Report

Stress and strain in drying wood - a literature survey.	
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Summary

When a plank dries in a warm air climate, a moisture gradient from the surface to the inner core of the wood will occur. As a result tension stress will develop in the outer layer of the plank when it dries under to the fibre saturation point.

The wood when loaded is capable of going through creep deformations. In the first phase of the drying process when there is tension stress in the outer layer of the plank, the mechano-sorptive creep is the most important. However, also the visco-elastic creep has some influence.

Strength and elasticity properties of wood change characteristics during changes in temperature, moisture content, density and species. This fact must be accounted for when considering stress development and checking probability during a wood drying process.

In the work of modelling strain and stress in wood during drying, there are many factors which must be considered. However, it is necessary to simplify and concentrate the attention on the most important phenomena. There are also phenomena which are not fully understood today, and therefore it is difficult in some cases to explain why a model does not satisfactorily fit the experimental results.

Stikkord:	Tretørking, spenninger, deformasjoner, styrkeegenskaper.
Keywords:	*Wood drying, stresses, deformations, strength properties.*

Preface

This report has been written in connection with a self-tuition course at Lund Institute of Technology, Department of Structural Engineering. The course should result in a literature survey over the subject of hygromechanical behaviour of wood during drying. The result is this report, "Stress and strain in drying wood – a literature survey". However, the report is somewhat modified in the process from evaluating to publishing and printing.

Many thanks to professor Sven Thelandersson and associate professor Annika Mårtensson who organized the course for me.

Oslo, 1996-09-18

Knut Magnar Sandland

Contents

1. Introduction

The wood drying process improves the mechanical properties of wood and is necessary for the production of high quality sawn timber. How the drying process elapses has vital importance for the sawn timber quality such as moisture content, checks, stress, discolourations and deformations.

The water content in green wood is high, and the variation between different parts of the saw log is great. In the sapwood the moisture content often ranges from 60 % to 250 %, but in the heartwood the moisture content is rarely over 45-50 %.

In the process of drying timber stresses are produced, and this may cause damage. Checking and undesired deformations are the most detrimental defects caused by drying stresses.

A good drying quality requires not only an optimized drying schedule. The whole history of the saw logs from harvesting to sawing is important for the quality of the sawn timber after drying. It is desirable to dry the sawn timber as green as possible. If this is impossible, it is very important to avoid uncontrolled drying of saw logs before the production of sawn timber starts.

The raw material costs in the sawn timber industry are high, and therefore it is important to minimize the value loss of materials during the process. In this connection it is of vital importance how the drying process is carried out. Likewise, high drying quality is also necessary to give wood as a material the possibilities to compete with other materials for various purposes.

2. Introduction to drying stresses

2.1 Background

Wood is a hygroscopic, anisotropic material, which means that it shrinks and swells as the moisture content is changed below the fibre saturation point, but the shrinkage and swelling values are different in the three directions of the wood. They are highest in the tangential direction, and lowest in the longitudinal direction.

The free shrinkage coefficient for pine (*Pinus silvestris*) and spruce (*Picea abies*) in the tangential direction is approximately twice that in the radial direction. The longitudinal shrinkage is much smaller than the shrinkage in the cross section, but the existence of reaction wood or juvenile wood in a plank results in twist, bow or crook deformation because of differences in longitudinal shrinkage within the board. The longitudinal shrinkage in juvenile wood and reaction wood is much greater than in "normal" mature wood.

Schniewind (1960) has classified the different kinds of drying stresses as follows:

> Stresses of the first order act on individual cells. The origin is to be found in a different shrinkage potential of the layers in the cell wall or in hydrostatic tension in the water-filled cell cavities.
>
> Stresses of the second order are located in the growth zones. They are caused by the interaction of cells and cellular tissues with different shrinkage potential.
>
> Stresses of the third order are encountered in pieces of timber comprising several growth zones. These stresses are produced by non-uniform moisture distribution at the time of drying or by differences in shrinkage potential between different growth zones (e.g. reaction wood vs. normal wood).

In addition to these, Siimes (1967) has termed stresses which act upon groups of molecules and which owe their existence to extraction of water from individual molecules as stresses of the fourth order.

2.2. Moisture gradient and stress development

When drying through circulation of warm air, a moisture gradient from the outer to the inner layers in a piece of wood will develop. The shrinkage starts when the moisture content sinks below the fibre saturation point. The fibre saturation point is reached first in the surface layer. In the inner layer the moisture content for a period is still above the fibre saturation point. An example of this condition is illustrated in fig. 1.

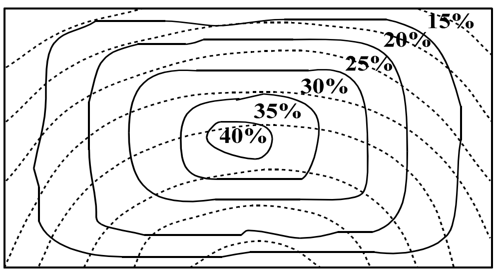

Fig. 1. An example of a moisture gradient in sawn timber while drying through circulation of warm air.

In this condition the outer layer tries to shrink, but the wet inner part will obstruct this. Tension stress will then occur in the outer layer and compression stress in the inner layer. This is illustrated in fig. 2.

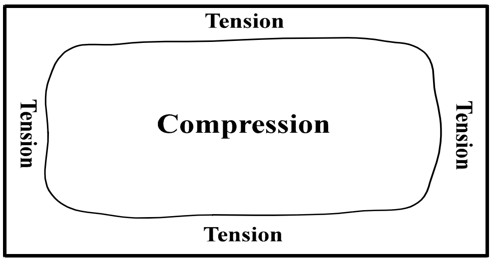

Fig. 2. Stresses in sawn timber during the first phase of the drying process (cross section).

The wood has the capability to creep, and the result is that the outer layer will be strained during the first phase of the drying process.

In a drying process the green wooden surface dries rapidly to under the fibre saturation point, which implies development of tension stresses. This occurs soon after the drying starts, and surely in many cases already during the heating period in industrial kilns (Morén 1993a). Tension stresses develop several hours later in sapwood than in heartwood because of higher content of free water in sapwood.

Later in the drying process, also the inner part of the sawn timber dries to under the fibre saturation point and starts to shrink. But now the outer layer, which is strained, is too large to match the shrinking inner core. Then there will be compression stress in the outer layer of the sawn timber and tension stress in the inner layer. When the middle moisture content in the sawn timber goes down to approximately 15-20 %, the stress are converted in such a manner. The new stress condition is illustrated in fig. 3.

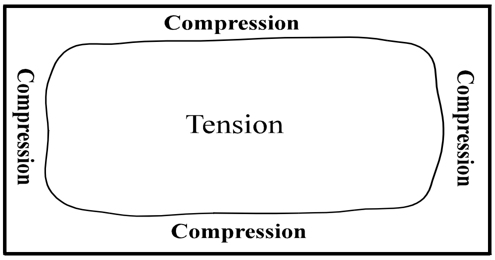

Fig. 3. Stresses in sawn timber during the last phase of the drying process (cross section).

The phenomenon when the outer layer in the sawn timber is strained, is often termed "case-hardening". Case-hardening is not considered to be a serious problem for construction timber which will not be splitted before use, but for timber which will be resawn or planed, the residual stress can cause excessive cupping and warping of the boards.

To remove the strain in the outer layer a conditioning process is used as a last phase in the drying process. By raising the relative humidity and the temperature the strain in the outer layer will to some extent be released.

