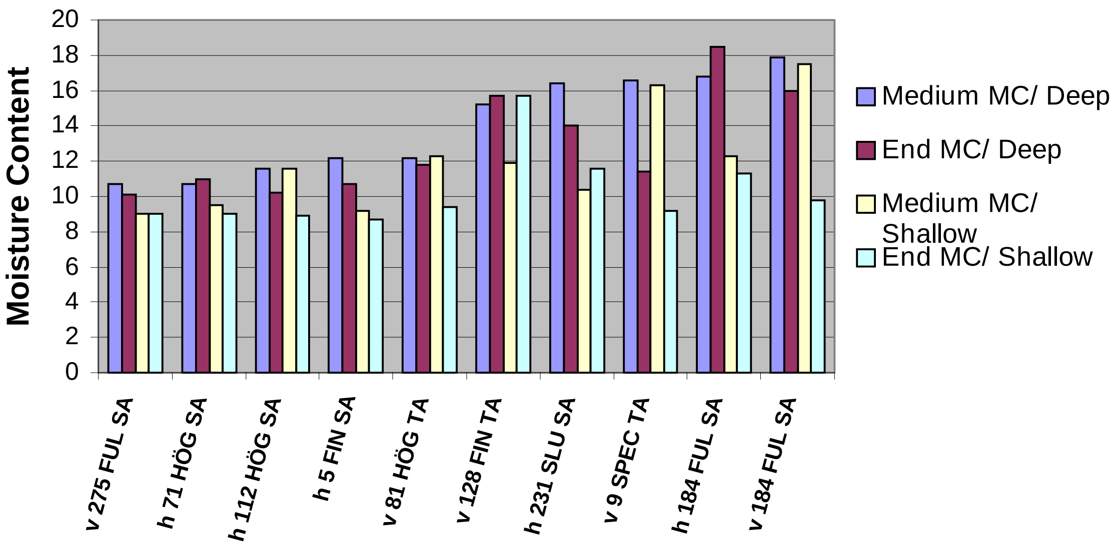

Figure 4.17: *Moisture Content on tested boards.*

In order to simplify the study of the moisture content influence on warp, the average of the called *Shallow MC* and *Deep MC* was calculated. These values, the *Average Middle MC* and the *Average End MC* are represented in Figures 4.18., 4.19. and 4.20.

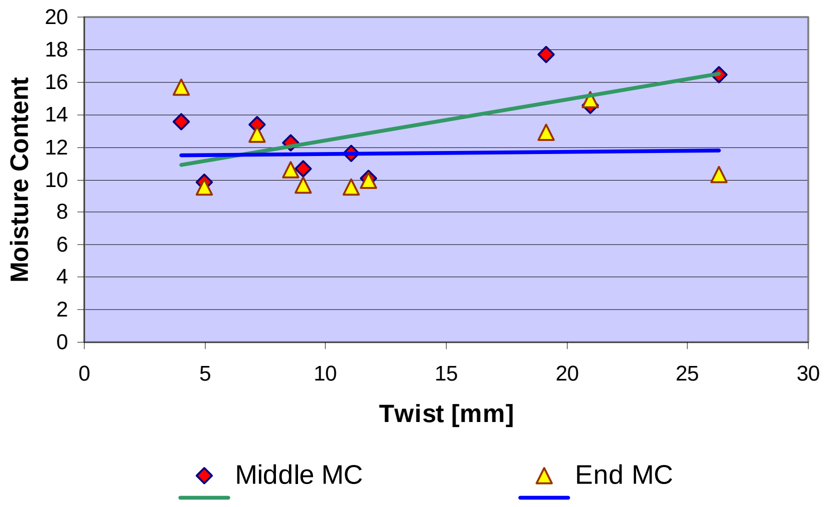

Figure 4.18: *Average End Moisture Content and Average Middle Moisture Content vs. Twist Deformation.*

