

Wood fibre deformation in combined shear and compression

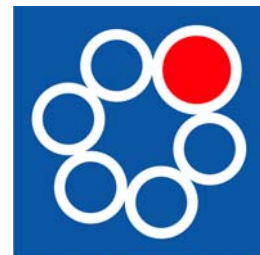
Federica De Magistris

Supervisors: Associate Professor Lennart Salmén
Professor Anders Eriksson

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I wanted to outline the boundary of an island
but what I discovered at the end
was the boundaries of the ocean.

Wood fibre deformation in combined shear and compression

Federica De Magistris, KTH, Department of Mechanics, Stockholm, Sweden

Abstract

Mechanical pulping for producing pulps from softwood suitable for printing grade papers, like news, is a highly energy-intensive process consuming around 2000 kWh/t in electrical energy. Due to increasing energy costs and environmental issues there is a high demand for decreasing this energy consumption. The mechanical treatment of wet wood pieces in a refiner, in the mechanical pulp plant, is a complex mechanical loading. This is a process occurring between rotating discs at high speed and temperatures of 140 °C - 160 °C, where by means of shear and compression forces the fibres are separated and then made flexible, fibrillated and collapsed for good bonding ability. In this process also fines are created giving the optical properties of the paper. In mechanical pulping only a fraction of the applied energy is used for the structural changes of the wood material. Thus fundamental studies of the loading modes of wood under refining conditions and in particular under combined shear and compression loading are desired to gain more information regarding the possibility of affecting the mechanical pulping in an energy efficient way.

The possibilities to study the behaviour of wood under a combined shear and compression load were in this thesis investigated using two methods: the Iosipescu shear test and the Arcan shear test. In both apparatus different combinations of shear and compression load were achieved by different rotations of the shear test device itself. Measurements with the Iosipescu device on a medium density fibreboard showed good agreement between experimental results and numerical simulations. Finite element analysis on wood showed, however, that with the use of a homogeneous material in the model the level of strain reached would be ten times smaller than experimentally measured. This fact is probably due to the honeycomb structure of the wood cells that allows for different local deformations that could not be represented by a continuous material model. Thus to study the deformations on the fibre level of wood an experimental equipment that uses smaller samples was needed.

With a modified Arcan shear device such deformations under combined shear and compression load and in pure compression were possible showing different deformation patterns. During pure compression the cell walls bend in a characteristic “S” shape, independently of the shape of the fibre cells and their cell wall thickness. Under combined shear and compression, however, mainly the corners of the fibre cells deform giving a “brick” shape to the cells. In a second deformation performed in compression, the fibre cells follow the same deformation pattern as given by the first deformation type whether in compression or in combined shear and compression. The interpretation is that permanent defects in the cells themselves are introduced already in the first load cycle of the wood samples.

The energy used under the different loading conditions showed that the first deformation required the largest amount of energy, for all loading conditions. The deformation in compression required larger amounts of energy than the deformation in combined loads. For subsequent deformations less energy was needed for compression if a combined load had preceded it. Due to the fact that less energy is needed to start to deform wood in combined load than under compression load, the application of a combined load as a first cycle may thus be a way to permanently deform fibres using less energy.

To investigate the critical parameters determining the permanent deformation of cells, a finite element model of a network of twelve cells was developed. Special care was given to the material properties to study how the variation of the fibril angle in the different layers affects the deformation pattern of the wood fibres under the different loading conditions. The model shows that whether modelled as homogeneous linear isotropic material or as an orthotropic material defined for every layer of the cells wall, no difference in the deformation of the network of the fibres was achieved. It is probable that the deformation type is more determined by the geometry of the fibres themselves than by their material properties.

Keywords: Arcan, compression, density, energy, finite element analysis, Iosipescu, Picea abies, shear, wood.

List of publications

This thesis is based on the following five papers, herein referred to by their Roman numerals:

- I. **Combined shear and compression analysis using the losipescu device: analytical and experimental studies of medium density fiberboard**
De Magistris F. and Salmén L.
Wood Science and Technology (2004) Vol. 37, No 6, p. 509-521
- II. **Combined shear and compression analysis using a modified losipescu shear test device. Experimental studies on dry wood**
De Magistris F. and Salmén L.
Holzforschung (2005) Vol. 59, No 5, p. 539-545
- III. **Deformation of wet wood under combined shear and compression**
De Magistris F. and Salmén L.
Wood Science and Technology (2005) Vol. 39, No 5
- IV. **Mechanical behaviour of wet wood in sequences of compression and combined compression and shear**
De Magistris F. and Salmén L.
Submitted for publication to Nordic Pulp and Paper Research Journal
- V. **Finite Element Modelling of wood cell deformation transverse to the fibre axis**
De Magistris F. and Salmén L.
Submitted for publication to Composites Science and Technology

Other relevant publications

Deformation of fungi-treated wet wood under combined shear and compression.