3. Strength and elasticity perpendicular to grain

It is obvious from the above that to investigate the checking phenomenon of sawn timber in the drying process, most attention has to be paid to the characteristics of the wood perpendicular to the grain. The quantities to be considered are then the tension and compression strengths and the moduli of elasticity.

Great variations in the drying climate (temperature and air humidity) and in the properties of wood, lead to the fact that there are very many combinations of the different parameters which have to be investigated in this connection. The wood properties are also changing through the drying process when the sawn timber goes from green to dry condition.

3.1. Tangential direction

Siimes (1967) has investigated the elasticity and strength properties as functions of temperature, moisture content and density. Most attention is given to the tensile properties in tangential direction perpendicular to the grain, because these properties are most significant for the checking probability in the outer layer of the wood in the first phase of the drying process. For these experiments the test specimens were cut from boards with the largest possible annual growth ring radius to obtain the best tangential properties. In the following sections it is referred to some results from Siimes' investigations on the three species of pine, "Finnish" spruce (*Picea excelsa*) and birch (*Betula verrucosa*).

As a comment to other investigations in this area, (Siimes 1967) says that a general feature which can be observed is that the strength values reported by different authors are rather varied, but the effects of the investigated parameters, temperature and moisture content are remarkably similar. However, investigations concerning how the tension and compression properties of timber perpendicular to the grain varies with moisture content and temperature are relatively few.

3.1.1. The effect of moisture content

In table 1 and 2 and figure 4 and 5 some results from Siimes (1967) are referred to illustrate the influence of moisture content and temperature on the strength and elasticity properties. The tables are based on experiments on pine with medium density, 490 kg/m³.

Temp.	20 °C		40 °C		60 °C		80 °C	
M.C.	E	σ_{max}	E	σ_{max}	E	σ_{max}	E	σ_{max}
4 %	561	3,4	455	2,9	431	3,2	380	3,5
8 %	517	3,4	400	3,2	343	3,3	289	3,3
12 %	466	3,3	330	3,3	277	3,0	226	2,7
16 %	416	3,1	267	2,9	214	2,5	152	2,1
20 %	344	2,8	214	2,4	167	2,1	96	1,6
Green	214	1,9	158	1,9	106	1,5	50	1,1

M.C.: Moisture content in wood
Temp.: Temperature in wood
E: Modulus of elasticity, MPa
σ_{max}: Tension strength, Mpa

Table 1. Values for strength and modulus of elasticity for tension in tangential direction for pine (Siimes 1967).

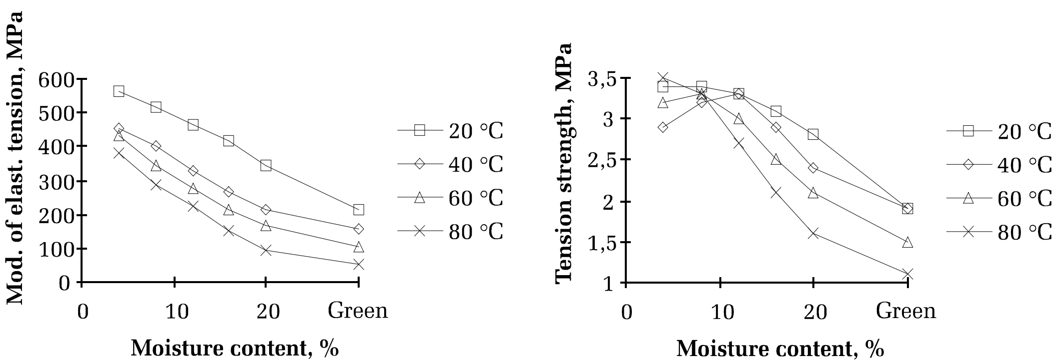

Fig. 4. Graphical presentation of the values in table 1.

Temp.	20 °C		40 °C		60 °C		80 °C	
M.C.	E	σ_{pl}	E	σ_{pl}	E	σ_{pl}	E	σ_{pl}
4 %	417	3,5	333	3,2	323	3,2	368	3,2
8 %	395	3,2	304	3,0	261	2,6	248	2,2
12 %	328	2,9	247	2,5	208	1,9	126	1,4
16 %	259	2,4	198	2,0	142	1,4	106	1,1
20 %	221	2,0	172	1,5	115	1,1	77	0,9
Green	132	1,2	129	1,1	87	0,9	50	0,6

M.C.: Moisture content in wood
Temp.: Temperature in wood
E: Modulus of elasticity, MPa
σ_{pl}: Compression strength at the proportionality limit, MPa

Table 2. Values for strength and modulus of elasticity for compression in tangential direction for pine (Siimes 1967).

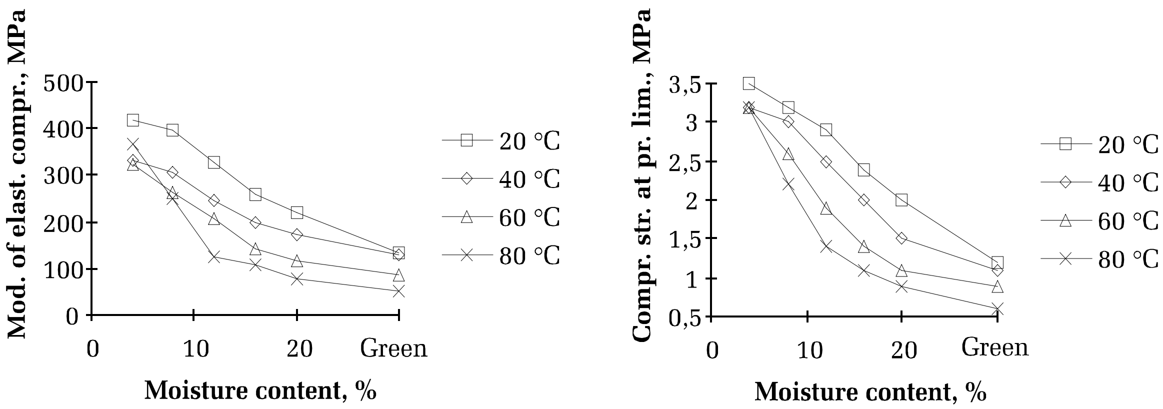

Fig. 5. Graphical presentation of the values in table 2.

To begin with, the tests with wet timber revealed that above the fibre saturation point the moisture content of the timber had no effect on strength or modulus of elasticity, and the results obtained at such moisture contents could be treated as one group (Siimes 1967). However, when the moisture content goes down below the fibre saturation point, the strength and the modulus of elasticity will increase.

Siimes (1967) has found that the increase of modulus of elasticity is relatively larger than that of the corresponding tensile strength, and that the changes are greater in heavy than in light timber. It is also found that at high temperatures both strength and modulus of elasticity in tension increase relatively more than when the timber is dried and tested at lower temperatures. As an example it is mentioned that when pine timber dries from fibre saturation point to 4 % moisture content, its tensile strength increases at 20 °C by a factor of 1,7 for low density wood, and 1,9 for high density wood, but by a factor of 3,0 and 3,4 at 80 °C respectively. The corresponding changes of the modulus of elasticity in the tension test, referred to the wet state, are equivalent to a factor of 2,4 and 2,9 respectively for low and high density wood at 20 °C, and to a factor of respectively 6,7 and 8,9 at 80 °C. In the tangential compression tests perpendicular to the grain, strength and modulus of elasticity both increase by approximately equal amounts when the timber dries.