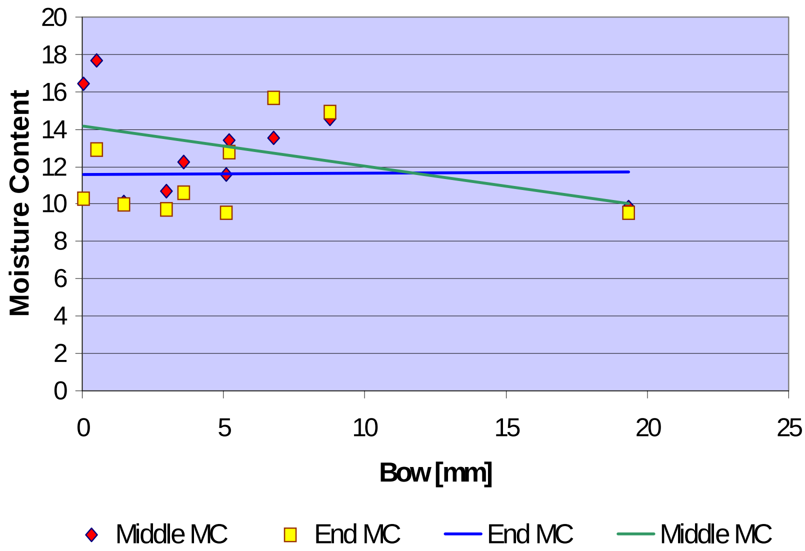

Figure 4.19: *Average End Moisture Content and Average Middle Moisture Content vs. Bow Deformation.*

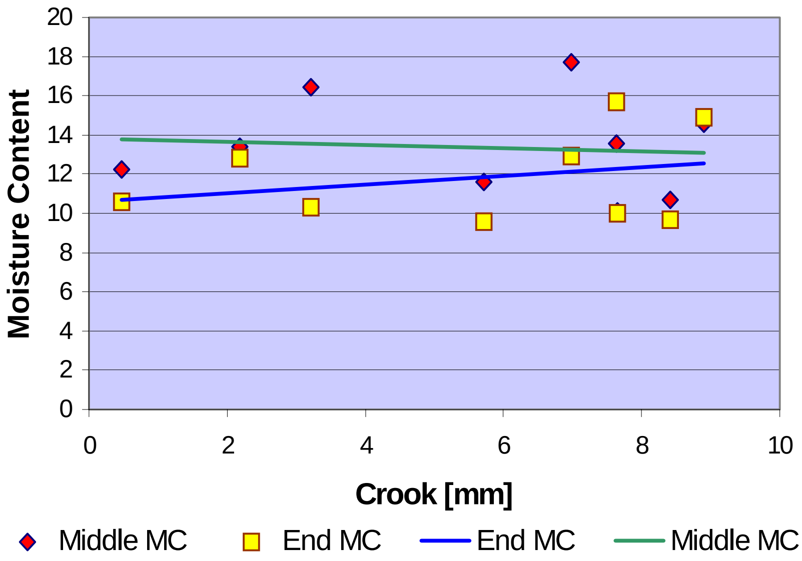

Figure 4.20: *Average End Moisture Content and Average Middle Moisture Content vs. Crook Deformation.*

The assessment of Appendix V.viii., Tables 4.18., and 4.19. and the figures inserted above gives clear conclusions of the implications of moisture content on deformations after drying.

As reported on Table 4.18. *middle moisture content* is regular correlated for twist (r = 0,66), while for crook and bow deformations such correlation doesn't exists or is considered as low and not significant (r = 0,00948 and r = 0,4527 respectively).

Table 4.18: *Middle Moisture Content (Average) versus deformations after drying on tested boards.*

Middle MC vs. Deformations after Drying						
	Middle MC	Twist	Middle MC	Bow	Middle MC	Crook
Std. Dev	2,5099851	7,0208672	2,5099851	5,3394756	2,5099851	2,8425365
Average [mm]	13,015	12,302	13,015	5,38	13,015	5,6844444
Maximum [mm]	17,7	26,3	17,7	19,35	17,7	8,905
Minimum [mm]	9,85	4,01	9,85	0,05	9,85	0,47
n	10	10	10	10	10	9
|Z|	0,3023995		4,0922002		5,9307037	
95% (1,645)	Correlation		No Correlation		No Correlation	

With regard to *End moisture content*, equal results are show in Table 4.20. A consistent tendency is found between moisture content and twist deformation, i.e., increase of moisture content results in higher twist deformation. On the contrary, no relationship is observed between bow or crook deformation and moisture content.