De Magistris F., Salmén L., Hinterstoisser B., Gradinger C. and Messner K.
Submitted for publication to Journal of Biotechnology

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1. INTRODUCTION

1.1 Background

One of the main industries in Sweden is the wood, pulp and paper industry, which supplies the Swedish economy with the largest net income. For production of paper wood pulp fibres are the main raw material of which the resources in Sweden are vast. The use of paper has, contrary to expectations, increased in the last years instead of diminishing with the increased use of computers. The consumption of paper has increased both in quantity as well as in quality demands. At the same time the awareness of the environmental demands have increased and an increased concern exists regarding available renewable resources and the overall global energy consumption. Here the pulp and paper industry faces several problems such as the energy consumed in mechanical pulp production, the usage of the wood raw material as well as the environmental effects of chemicals used.

1.2 Mechanical pulping

To make paper out of wood fibres these have to be separated from each other and then to be treated to develop good flexibility and bonding ability. There are two ways of doing this: either using chemicals or a mechanical process. In chemical pulping the lignin, the component holding fibres together is broken down and dissolved together with some of the other components leaving only around 50 % of the original mass for use as fibres in the papermaking pulp. In mechanical pulping, the fibres are separated by mechanical processes: refining or grinding. In the mechanical pulping the whole wood fibre, with its three main polymer components: lignin, cellulose and hemicellulose, is nearly fully maintained.

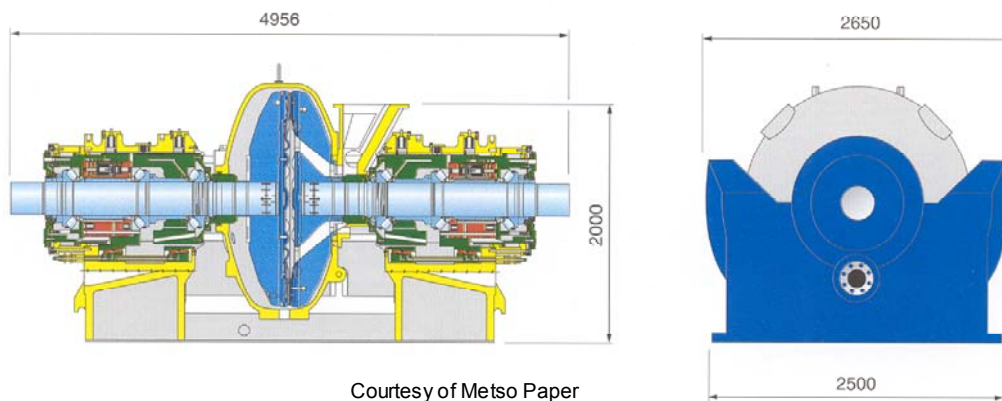


Figure 1 Illustration of a disc refiner for the mechanical pulping process. Dimensions are in mm.

The objective in mechanical pulping is to separate and collapse a good part of the wood fibres to have enough fibres with good ability to bond as well as producing a fine material with good optical properties. In the mechanical refining process, which is more common than the grinding of logs, this is done on wet wood chips (usually Norway spruce) that are repeatedly beaten under high temperature (140 °C - 160 °C), thermomechanical pulping (TMP). **Figure**

1 shows a schematic drawing of a double disc refiner, a typical equipment used for this purpose (Sundholm 1999).

In a refiner wet wood pieces are fed into the middle between high speed rotating discs. The centrifugal force together with the steam flow moves the wood pieces outwards from the centre where they are smashed to fibre bundles and fibres, which are ground between bars. In this process, the fibres are subjected to repeated compression and shear forces. This process is extremely energy intensive and a small process improvement may give large reduction of the energy costs.

Figure 2 shows a schematic illustration of a mechanical pulp plant. Generally the refining is done in two stages although a number of one-stage refiners are in operation. In the first stage fibres are mainly separated at temperatures of about 140 °C - 160 °C. The second stage that develops the fibres is nowadays usually also run at a similar temperature as the first stage refiner although some older systems with atmospheric secondary stage still are in operation.