When the moisture content falls below 12-14 %, the increase of the investigated strength characteristics begins to slow down, particularly in heavy timbers. The tensile strength of pine and "Finnish" spruce timber then attains an optimum value, which moves towards lower moisture content with increasing temperature. This effect can be seen in table 1 and fig. 4. Siimes (1967) says that similar phenomenon has been reported in other investigations in various strength characteristics of timber. It is pointed out that no corresponding optimum values were generally established in the modulus of elasticity nor in the compression strength. Neither is this effect found in birch.

According to Thelandersson & Morén (1992), the elastic modulus in tension in tangential direction is assumed to depend on moisture content u as shown in formula (1).

$$E(u) = E_f\left[1+(\lambda-1)\frac{u_f-u}{u_f}\right] \qquad (0 \leq u \leq u_f) \qquad (1)$$

where u_f is the moisture content at fibre saturation point, E_f is the elastic modulus for $u \geq u_f$ (green material) and λE_f is the elastic modulus for $u=0$. It is pointed out that $\lambda=3$ is a typical value for softwood in tension.

3.1.2. The effect of temperature

In most cases, when the temperature increases, the strength and modulus of elasticity consistent with a given moisture content of timber will decrease. However, according to Siimes' results in states of low moisture content the temperatures have little influence on the tensile strength, but the compression strength and the modulus of elasticity will decrease with increasing temperature over the whole moisture content range.

When the moisture content equals or exceeds the fibre saturation point, the relative lowering of the investigated characteristics with increasing temperature is to a small extent dependent on species and density (Siimes 1967). These relationships can bee seen in table 3.

Species	Pine		"Fin." spruce		Birch	
Density level	Low	High	Low	High	Low	High
Modulus of elast., tension	74 %	79 %	68 %	72 %	68 %	68 %
Tensile strength	43 %	41 %	40 %	38 %	47 %	49 %
Modulus of elast., compression	65 %	58 %	50 %	55 %	66 %	72 %
Compression strength	47 %	52 %	50 %	41 %	49 %	50 %

Table 3. Relative reduction in different elasticity and strength characteristics when the temperature is raised from 20 °C to 80 °C for wet wood of pine, "Finnish" spruce and birch (Siimes 1967).

Siimes (1967) has also investigated the influence of the heating time on the strength and elasticity characteristics by placing test specimens with uniform moisture content in temperatures of 40 °C, 60 °C and 80 °C in air with a relative humidity consistent with the moisture content of the timber, for a period of 4 hours, 20 hours, 44 hours or 92 hours.

It was found that heating periods varying in the range of 4 hours to 92 hours do not have any influence on the investigated strength characteristics. Siimes (1967) refers to other investigations were an effect of heating time on the strength properties is found, but it is concluded that this effect occurred after a considerably longer heating period than 92 hours.

3.1.3. Comparison between moduli of elasticity

The relationship between the moduli of elasticity in tension and compression can be seen from table 1 and 2. As an example Siimes (1967) has considered medium density pine at 20 °C and 80 °C in tangential direction. The values are highest for tension tests. The difference between the modulus of elasticity in tension and in compression decreases when the timber approaches the wet state. The difference is highest in the range of 8-16 % moisture content. Siimes (1967) says that similar observations can also be made at temperatures of 40 °C and 60 °C and, likewise, with respect to "Finnish" spruce and birch as well. It is pointed out that the modulus of elasticity in the compression test was only about 75-90 % of the corresponding values found in tension tests. It is noticed that these results are supported by other investigations.

3.2. Radial direction

Siimes (1967) has also done compression tests in radial direction. Only two temperatures were included, 40 °C and 60 °C. The specified moisture content were 4 %, 12 %, 16 % and wet state. Only two heating times were used, 4 hours and 44 hours. The timber species were only pine and birch.

It is found that the moisture content in principle acts as it does in tangential compression, but it seems that in the direction toward lower moisture contents (4 %) the radial strengths and elasticities would increase, both in pine and in birch, at a somewhat faster rate than the corresponding tangential strengths and elasticities.

Siimes (1967) says that increasing temperature lowers the radial compression strengths by approximately the same amount as the tangential compression strengths are lowered in the range of 40-60 °C, and the lowering of the radial modulus of elasticity surpasses that of the corresponding tangential characteristics. Likewise, it is pointed out that the strength and elasticity values obtained by the two different lengths of heating time, 4 hours and 44 hours, are not essentially different.

It is also found that the ratio between the effect of the direction of the annual ring, radial and tangential direction, are not essentially different at 40 °C and at 60 °C. In pine the effect of the direction of the annual growth ring is less than in birch. The radial compression strengths of light pine timber are 20 % higher than those in tangential direction, while in heavy pine timber the former are 20 % lower than the latter. The moduli of elasticity for compression in radial direction surpasses those in tangential direction by about 70 % and by about 10 % on the average, in light pine and heavy pine, respectively. The compression strengths of birch are about 60 % higher in radial than in tangential direction. Its moduli of elasticity for compression in radial direction exceeds those in tangential direction by about 120 %.

4. Visco-elastic theory

Wood also exhibits time dependent behaviour such as creep and relaxation when it is loaded. At this point it is natural to define a new expression, “rheology”. Rheology is the study of the time-dependent stress-strain behaviour of materials, and is derived from the Greek word *rheo* which means flow (Bodig & Jayne 1982).

The application of a constant stress to a piece of wood results in a deformation which does not remain constant with time. At the moment when the stress is applied, an initial elastic strain appears. However, over time additional deformations are developing. The magnitude of this additional time-dependent strain depends on a large number of factors such as the magnitude and type of stress, the rate and/or duration of load, moisture content, and temperature.

As an example of the phenomenon it can be mentioned that beams can fail under sustained loads which are less than the ultimate static load.

4.1. Stress-strain diagram

If stress and strain were the only variables involved, the relationship would show no change of form regardless of the rate of deformation (Bodig & Jayne 1982). However, most materials respond differently depending on the time required to complete a mechanical test. As an example, the stress required to stretch a piece of wood to a particular value of strain is greater when the strain rate is increased. In fig. 6 this phenomenon is illustrated.

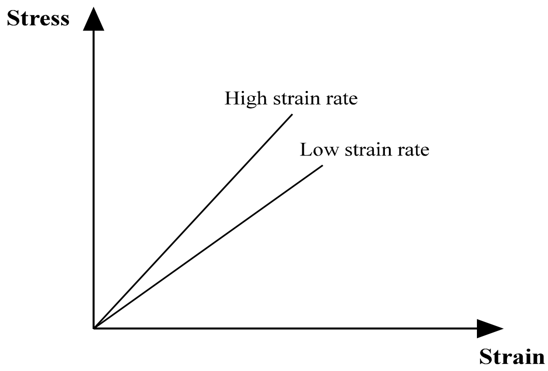

Fig. 6. Effect of rate of strain on the stress-strain relationship.

A material which follows a particular stress-strain path during load application, but does not return to zero when unloaded, is not fully elastic. Wood composites display this type of behaviour almost without exception. Materials with dual stress-strain curves are said to exhibit stress-strain hysteresis (Bodig & Jayne 1982).

The stress-strain relationship depends also of at which rate the stress is applied. In general, increasing time produces a lower ultimate stress as well as a lower proportional limit stress, and, similarly, extending the time of a test allows more strain to develop before failure.

4.2. Creep and relaxation

Creep and relaxation can be defined as follows:

Creep: Time-dependent deformation exhibited by a material under constant load.

Relaxation: A displacement is applied instantaneously and held constant over time. The stress will then subside with time.

The terms “creep” and “relaxation” are highly descriptive of the phenomena involved, the displacement increases or "creeps" with time under constant stress, and the internal resistance stress "relaxes" under constant strain (Bodig & Jayne 1982).