Table 4.19: *End Moisture Content (Average) versus deformations after drying on tested boards.*

End MC vs. Deformations after Drying						
	End MC	Twist	End MC	Bow	End MC	Crook
Std. Dev	2,1930572	7,0208672	2,1930572	5,3394756	2,1930572	2,8425365
Average [mm]	11,6	12,302	11,6	5,38	11,6	5,6844444
Maximum [mm]	15,7	26,3	15,7	19,35	15,7	8,905
Minimum [mm]	9,55	4,01	9,55	0,05	9,55	0,47
N	10	10	10	10	10	9
|Z|	0,301808		3,4075414		5,0379754	
95% (1,645)	Correlation		No Correlation		No Correlation	

In conclusion, in order to understand the occurrence of twist, one must take into consideration the significance of moisture content on such deformation, while in relation to bow or crook deformation moisture content does not contribute to explain their existence.

5. NUMERICAL RESULTS

5.1. Calculation of Bow after Sawing.

As explained in Chapter 2, bow deformation found in sawed timber is caused by internal (growth) stresses. Looking at the distribution of growth stresses in the longitudinal direction of a log and considering that it does not contain any reaction wood (perfect log), stress distribution will be, in every possible axes from bark to bark, as shown in Figure 5.1.

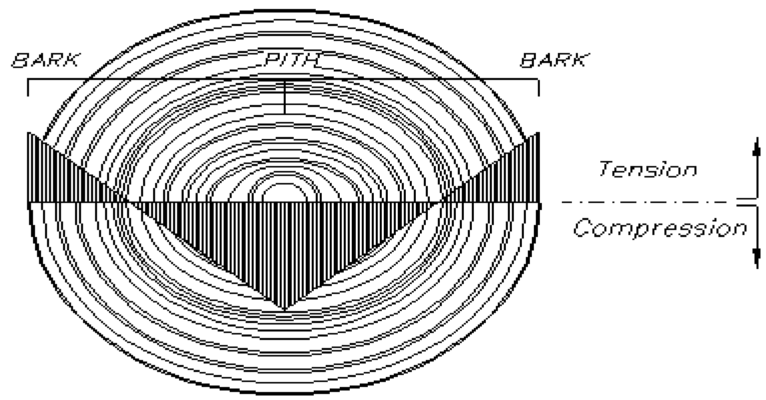

Figure 5.1: *Cross-section of a log. Stress distribution in a perfect log. (Alhasani, 1999).*

When a log contains reaction wood, the stress distribution is affected by the amount of the abnormal wood and hence, that will be different depending on the quantity of reaction wood. Theses stresses are, in contrary to the perfect growth stresses shown in figure 5.1.,not symmetric. (Alhasani, 1999).

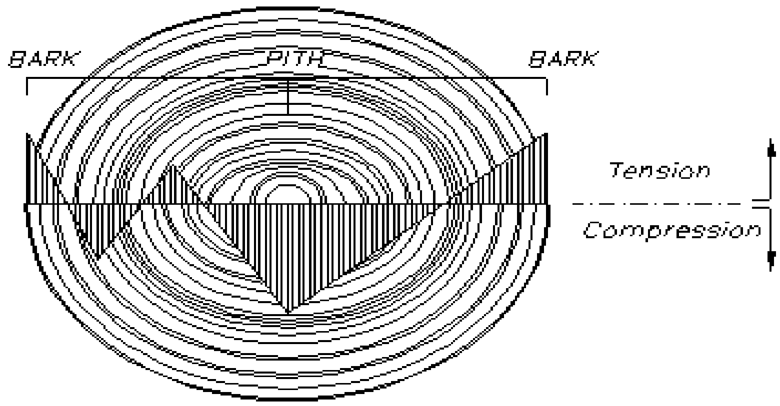

Figure 5.2: *Example of the stress distribution in a log containing reaction wood. (Alhasani, 1999).*

The longitudinal stress distribution will give an initial deformation of a log after sawing. For a board from a perfectly straight log with uniform stress distribution over its specific length, bow deformation can be calculated.

Specific length.