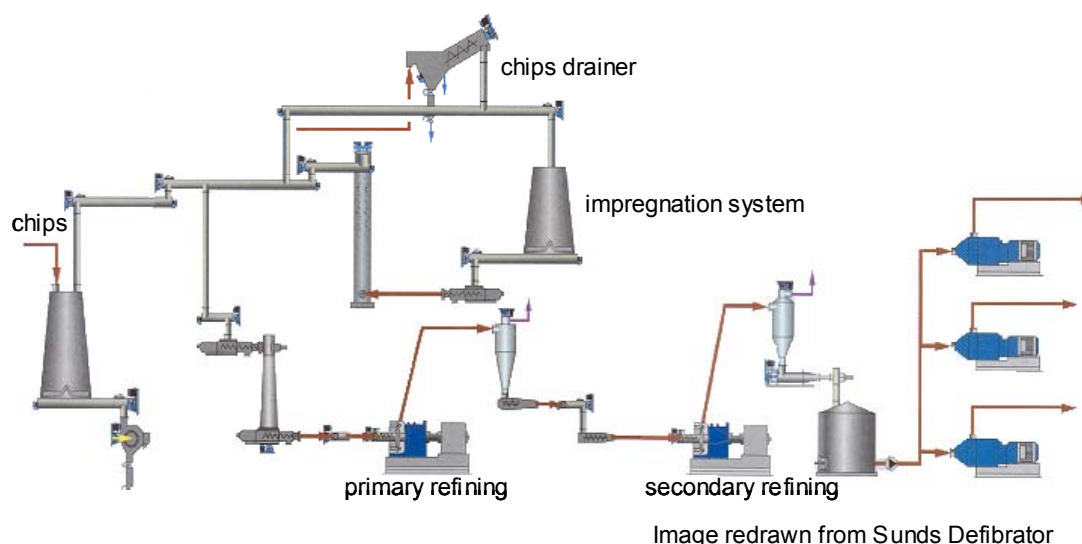


Figure 2 Schematic illustration of the refining part of the mechanical pulp process.

Of the total energy consumption in the mechanical pulp plant around 90 % of the energy is used for defiberizing and refining. Of this only a fraction is consumed in the actual fracturing process, the rest of the energy through the viscoelastic deformation of the wood is converted to heat producing the steam in the refiner. The energy consumption is high for all mechanical pulping methods as illustrated in **figure 3** where the energy is plotted against the freenes level. The freenes level can be taken as an indication of the quality of the pulp; in fact it usually gives an indication of properties such as tensile index and opacity of the paper. The total electrical energy consumption in Sweden for mechanical pulp production amounts to about 6 TWh/year, equal to the average production of a normal nuclear reactor or equal to the total energy used during a year by a town of about 300 000 inhabitants.

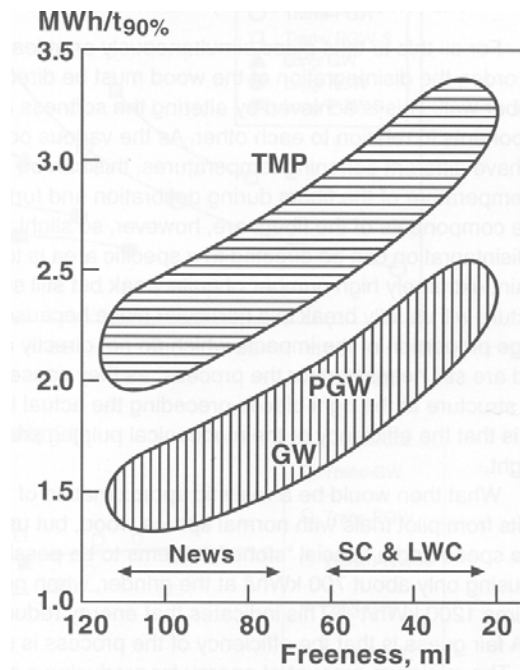


Figure 3 The total electric energy consumption for different mechanical pulping processes as a function of freeness and different end uses: GW = stone groundwood, PGW = pressure groundwood and TMP = Thermomechanical pulp where SC = Supercalendered paper, uncoated magazine paper and LWC = Lightweight coated paper, coated magazine paper (Sundholm 1999).

The reason for the high energy consumption in mechanical pulping is the viscoelastic nature of the wood material, which means that its mechanical behaviour is affected by temperature, moisture and time under load (**figure 4**). Every polymer material has a transition temperature at which it rather abruptly changes from a stiff to a soft material. This is called its softening temperature.