The phenomena of creep and relaxation is illustrated in fig. 7 and 8.

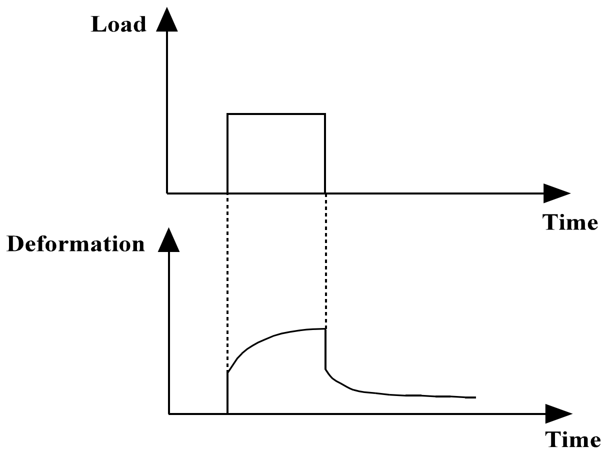

Fig. 7. Creep curve. Load-time function and deformation-time function.

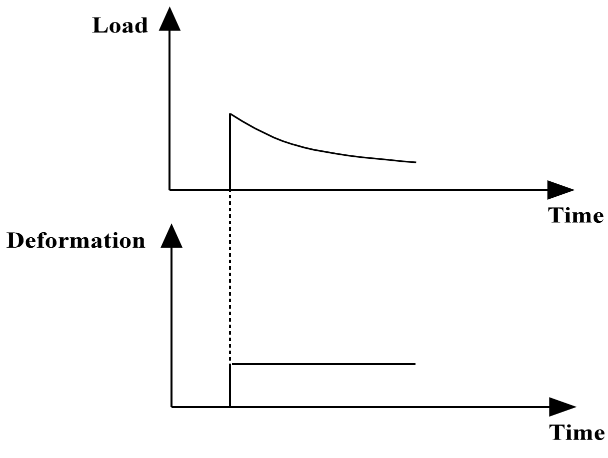

Fig. 8. Relaxation curve. Load-time function and deformation-time function.

If creep causes failure three distinct stages of deformation can be identified: primary, secondary and tertiary. Primary creep includes the region in which the rate of deformation is decreasing, and suggests stress stabilisation. The region for which creep deformation is approximately linear is designated as secondary creep, and is a transitional condition between primary and tertiary creep. Tertiary creep takes place in the region of accelerating deformation, and signifies failure. Not all wood composites will display three stages of creep (Bodig & Jayne 1982). The level, duration, and type of loading applied is highly important.

The total deformation can be treated as the sum of three different components:

– Elastic deformation:	Instantaneous and recoverable
– Delayed elastic deformation:	Time dependent and recoverable
– Viscous deformation:	Permanent and non-recoverable

The different deformation components are illustrated in fig. 9 for a creep process.

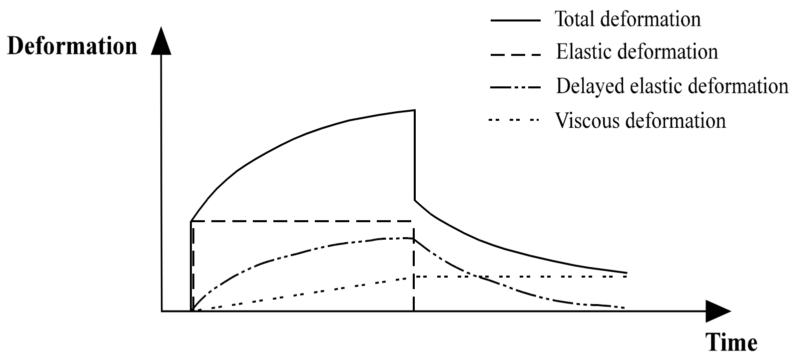

Fig. 9. Components of creep deformation.

During a relaxation process the same deformation components as mentioned above are involved. However, instantaneously the whole deformation is elastic, but when time elapses the part of delayed elastic deformation and viscous deformation are increasing, and the part of elastic deformation is decreasing. The total deformation is constant.

4.3. Models of rheology

Rheological processes in wood are very complicated and have a complex nature, and care must be taken to avoid oversimplification (Bodig & Jayne 1982). However, to compose models which consist of different combinations of springs and shock absorbers, the different phenomena in the rheological processes can be illustrated.

The behaviour of a Hookean spring is described by:

$$P = ku_e \qquad (2)$$

The Hookean spring constant k relates the load P to the elastic deformation u_e.

The force-displacement behaviour of a shock absorber with linear characteristic is given by:

$$P = r\left(\frac{du_v}{dt}\right) \qquad (3)$$

where r is damping constant, u_V is viscous displacement and du_V/dt is rate of displacement.

When combining springs and shock absorbers in different bodies, and by using empirical data for wood composites to decide the values for spring constant and damping constant, mathematical models for the rheological processes in wood can be worked out.

In the following some combinations of springs and shock absorbers which describe creep and relaxation processes in wood are shown.

4.3.1. Creep

Three deformation components must be considered, elastic deformation, delayed elastic deformation and viscous deformation. The elastic and viscous deformation is described by a Maxwell body, which consists of a spring and a shock absorber in series. This is shown in fig. 10.

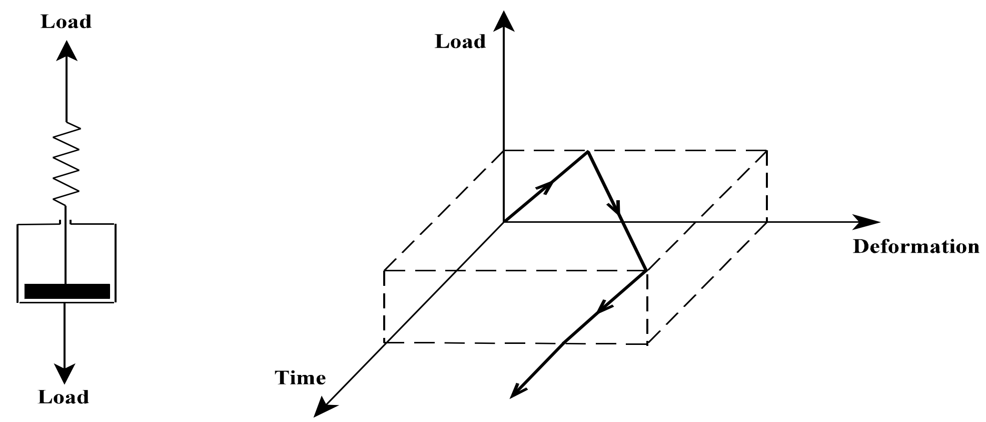

Fig. 10. Load-deformation-time response of a Maxwell body.

The delayed elastic deformation is described by a Kelvin body, which consists of a parallel arrangement of a spring and a shock absorber. This is shown in fig. 11.

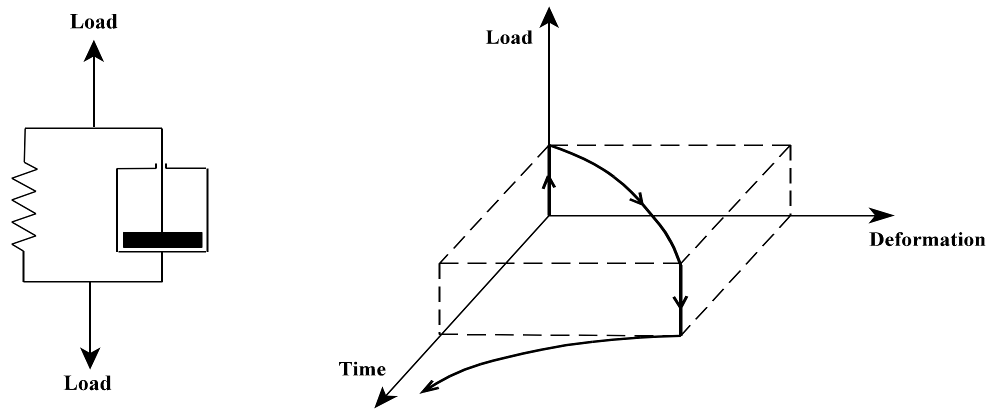

Fig. 11. Load-deformation-time response of a Kelvin body.