When a log is sawn from the long stem of a tree containing internal stresses, the stresses closest to the extremes of the sawn log are released and, as a consequence, uniform stress will change according to Figure 5.3.

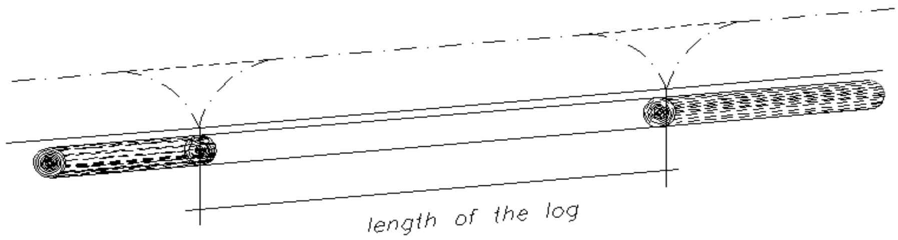

Figure 5.3: *Distribution of internal stresses before (- - - - -) and after sawing (-.-.-.-.-).*

The magnitude of the stresses relaxation depends on factors such as elastic modulus, shear modulus, Poisson ratio, etc. Research results on Norway spruce (Alhasani, 1999) show that the stress relaxation affects about 280 mm of length inward from the sawn end, if the stress situation along the sawn boards used in this investigation is idealised, it will look like Figure 5.4.

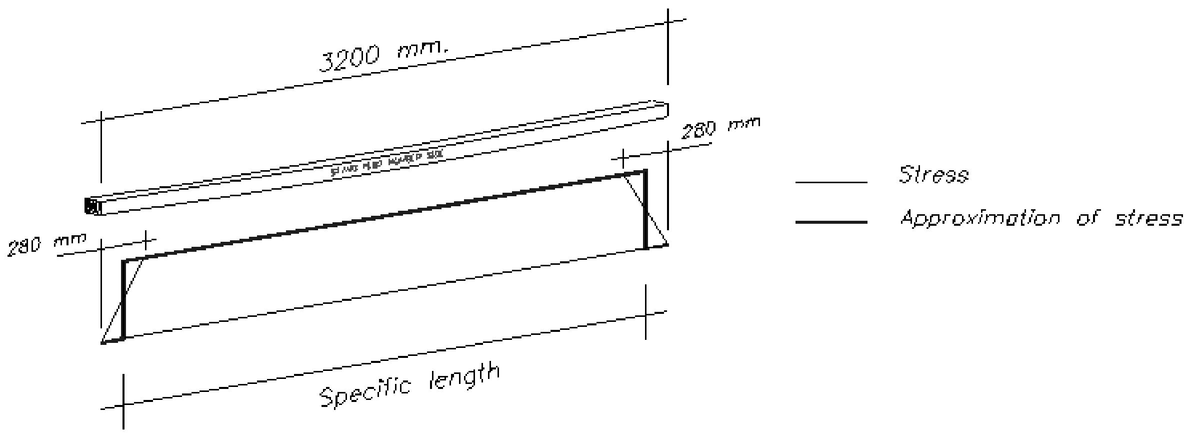

Figure 5.4: *Idealisation of stress situation along a tested board.*

Were the specific length is the length for which it can be said that over this length, stress can be considered uniform.

Specific length for the studied boards is

$$L_S = 3200 - 2 \cdot \frac{280}{2} = 2920mm.$$

The deformations (y_{Tot}) for a perfect board can now be calculated with a simple elastic beam equation for a beam with constant moment (*M)* according to Figure 5.5.

$$y_{Tot} = y_{Beam} + y_{Straight\text{-}ends.}$$

$$y_{Beam} = \frac{M \cdot L_S^2}{8 \cdot EI}$$

Where L_S is the specific length, E is the elastic modulus and I the moment of inertia.