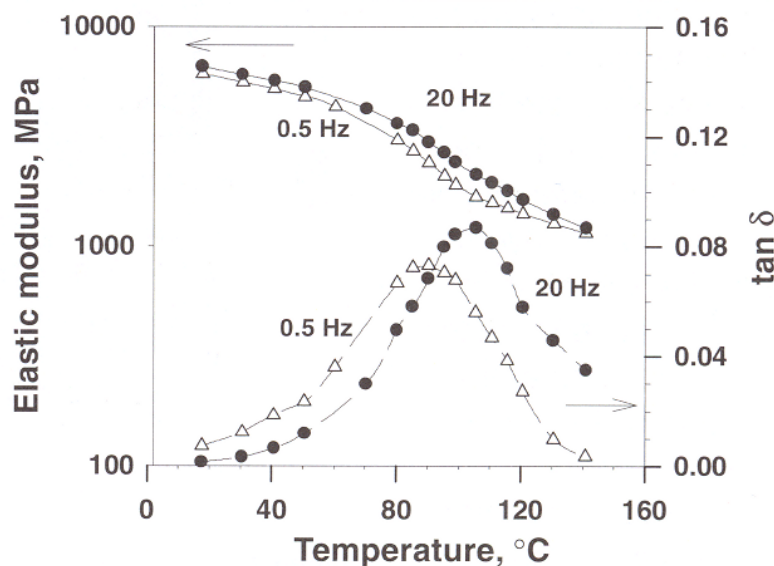


Figure 4 Elastic modulus and mechanical loss coefficient, $\tan \delta$, for wet spruce wood tested in the direction along the fibre axis as function of temperature at two different frequencies of testing; 0.5 Hz and 20 Hz. The maximum in the $\tan \delta$ curve is taken as the transition (softening) temperature for the wood (Salmén 1988).

This temperature is of great importance both for the quality of the pulp produced as well as for the energy consumed. The wood material used for mechanical pulp is saturated with water, which means that two (cellulose and hemicellulose) of the three polymers of wood are softened already at 20 °C (Back and Salmén 1982). Only lignin has a softening temperature of about 70 °C at low speed (Salmén 1984). This temperature increases with the speed of the mechanical treatment so that in the refiner a temperature of about 120 °C is needed for softening the lignin. If the temperature in the refiner is lower than this temperature the lignin appears stiff and the fibres break to pieces that produces a rather poor mechanical pulp. However at the proper fibre separation temperature for producing a sufficient amount of long separated fibres the wood is most highly viscoelastic thus absorbing a higher amount of energy as indicated by the maximum in the mechanical loss coefficient, $\tan \delta$, of **figure 4**. Thus processes have been developed for increasing the temperature in the second stage refining to pass the maximum in the viscoelastic losses, refining the separated fibres with lower viscoelastic losses thus reducing the energy demand (Höglund et al. 1995).

Still a better understanding of the behaviour of the wood fibres under loading and during collapse is a key issue when aiming for a reduction of the energy consumption in the mechanical refining process. Thus predicting the cell wall deformation behaviour under conditions of shear and compression could be a valuable tool in optimising the loading sequence in refining.

1.3 Objectives

Separating fibres and creating internal fracture surfaces has been estimated to require between about 1 % and 33 % of the total energy consumption in mechanical pulping to produce a useful papermaking pulp (Uhmeier and Salmén 1996a). Most of this energy is then probably used for development of the bonding ability and the flexibility of the fibres. This flexibility may increase significantly by irreversible collapse of the fibres, which would also give a stronger paper sheet. One of the main aims of mechanical pulping is then to achieve the desired fibre change with a minimum of energy expenditure.

Thus the objective of this work has been to increase the knowledge on how wet wood fibres deform by compression and combined shear and compression loading as well as sequences of these loadings under refining conditions to be able to develop mechanical pulps with better quality using less energy.

2. STRUCTURE AND PROPERTIES OF WOOD AND WOOD FIBRES

Mechanical pulps are mostly produced from conifers and in Sweden then from Norway spruce although some hardwood is also utilized. The most common conifers in Sweden are Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). The analysis, experiments and discussions presented here refer only to spruce it being the main specie used in mechanical pulping.

2.1 Structural levels of wood

Looking at a cross section of a tree, the dead bark is the outermost layer, inside the outer bark is the live inner bark and then comes the cambium layer (see **figure 5**) which is where the tree growth occurs both too the inner bark and to the real wood structure of the sapwood.