The Maxwell body alone can account for the elastic and viscous behaviour and the Kelvin body alone for the delayed elastic behaviour. When combined, these two models represent the principal features of the time-dependent behaviour of wood composites (Bodig & Jayne 1982). This combination can be expressed as a Burger body. This is shown in fig. 12.

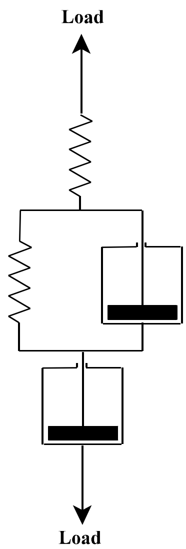

Fig. 12. Burger body.

4.3.2. Relaxation

To illustrate relaxation processes, a single spring can be added to a Maxwell body in a parallel arrangement.

4.4. Creep investigations

Svensson (1995b) has done experiments with specimens of pine. The specimens were loaded in different constant climates over a period. From these results it is concluded that creep evidently depends on both temperature and moisture content, though moisture content is the most dominant variable of the two. Likewise, time plays a role for the amount of creep. It is also found that for the tests in the radial direction the relative creep for a given humidity and temperature was smaller than in the tangential direction.

Several studies of creep behaviour of solid wood has been performed over the years. It is found that the creep and relaxation behaviour is very much influenced by moisture variations in the wood, and that there seems to be an interaction between stress and moisture adsorption or desorption (Morén 1993b). The term "mechano-sorption" is introduced indicating the coupling between stress and sorption. In the following section this term is discussed.

5. Mechano-sorption

As a result of wood drying, internal stress are developed on the micro level in the wood structure. If an external stress is applied during drying, it is natural to infer that the internal stress state is modified and that the relative orientation of shrinkage in different directions is changed (Thelandersson & Morén 1992).

Creep behaviour of wood during drying appears to depend on temperature level, stress and the moisture content variation. The mechano-sorptive creep observed for wood indicates the existence of a set condition characterised by a coupling between the moisture change and externally imposed or drying induced stress (Morén & Sehlstedt-Persson 1993).

Thelandersson & Morén (1992) refer to investigations where it is found that shrinkage in the tangential, loading, direction is inhibited by the applied stress, and that in the radial direction, perpendicular to the loading direction, shrinkage increases linearly with the stress level. It is pointed out that the presence of external tensile stress causes a reorientation of shrinkage from the loading direction to the transversal direction, but this reorientation is not complete, however, since the tensile stress also to some extent inhibits volume shrinkage. It is also mentioned that an analogous response is obtained when the stress is applied in the radial direction, and that compressive stress during drying also will alter the response so that shrinkage is enhanced in the loading direction and inhibited in the transversal direction.

The phenomenon described here as an effect of stress on shrinkage is commonly referred to as mechano-sorption, i.e. an interaction between mechanical loading and moisture induced strains (Thelandersson & Morén 1992).

Thelandersson & Morén (1992) say that mechano-sorption is by far the most significant effect to be considered in any prediction and analysis of drying stress and cracking in timber, and that ordinary creep effects, i.e. delayed response from an applied stress, are usually considerably smaller than the mechano-sorptive effects.

Grossman (1976) says that among the least understood manifestations of the behaviour of wood is the interaction of moisture change with mechanical loading or restraint. Further it is pointed out that the term "mechano-sorptive effect" has been coined to convey succinctly that mechanical influences combine with moisture sorption to produce a response that cannot be predicted from the response to each influence separately. To illustrate the effect, Grossman (1976) is using the following examples:

> The deflection of a loaded beam that is taken through one or more cycles of humidity increases far beyond the deflection of loaded beams which have been conditioned to either of the extreme moisture contents, but are not going through the cycles of humidity during the loading period.
>
> When a rigid restraint prevents swelling of a block of wood as it absorbs moisture, the final pressure required to keep it within its original dimensions is an order of magnitude lower than the pressure required to compress it after it has been allowed to swell freely.
>
> Timber that tends to distort during drying because of spiral grain, growth stress, reaction wood or other variants in characteristics can be kept straighter by the application of loads to the stacks while drying takes place.

5.1. Mechano-sorptive characteristics

Grossman (1976) says that a model that interprets the mechano-sorptive effects satisfactorily in terms of botanical or molecular structure of wood must be compatible, at least qualitatively, with all experimental findings. In the following, it is referred to Grossman (1976) who has listed up different relationships which are the most important in this connection.

> Whereas visco-elastic creep depends on the duration of loading, mechano-sorptive deformation at constant stress is not directly dependent on time.

The deformation retained in wood after load removal normally increases with any change of moisture content, whatever its direction, during the loading period.

A large part of the deformation retained after load removal is at least recoverable when the unloaded wood is taken through another moisture cycle.

A continuous movement of water molecules through the material without any local change in concentration does not produce mechano-sorptive deformation.

Mechano-sorptive deformation does not occur without swelling or shrinkage.

The effect is of different magnitude for the different grain directions and modes of loading.

The increase in deformation due to a given moisture step is smaller when this step is preceded by another step in the same direction. The first complete cycle of moisture content produces a larger deflection than later cycles except when the beam approaches failure.

Repeated moisture cycling, even at moderate loads, leads to structural damage and maybe to failure. The strains prior to failure are very high, much higher than maximum strains recorded in short-term tests.

There seem to be no qualitative differences between species. The main effect seems to be due to features on a level of fine structure common to all wood.

The mechano-sorptive effect has been observed in hardboard and in particle board, and is even more pronounced in these materials than in solid wood.

Related phenomena have been observed in wool and other textiles and also in concrete.

Analogous effects have been reported when temperature was changed and the moisture content kept constant.

5.2. Mechano-sorptive material parameters

The mechano-sorptive parameter is larger in the tangential than in the radial direction (Thelandersson & Morén 1992). It is pointed out that from different investigations there is no evidence of correlation between the coefficient of mechano-sorption in the tangential direction and the density of different species.

Thelandersson & Morén (1992) say further that in the case of kiln drying, it is of great interest to know material parameters at higher temperatures as well. It is referred to different investigations where it is found that the mechano-sorptive parameter in the tangential direction increases with temperature in the interval 20-80 °C. However, the effect is rather limited up to 40 °C, but at 80 °C the value is doubled compared with the value at 20 °C.

It is underlined that the results presented above mostly originate from tests on hardwood species, and that to our knowledge very few tests have been published for European or North-American softwoods. More systematic information is lacking on European softwoods.

However, Svensson (1995a) has done experiments with drying of loaded and unloaded specimens of pine. It is pointed out that it is obvious that the difference in shrinkage between the loaded and the unloaded specimens cannot be explained to any extent by pure elastic theory. Svensson (1995a) say further that the influence of simultaneous desorption and mechanical loading (mechano-sorptive effect) is significantly smaller for this species than for most other species, and that this means that pine should be more prone to checking than other comparable species. This is also in accordance with practical experience.