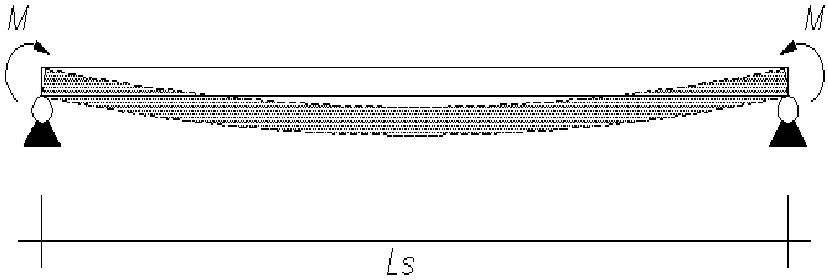

Figure 5.5: *Deformation in a beam with constant moments.*

Some extra deformation *(*$y_{Straight\text{-}ends.}$*)* occurs since measurements were done over 3 meters and not over the specific length (L_S = 2920 mm.)

$$y_{Straight-ends} = 2 \cdot sin\left(\frac{3 \cdot ML_S}{6 \cdot EI} \cdot \frac{L - L_S}{2}\right)$$

The bending moment of the beam *M* can be solved from the knowledge of internal stresses (σ).

If the board is sawn according to Figure 5.6.

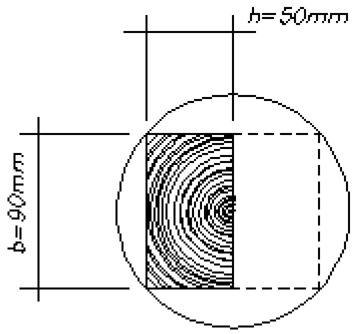

Figure 5.6: *Sawn board from a log.*

The difference in stress will be

$$\sigma = E \cdot \frac{\Delta\varepsilon}{2}$$

Where $\Delta\varepsilon = 4.1 \cdot 10^{-4}$ *has been documented in Alhasani (1999)*

Since: $M = \sigma \cdot \omega$

Where: $\omega = \frac{b \cdot h^2}{6}$

for rectangular cross-sections having *h* depth and *b* width.

Therefore

$$y_{Beam} = \frac{M \cdot L_S^2}{8 \cdot EI} = \sigma \cdot \omega \cdot \frac{L_S^2}{8 \cdot EI} = \frac{\sigma \cdot b \cdot h^2 / 6 \cdot L_S^2}{8 \cdot EI}$$

and since

$$I = \frac{b \cdot h^2}{12}$$

for a rectangular section.

It results

$$y_{Straight-ends} = 2 \cdot sin\left(\frac{3 \cdot ML_S}{6 \cdot EI} \cdot \frac{L - L_S}{2}\right)$$

$$y_{Beam} = \frac{\Delta\varepsilon \cdot L_S^2}{8 \cdot h} = \frac{4.1 \cdot 10^{-4} \cdot 2920^2}{8 \cdot 50} = 8.73mm.$$

and assuming $Sin\ \alpha \approx \alpha$ if $\alpha \ll 1$

then $$y_{Straight-ends} \approx 2 \cdot \frac{\Delta\varepsilon \cdot L_S}{2 \cdot h} \cdot \frac{L - L_S}{2} = 2 \cdot \frac{4{,}1 \cdot 10^{-4} \cdot 2920}{2 \cdot 50} \cdot \frac{3000 - 2920}{2} =$$

$$y_{Straight-ends} \approx 0.957mm.$$

and the total deformation is found to be

$$y_{Tot} = y_{Beam} + y_{Straight-ends.} = 8.73 + 0.957 = 9{,}687 \approx 9.7\ mm.$$

It is important to note that the total deformation (y_{Tot}) has been calculated considering that the beam does not contain reaction wood and assuming

5.2. Calculation of Bow Deformation after Drying.

Since wood is an anisotropic material, the shrinkage coefficient α is direction dependent for wood, in others words, longitudinal, radial and tangential shrinkage is different.

The main reason for bow and crook of dried timber is the variation of Longitudinal Shrinkage Coefficient α_L. There is a close relationship between moisture content μ and shrinkage ε^S.

The variation of shrinkage ($\Delta\varepsilon^S$) as a function of the moisture content change can be written as

$$\Delta\varepsilon^S = \alpha \cdot \Delta\mu$$

In addition, there is also a radial variation of the longitudinal shrinkage coefficient, i.e. dependency on where in the log (close to the pith or farther away) the longitudinal shrinkage is studied. This relationship is shown in figure 5.7.