In connection with the same experiment as in the section above, it is found that the rate of mechano-sorptive strain is approximately independent on the stress history, i.e. at the time when the stress was applied. Likewise, it is mentioned that the mechano-sorptive strain rate late in the drying seems to be the same whether or not there has been a wetting cycle earlier in the drying process. It is concluded that it is evident from the results that the interaction between shrinkage and mechanical stress (mechano-sorption) is a very important element for the constitutive relations of wood.

Mårtensson & Svensson (1995) have investigated the mechano-sorptive strain during constant load tests of specimens of pine. It is found that during desorption periods, the mechano-sorptive strain rate is highest in the beginning of the process and decreases during drying. During wetting the result is not that clear, however, during the whole wetting period some increase in mechano-sorptive strain occurs. Likewise, it is pointed out that tests have shown that the higher the stress level the larger the mechano-sorptive strain rate.

After their investigations, Mårtensson & Svensson (1995) are concluding as follows:

> The mechano-sorptive effect is largest at 60 °C and smaller at 20 °C and 80 °C for the tested pine in the tangential direction, while the effect increases with decreasing temperature in the radial direction.

> The few test results that exist for shear indicate that mechano-sorption is larger in that mode compared with pure tension in radial and tangential direction.
>
> To evaluate the mechano-sorptive behaviour which is of interest in studies of wood drying, both restraint and constant load tests are necessary.

Molinski & Raczkowski (1988) have investigated the mechano-sorptive behaviour for beech in tension during adsorption. It is found that the value for the mechano-sorptive parameter for adsorption in the radial direction is of the same order as that for desorption.

6. Shrinkage, strain, stress and checking

In the above sections, different phenomena in connection with wood drying are considered. However, in a real wood drying situation the relations are very complex, and many factors have to be considered at the same time. In this section different theories and models are referred to which account for some of the effects in wood drying.

6.1. Shrinkage

The shrinkage potential is different in the radial, tangential and longitudinal direction in wood. Roughly one can say that the shrinkage is twice as large in tangential direction as in radial direction. The shrinkage is approximately a linear function of the changes in the moisture content in wood.

Svensson (1995b) says that the free shrinkage of unloaded specimens depends strongly on temperature, and higher temperature tends to give lower shrinkage. For the radial specimens of pine, drying at 80 °C gave the lowest shrinkage, and drying at 20 °C gave the highest shrinkage. In the tangential direction, drying at 60 °C gave the highest shrinkage, while drying at both 20 °C and 80 °C gave lower shrinkage.

6.2. Strain

Morén (1993a) has done experiments to study restrained uniaxial shrinkage in the tangential direction when the wood dried. This situation can be compared with the situation in the outer layer of a plank under the first phase of the drying process. The strain at failure for the species was determined, and it was found that the regression equations for strain at failure, ε_f, representing the best model are:

Pine: $$\varepsilon_f = \frac{1{,}078 - 0{,}8267u - 0{,}000839\rho + 0{,}0753uT}{100} \qquad r^2=0{,}88 \qquad (4)$$

Spruce: $$\varepsilon_f = \frac{0{,}609 + 0{,}00395T + 0{,}0616uT}{100} \qquad r^2=0{,}79 \qquad (5)$$

Birch: $$\varepsilon_f = \frac{2{,}570 + 0{,}840u - 0{,}00232\rho + 0{,}111uT}{100} \qquad r^2=0{,}93 \qquad (6)$$

u is moisture content, ρ is density in kg/m^3, T is temperature in °C and r^2 is the coefficient of determination.

Morén (1993a) says that it can be noticed that pine, the species reaching the highest tension stress during the drying experiment, has the lowest strain at failure approximately 0,8 % at 47 °C. For spruce and birch the corresponding strain values are 1,0 % and 1,4 %. It is also found that apparently there exists a negative correlation between maximum stress level and strain at failure for these species, and it is concluded that the susceptibility of checking is correlated to the strain at failure value.

It is concluded that the most important single variable that explains creep, was the change in moisture content at the range below the fibre saturation point, and that this supports the idea of a significant mechano-sorptive creep phenomenon acting across the grain during drying. It is pointed out that this creep behaviour is of fundamental importance for the possibility of drying timber without checking when using hot air in a kiln.

Rice & Youngs (1990) have studied mechano-sorptive creep in the tangential direction perpendicular to the grain when drying red oak. The conclusion is that mechano-sorptive creep is the major strain early in the drying process, and that the magnitude of this creep is a linear function of moisture content. The time dependent visco-elastic creep component was small and a function of the applied load, overall less than 1/20 of the value of the mechano-sorptive creep strain.

Morén (1993b) has studied restrained uniaxial shrinkage when drying specimens made from pine and spruce. When the models are worked out, the time-dependent visco-elastic creep is neglected, and then the total strain, ε, is the sum of pure elastic strain, ε_e, free shrinkage strain, ε_s, and mechano-sorptive strain, ε_m:

$$\dot{\varepsilon} = \dot{\varepsilon}_e + \dot{\varepsilon}_s + \dot{\varepsilon}_m \qquad (7)$$

The dot is derivative according to time.

Svensson (1995b) has measured strain during drying at 60 °C for specimens loaded during drying with a stress level of 0,8 MPa, and the total strain, ε, is assumed to consist of the following additive components:

$$\varepsilon = -s + \varepsilon_e + \varepsilon_c + \varepsilon_m \quad (8)$$

where s is the free shrinkage, ε_e the elastic strain, ε_c the creep, and ε_m the mechano-sorptive strain.

Mårtensson & Svensson (1995) have done experiments with loaded and restrained specimens during drying. The general strain rate formulation during moisture changes is formulated as:

$$\frac{d\varepsilon}{dt} = \frac{d\varepsilon_e}{dt} + \frac{d\varepsilon_s}{dt} + \frac{d\varepsilon_m}{dt} + \frac{d\varepsilon_c}{dt} \quad (9)$$

where ε is the total strain, ε_e is the elastic strain, ε_s is the free shrinkage, ε_m is the mechano-sorptive strain, ε_c is the creep strain and t is time.

Morén & Sehlstedt-Persson (1993) have studied the surface opposite to the pith side on sawn timber during a drying process. It is found that the mechano-sorptive creep response across the grain develops rapidly in all cases, as the moisture content of the surface lamella decreases below fibre saturation point. At the same time the tension increases to levels of approximately 1 MPa. The creep level varied between 1 % and 2 % when the wood was dried to about 10 % moisture content, with the lowest value at the lowest temperature. After the initial period characterised by the rapid decrease of moisture content at the surface, the creep remained at a fairly constant level.

It is pointed out that from the comparison of the different surface types it is evident that the presence of heartwood results in a quicker creep development and also to a somewhat higher level. This is explained by the initially lower moisture content of the heartwood portions of the surface lamella, causing the almost immediate tension development at the beginning of the drying.

6.3. Stress

6.3.1. Stress models

The sapwood side of a board is the most interesting to study in the drying of sawn timber, because here is the proportion of tangential shrinkage much larger than on the other sides. To simulate the tension stress conditions in the outer layer of the sawn timber during the first phase of the drying process, one can study the stress development when specimens of wood are prevented from shrinkage.

In order to study restrained uniaxial shrinkage, Morén (1993b) made specimens from pine and spruce, and to measure the drying-induced stress one specimen was restrained from shrinkage in tangential direction during drying. A matched specimen from the same board adjacent to the restrained one was used to determine the free shrinkage and the moisture content. Experiments were performed at temperatures ranging from 26 °C to 48 °C, and relative air humidity ranging from 25 % to 45 %.

In the case of restrained drying, the net strain is ideally identical to zero. Morén (1993b) says that it is assumed that the mechano-sorptive strain is now independent of time, and that the stress for $u<u_f$ can be calculated:

$$\sigma = E\left(\frac{u-u_f}{u_f}s + \Delta\varepsilon_m\right)\frac{|\dot{u}|}{\dot{u}} \tag{10}$$

where E is the modulus of elasticity, u is the moisture content, u_f is the moisture content at fibre saturation point, s is the total shrinkage from green to oven dry condition and $\Delta\varepsilon_m$ is the mechano-sorptive strain. Dot is derivative according to time.

The mechano-sorptive effect is reduced to simply a reduction of the free shrinkage by a factor k, and this gives the final equation:

$$\sigma = E\left(\frac{u-u_f}{u_f}(1-k)s\right)\frac{|\dot{u}|}{\dot{u}} \tag{11}$$

The proposed approach to mechano-sorptive behaviour during drying indicates that the mechano-sorptive creep can be seen simply as a reduction of the shrinkage coefficient of an unrestrained specimen when drying itself is causing the stress of a restrained specimen (Morén 1993b). It is also concluded that mechano-sorptive creep is a major effect that needs to be accounted for in explaining the behaviour of restrained shrinkage during wood drying.

Thelandersson & Morén (1992) give a constitutive relation for wood under moisture changes where the total strain rate is assumed to be given as the sum of three separate parts, one elastic part, one corresponding to free moisture induced strain and one part describing mechano-sorptive strain. It is assumed that time-dependent strains can be neglected. This is supported by tests showing that the response to drying under stress is nearly independent of the rate of drying.

Regarding drying of timber it is feasible to consider the special case of generalized plane strain. A plane idealisation of drying timber is neither pure plane strain nor pure plane stress, but the coupling effects between the axial direction and the other directions are generally small and may therefore be neglected (Thelandersson & Morén 1992). Mårtensson & Svensson (1995) say that in the most general case it is necessary to have a three-dimensional formulation to be able to describe the behaviour of drying timber, but such a formulation will be rather complex. It is pointed out that for studies of a board cross-section a two-dimensional formulation will be sufficient, and the effects in the longitudinal direction and the coupling effects between this direction and the tangential and radial directions may therefore be neglected.

In the special case of uniaxial stress, Thelandersson & Morén (1992) express the strain as follows:

$$\dot{\varepsilon}_\beta = \frac{\dot{\sigma}_\beta}{E_\beta} + s_\beta \dot{u} + m_\beta \sigma_\beta |\dot{u}| \tag{12}$$

ε is strain, E is modulus of elasticity, σ is stress, s shrinkage coefficient, m is mechano-sorptive material coefficient and u is moisture content. Dot is derivative according to time. $\beta=t$ for the tangential direction, and $\beta=r$ for the radial direction. In general, the elastic coefficients E_β, the shrinkage coefficient s_β, as well as the mechano-sorptive material parameters m_β are functions of the moisture content u.

Thelandersson & Morén (1992) say that this constitutive model is fairly simple, but seems to describe the material behaviour in a reasonably accurate manner, and that the agreement between theory in the model and tests is excellent.

The same authors have continued to work out a model for the restrained stress when drying under complete uniaxial restraint in the tangential direction (initial condition $\sigma(0)=\sigma_0$).

$$\sigma(\bar{u}) = \frac{s}{m} + \left(\sigma_0 - \frac{s}{m}\right) \exp\left\{-mE_f\bar{u}\left[1 + 1/2(\lambda - 1)\frac{\bar{u}}{u_f}\right]\right\} \tag{13}$$

where σ is stress, u is moisture content $(\bar{u}=u_f-u)$, index f indicates fibre saturation point, index 0 indicates start value, s is shrinkage coefficient, m is mechano-sorptive material coefficient, E_f is elastic modulus for $u \geq u_f$ and λE_f is elastic modulus for $u=0$.

In this model it assumed that s and m are independent of moisture content, while E is assumed to depend on moisture content according to formula (1).

For the special case $\sigma_0=0$, the restraint stress $\sigma(\bar{u})$ approaches the value s/m asymptotically, and the rate at which this occurs depends on the dimensionless quantity mE_fu_f. For most species mE_fu_f is in the interval 5-20, which means that the asymptotic value s/m is reached already when $u=1/2u_f$ or earlier (Thelandersson & Morén 1992).

Thelandersson & Morén (1992) say that time-dependent effects may be considered approximately by a reduction of the elastic modulus, and the consequence of this is that the asymptotic value is attained later in the drying process, but the maximum stress is not affected by such a reduction.

The ratio *s/m* is called the drying stress limit, and a high value of *s/m* means that large drying stresses can be developed in the material.

Thelandersson & Morén (1992) conclude that it is clear that the simulation gives a fairly good description of the behaviour in comparison with different tests, but the asymptotic behaviour predicted by the theory, is not quite clear from the tests. They say further that although the predicted maximum stress in this case is nearly the same as the measured one, there is no evidence from the test that a drying stress limit exists.

Ranta-Maunus (1992) has used a new test method to measure the stress development in the wood during drying. The basic idea of this test is to place a circular ring made of green wood which follows the annual rings as closely as possible around a metal ring which prevents the shrinkage of wood during drying. The force in the metal ring was measured. The force is directly related to the stress in the wood, and the stress can be determined as a function of time. The test rings were made of green pine. Tests at 40 °C were made in a room where the relative humidity was controlled (70-80 %). Tests at 60 °C were made in a small chamber (1 m^3) in which the moisture content was regulated in order to obtain a cyclical stress history.

It was found that at 40 °C, the lowest ultimate stress was 0,55 MPa (43 °C, density 490 kg/m^3 at 12 % moisture content), and the highest 2,79 MPa (37 °C, density 530 kg/m^3 at 12 % moisture content). At 60 °C, the lowest ultimate stress found was 1,67 MPa (density 470 kg/m^3 at 12 % moisture content), and the highest 1,97 MPa (density 460 kg/m^3 at 12 % moisture content).

Ranta-Maunus (1992) has in his work determined a reliable creep model for wood when applied to the analysis of drying stress of sawn timber. It is pointed out that in many models the visco-elastic creep is neglected in order to simplify the stress analysis. The argument for this is that the mechano-sorptive creep has a much greater influence on the stress development than the visco-elastic creep. However, he says that in different investigations the models do not fit very well to the experiments, and therefore he has in his work included a visco-elastic creep function in the stress model.

6.3.2. Factors which influence the stress level

The stress development in drying wood decreases when the temperature level increases. Svensson (1995b) says that at temperatures around 20 °C, the stress level in a restrained test of pine becomes so large that failure often occurs, but at higher temperatures the risk of failure is lower. However, also the ultimate strength in wood decreases with increasing temperature, and therefore the relationship between ultimate tension strength and drying stress limit will not necessarily be greater.

Also the density level is influencing the stress development when considering one species. Morén (1993b) says that simulations as well as experiments indicate that the level of stress given a drying rate is higher for higher wood density. Between different species this is not so clear. In some cases the drying stress will probably be lower in a species with high density than in one with low density.

Morén (1993a) noticed a fairly big difference between pine, spruce and birch in the stress behaviour. Pine appears to be the most stress disposed species among them under the present conditions.

Likewise, the shrinkage behaviour has an effect on the stress development. The level of stress given a drying rate is higher for higher shrinkage coefficient. Svensson (1995b) has dried partially constrained specimens at constant temperature in tangential direction. The results indicate that the stress is not a linear function of shrinkage for constrained specimens, instead the rate of stress is increasing with shrinkage.