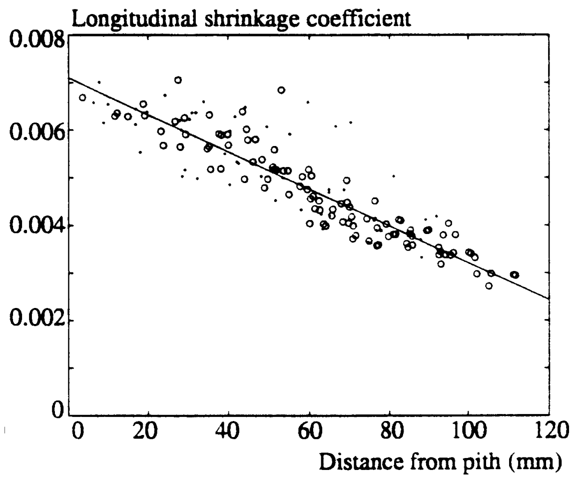

Figure 5.7: *Influence of distance from pith on longitudinal shrinkage coefficient. (From Ormarsson, 1999).*

With the use of the definition of shrinkage and making applicable some idealisations such as uniformity in drying and no reaction wood, the bow can be approximated for a *perfect* board.

Considering an initially straight board and a uniform drying from 30% moisture content to 16%, then

$$\Delta\mu = 30 - 16 = 14\% \quad \text{and} \qquad \Delta\varepsilon_L^S(R) = \alpha_L(R)\cdot\Delta\mu$$

From Figure 5.7., we can consider that the Longitudinal Coefficient of Shrinkage is

$$\alpha_L(R) \approx 0{,}008 - \frac{0{,}006}{100}\cdot R \qquad \text{when} \quad R < 100$$

$$\alpha_L(R) \approx 0{,}002 \qquad \text{when} \quad R > 100$$

and, since the mean longitudinal shrinkage at pith side (ε_{LP}^S) and bark side (ε_{LP}^B) are

$$\hat{\varepsilon}_{LP}^S = \frac{1}{3}\cdot 0{,}14\cdot(0{,}008 + 2\cdot 0{,}005) = 0{,}84‰$$

$$\hat{\varepsilon}_{LB}^S = \frac{1}{3}\cdot 0{,}14\cdot(0{,}005 + 2\cdot 3{,}76\cdot 10^{-3}) = 0{,}58‰$$

bow deformation will be

$$B = \frac{(\hat{\varepsilon}_{LP}^S - \hat{\varepsilon}_{LB}^S)\cdot L^2}{8\cdot h} = \frac{0{,}26\cdot 3^2}{8\cdot 0{,}05} = 5{,}85mm.$$

however, it should be pointed out that, since is not possible to have uniform drying of a board with the length of 3,2 meters, this bow deformation is the maximum obtained.

5.3. Calculation of Twist Deformation after Drying.

The twist of a dried board can be estimated by considering the fiber angle (spiral grain) of the board.

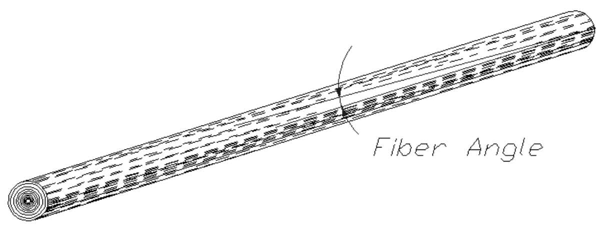

Figure 5.7: *Fiber angle (γ) present in a log.*

The fiber angle, as explained before, is the angle exists between the grain and the longitudinal direction of the wooden element.

If a plane strain situation is assumed, strain (shrinkage) can be defined as

$$\varepsilon_L = \varepsilon_f \cdot \cos^2\gamma + \varepsilon_t \cdot sin^2\gamma + \varepsilon_{ft} \cdot sin\gamma \cdot \cos\gamma$$

where ε_L is the shrinkage along the longitudinal direction, ε_f is the shrinkage along the fiber, ε_t is the shrinkage on the transverse direction, and ε_{ft} refers to the shrinkage along an axes perpendicular to both transverse and fiber directions.

Since $\varepsilon_{ft} = 0$; shrinkage is

$$\varepsilon_L = \varepsilon_f \cdot \cos^2\gamma + \varepsilon_t \cdot sin^2\gamma$$

There exits a close relationship between change moisture and shrinkage that can be defined as

$$\varepsilon_L = \alpha_L \cdot \Delta\mu$$

where α_L stands for the coefficient of shrinkage on transverse direction, and therefore it can be written

$$(\varepsilon_f \cdot \cos^2\gamma + \varepsilon_t \cdot sin^2\gamma) \cdot \Delta\mu = \alpha_L \cdot \Delta\mu$$

Knowing that coefficient of shrinkage on transverse direction is on the range

$$\alpha_t \approx (150 \div 200)\ \alpha_f$$

and assuming the approximation

$$\alpha_t \approx 175 \cdot \alpha_f$$

coefficient of longitudinal shrinkage, as a function of fiber angle and coefficient of shrinkage on the fiber direction, can be expressed as

$$\alpha_L \approx \alpha_f\ (cos^2\gamma + 175 \cdot sin^2\gamma)$$

Considering a log with a fiber angle γ, the shrinkage of the fiber and the longitudinal direction of the log will differ.

Longitudinal shrinkage (ε_L^S) is

$$\Delta\varepsilon_L^S = \alpha_L \cdot \Delta\mu$$

and shrinkage along the fiber (ε_f^S) will be

$$\Delta\varepsilon_f^S = \alpha_f \cdot \Delta\mu \qquad \text{where always } \alpha_f \leq \alpha_L$$

Since longitudinal shrinkage coefficient can be written as

$$\alpha_L \approx \alpha_f\,(cos^2\,\gamma + 175 \cdot sin^2\,\gamma)$$

Considering the shortening of a log to be

$$\Delta L = L_o \cdot \varepsilon_L^S$$

where L_o is the initial length before drying, and considering that the initial length of the fiber is

$$f_o = \frac{L_o}{\cos\gamma}$$

the shortening of a fiber in the log can be written as

$$\Delta f = \frac{L_o}{\cos\gamma \cdot \varepsilon_f^S}$$

It is also known that final length after drying is defined as

$$L = L_o - \Delta L = L_o(1 - \varepsilon_L^S)$$

$$f = f_o - \Delta f = \frac{L_o}{\cos\gamma \cdot (1 - \varepsilon_f^S)}$$

and operating we find that, since the initial length of a fiber is

$$f = \frac{L}{\cos\vartheta}$$

Where ϑ is the fiber angle after drying, thus twist plus fiber angle before drying $\vartheta = \phi + \gamma$ then

$$f = \frac{L}{\cos\vartheta} = \frac{(L_o - \Delta L)}{\cos\vartheta} = L_o \cdot \frac{(1 - \varepsilon_L^S)}{\cos\vartheta}$$

and therefore

$$\frac{L_o}{\cos\gamma \cdot (1-\varepsilon_f^S)} = L_o \cdot \frac{(1-\varepsilon_L^S)}{\cos\vartheta}$$

$$\cos\vartheta = \cos\gamma \cdot \frac{(1-\varepsilon_L^S)}{(1-\varepsilon_f^S)} = \cos\gamma \cdot \frac{(1-\Delta\mu \cdot \alpha_L)}{(1-\Delta\mu \cdot \alpha_f)}$$

Hence, fiber angle after drying is as a function of fiber angle before drying can be written as

$$\cos\vartheta = \cos\gamma \cdot \frac{1-\Delta\mu \cdot \alpha_f (\cos^2\gamma + 175 \cdot sin^2\gamma)}{1-\Delta\mu \cdot \alpha_f}$$

Table 5.1: *Values of twist deformation (δ) for boards 3 m long as a function of the twist angle and fiber angle after drying. (Ormarsson, 1999).*

ϕ [degrees]	γ [degrees]	L [m]	$\delta = L \cdot sin\phi$ [mm]
0,05	1	3	2,61
0,1	2	3	5,23
0,14	3	3	7,33
0,19	4	3	9,94
0,24	5	3	12,5
0,28	6	3	14,6

Since the twist angle of a dried board is

$$\phi = \vartheta - \gamma$$

considering some different values of fiber angle after drying's value, the twist deformation after drying can be known. See Table 5.1.