Svensson (1995b) has also investigated the effect of wetting cycles during drying of restrained wood specimens. It is found that the magnitude of the shrinkage stress at the end of the drying process seems to be rather unaffected by a wetting cycle earlier in the process.

6.3.3. Conditioning

Conditioning is a way of relaxing residual stress after the drying period, and is most important to carry out for sawn timber which is splitted before use. The conditioning process is carried out by increasing the relative air humidity, and probably the temperature surrounding the sawn timber. The outer layer will then try to swell, but the compression stress does not allow this, and the result is that the outer layer is compressed. Morén (1993a) refers to experiments on pine where the magnitude of the creep strain was 2,5 % after drying, but decreased at the end when the moisture content of the surface increased during conditioning. It is also noticed that this creep reversal to some extent relaxed the stress, although not completely. The results show further that the effectiveness of the conditioning treatment was improved by increasing the temperature from 40 °C to 60 °C. It is pointed out that at 40 °C it was not possible to relax the residual stress at all for industrial applications within reasonable time, where normally maximum two days are used for conditioning.

6.4. Checking

The probability of cracking is related to the ratio between the predicted drying stress and the tensile strength of the material, and it is necessary to consider how the tensile strength depends on both moisture content and temperature.

If wood behaved as a linear elastic body during air drying, most boards would check in most drying schedules used today (Morén 1993a). This is fortunately not the case, since wood responds to drying stress by creeping. However, some checks will still develope during the wood drying process.

Surface checking occurs on the flat side of a board opposite to the pith. This can be explained by that at this area the local shrinkage is at maximum (tangential direction) and here the wood rays run perpendicular to the surface as a weakening structure of the wood.

The effect of moisture gradients caused by drying with air flow as in kiln drying is an important phenomenon. As mentioned in earlier sections, moisture gradients cause the outer layer of a board's cross section to shrink more than the inner part, which creates stress. Siimes (1967) says that checking appears to start already at the stage of drying when the average moisture content of the boards is still 40 %, and that the first checks have been found to appear when the average moisture content of the board or batten is still well above 30 %. Further it is mentioned that when the average moisture content of the charge has gone down to 30-40 %, already half of the checks are present, but when the average moisture content comes close to 20 %, the growth of the checks becomes smaller.

Thelandersson & Morén (1992) say that the ratio between the drying stress limit and the tensile strength may be seen as a measure of the drying crack liability, and this ratio is highest in the tangential direction since the radial and tangential drying stress limit is of the same order of magnitude and the tensile strength is generally higher in the radial direction.

Morén (1993a) says that low temperature and/or high density makes wood susceptible to checking, and that in fact a similar relation can be found for strain at failure: Low temperature, high density, at least for pine (and low moisture content) give low strain levels. It is concluded that this appears to be a fundamental property for solid wood. Siimes (1967) has found that the checking of heavy timber was considerably greater in amount than that of light timber.

7. Need for research

Variation of elastic moduli and strength parameters with moisture content and temperature must be taken into account in analyses of drying stress and crack predictions (Thelandersson & Morén 1992). In this connection it is of great importance to have values for strength and elasticity both for tension and compression in direction perpendicular to the grain. Some work has been done in this field, but further investigations are necessary to get a satisfactory survey for the species in the Nordic part of Europe, both hardwood and softwood species. The effect of temperature, moisture content, heating time and wood density have to be considered in this connection.

Thelandersson & Morén (1992) say that the experimental data base for mechano-sorption for structural softwoods commonly used in Europe and North-America is very incomplete, and further experimental research is highly needed to improve our knowledge about these species. It is emphasized that very few tests have been published for European or North-American softwoods.

Most studies of mechano-sorptive creep have been carried out for load in the longitudinal direction of boards, and less effort has been made to explain the creep response across the grain resulting in the described case-hardening or drying set problems in timber drying (Morén & Sehlstedt-Persson 1993). The same authors are concluding that a constitutive equation capable of fully predicting mechano-sorptive creep during drying needs further investigations, and factors such as temperature, grain angle and wood density should be included in such a model.

References

Bodig, J. & B. A. Jayne. 1982. Mechanics of Wood and Wood Composites. Van Nostrand Reinhold Company Inc. United States of America.

Grossman, P. U. A. 1976. Requirements for a Model that Exhibits Mechano-Sorptive Behaviour. Wood Science and Technology 10: *163-168*.

Molinski, W. & J. Raczkowski. 1988. Mechanical stress generated by water adsorption in wood and their determination by tension creep measurements. Wood Science and Technology 22: *193-198*.

Morén, T. 1993a. Creep, Deformation and Moisture Redistribution During Air Convective Wood Drying and Conditioning. Doctoral Thesis 1993:116D. Department of Wood Technology, Skellefteå Campus, Luleå University of Technology, Sweden.

Morén, T. 1993b. Creep, Deformation and Moisture Redistribution During Air Convective Wood Drying and Conditioning. Mechano-sorptive creep during drying. Doctoral Thesis 1993:116D. Department of Wood Technology, Skellefteå Campus, Luleå University of Technology, Sweden.

Morén, T. & S. M. B. Sehlstedt-Persson. 1993. Creep, Deformation and Moisture Redistribution During Air Convective Wood Drying and Conditioning. Creep Response to Drying of Timber Boards of Scots Pine. Doctoral Thesis 1993:116D. Department of Wood Technology, Skellefteå Campus, Luleå University of Technology, Sweden.

Mårtensson, A. & S. Svensson. 1995. Hygro-Mechanical Behaviour of Drying Wood. Stress-strain relationship of drying wood. Licentiate thesis. Report TVBK-1010. Lund Institute of Technology, Department of Structural Engineering, Lund, Sweden.

Ranta-Maunus, A. 1992. Determination of drying stresses in wood when shrinkage is prevented: Test method and modelling. 3RD IUFRO International Wood Drying Conference, August 18-21, 1992, BOKU, Vienna, Austria: *139-144*. Editor: Manfred Vanek.

Rice, R. W. & R. L. Youngs. 1990. The mechanism and development of creep during drying of red oak. Holz als Roh- und Werkstoff 48: *73-79*.

Scniewind, A. P. 1960. On the nature of drying stresses in wood. Holzforschung 14(6): *161-168*.

Siimes, F. E. 1967. The effect of specific gravity, moisture content, temperature and heating time on the tension and compression strength and elasticity properties perpendicular to the grain of finnish pine spruce and birch wood and the significance of these factors on the checking of timber at kiln drying. The State Institute for Technical Research. Helsinki, Finland.

Svensson, S. 1995a. Hygro-Mechanical Behaviour of Drying Wood. Strain and Shrinkage Force in Wood under Kiln Drying Conditions. I: Measuring Strain and Shrinkage under Controlled Climate Conditions. Equipment and Primary Results. Licentiate thesis. Report TVBK-1010. Lund Institute of Technology, Department of Structural Engineering, Lund, Sweden.

Svensson, S. 1995b. Hygro-Mechanical Behaviour of Drying Wood. Strain and Shrinkage Force in Wood under Kiln Drying Conditions. II: Strain, Shrinkage and Stress Measurements under Controlled Climate Conditions. Licentiate thesis. Report TVBK-1010. Lund Institute of Technology, Department of Structural Engineering, Lund, Sweden.

Thelandersson, S. & T. Morén. 1992. Tensile stresses and cracking in drying timber. Report TVBK-92/3029. Lund Institute of Technology, Department of Structural Engineering, Lund, Sweden.