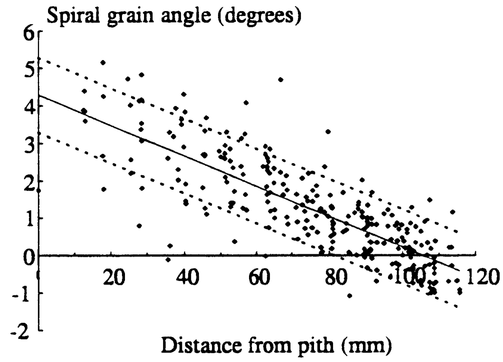

Figure 5.8: *Experimentally obtained results in spiral grain of Norway spruce. Variation from pith to bark.(From Ormarsson, 1999)*

According to Ormarsson (1999), See also Figure 5.8., fiber angle of boards from Norway spruce specie varies from about 6 to 4 degrees when measured at 50mm from the pith. Hence, twist deformation after drying will be approximately 15 to 10mm.

6. CONCLUDING REMARKS

The main conclusions of this research can be summarised as follows:

6.1. Concluding Remarks on Bow after Sawing Deformation.

1. Only a small correlation is found between the location of the compression wood and the orientation. It can therefore be concluded that the surrounding of the tree determines the degree of Forest Crook as well as wind and light.

2. According to $\chi^2 - Test$, bow deformation of sawed timber can not be determined from the degree of Forest Crook. No correlation is found between the degree of Forest Crook on still standing trees and bow deformation after sawing. However, it should be pointed out that results may be due to the applied sort criterion. See Section 4.3.2.

3. When the orientation of bow after sawing deformation was considered, boards showing towards pith orientation were much more frequent than boards containing outwards the pith orientation. Moreover, the average deformation for boards containing deformation towards the pith was much larger than bow deformation on boards showing a deformation outward the pith.

4. As expected, boards from the right side of the log (h Boards) and boards from the left side of the log (v Boards) show different values of deformation. Boards from the right side show an average deformation higher than boards coming from the left side. This is considered a consequence of the relief of growth stresses on h Boards, since they were improperly handled at the sawmill.

5. With regard to the influence of the silvicultural methods, the study summarises that, respecting to the bow after sawing, it does not appear an appreciable difference among plots. Bow after sawing is almost equal independently the plot where the board comes from.

6.2. Concluding Remarks on Deformations after Drying.

1. Forest Crook can be considered to be a good predictor of the deformations' values after drying. It may be stated that it exits a correlation between the degree of crook in a tree (determined with respect to visible classification) and bow, crook and twist deformations after drying. The study of the over all tested boards shows a larger correlation between forest crook and twist than the correlation between forest crook and bow or crook deformation.

2. With respect to the orientation of bow deformation after drying it can be concluded that outwards the pith orientation and towards the pith orientation are significantly different. The average value deformation for boards showing outwards pith orientation is slightly larger than the average value for boards showing towards pith orientation.

3. No differences have been found between h Boards and v Boards when studying the bow and crook deformations. It may be assumed, therefore, that the handling of the boards has no repercussion on those deformations after drying. With respect to twist deformation, differences between h Boards and v Boards can be considered as significantly different, however, this result should be considered as a consequence of the sawing pattern instead of the rough handling of h Boards.

4. Correlation between deformations shows that the relationship between the deformations is very little. Most of the studied plots show no or little correlation between twist and crook and between bow and crook. Some other plots show a larger correlation although they can not be considered as significant.
   It should also be pointed out that no significant correlation has been found among the deformations of the boards coming from SLU Plot and the deformations of the boards from the remaining plots. From this, since thinning in SLU Plot was done with no special pattern, i.e., thinning without considering size or quality, it may be assumed that thinning have no influence on the deformation after drying, however, this contradicts previous investigations that state the importance of the application of thinning methods.

5. With respect to the influence of the silvicultural methods, the correlation among different plots when studying deformations after drying is not significant. It can, therefore, be stated that thinning methods have no influence. This result agrees with the fact that, since all the trees remaining in its corresponding plot exhibited equal characteristics, all trees may be considered as co-dominant trees and, therefore, have stimuli to reorient themselves.

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