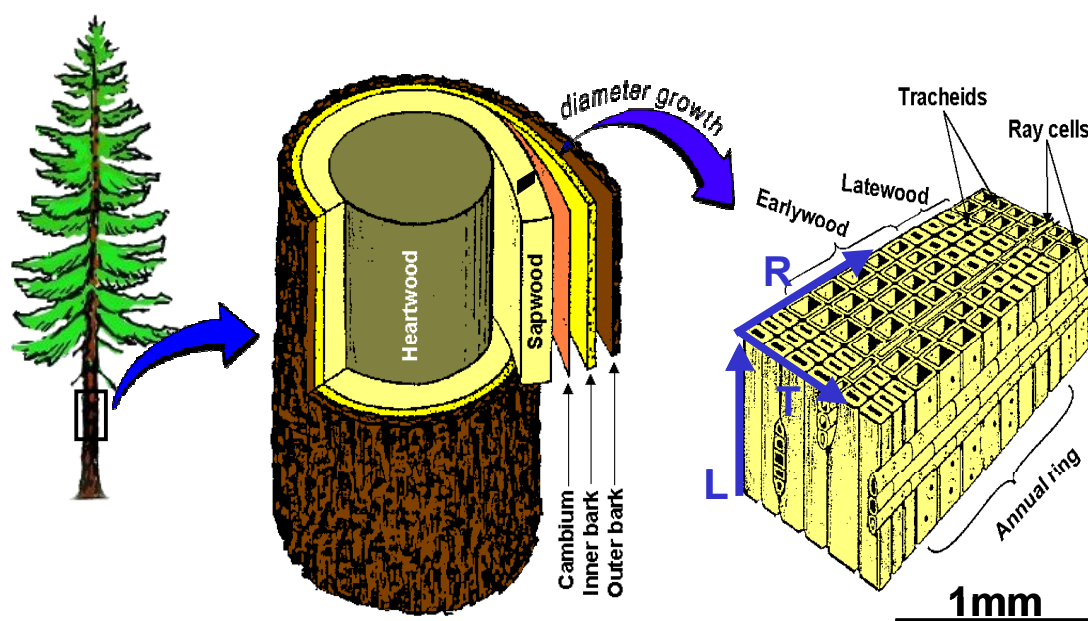


Figure 5 Schematic illustration of the different levels of a softwood structure.

The tree transports water and nourishment in this sapwood region. The innermost part of the wood is called heartwood, which is the old sapwood where no transportation of liquids takes place. This part of the stem is thus much drier than the outer part, remaining so long after felling of the tree. All trees growing in temperate climate have characteristic differences in fibre wall thickness and diameter over the growing season, resulting in earlywood and latewood. These differences in growth make the appearance of the annual ring structure. The earlywood is formed during the spring under the most intensive growth period and has an open structure with thin fibre walls allowing for large amounts of water transportation. The latewood is formed during the summer with decreasing growth rate, the fibre walls being thicker and thus the density of the wood increases. The change between earlywood and latewood occurs gradually and the region between the two is called transition wood. The cylindrical stem and the orientation of the wood cells make the cylindrical coordinate system convenient to use when describing the wood structure. The main directions are called longitudinal (*L*), radial (*R*) and

tangential (T), and are defined in **figure 5**. In spruce around 90 % of the cells are tracheids, and the rest consist of ray tracheids and ray parenchyma cells (Bodig and Jayne 1982). Tracheids are 3-5 mm long and have a diameter around 30 μm (diameter $\ll$ length) and are generally referred to as just fibres.

2.2 Properties of wood

The properties of wood depend primarily on the properties of the cell wall, on the relative density of the wood and on the shape of the cells (Gibson and Asby 1997).

If a sample of wood is cut at a sufficient distance from the centre of the tree in such a way that the curvature of the growth ring can be neglected, its properties are orthotropic. It has three orthogonal planes of symmetry: the radial, the tangential and the axial. The stiffness and strength are greatest in the axial direction, that is, parallel to the trunk of the tree in the longitudinal direction of the fibres. In the transverse directions the wood is somewhat stronger and stiffer in the radial direction as compared to the tangential one. These differences are related to the structure of the wood. At a scale of millimetres, wood is a cellular solid, which can be modelled as hexagonal prisms, enclosing a pore space (Gibson and Asby 1997).

Three features characterize the microstructure of wood (Dinwoodie 1981, Bodig and Jayne 1982):

- the highly elongated cells which make up the bulk of the wood.
- the *rays*, made up of radial arrays of smaller, more rectangular, parenchyma cells where some are living and storing energy while other conduct fluid radially, and
- the *sap channels* which are enlarged cells with thin walls and large pore spaces which conduct sap up the tree. They make up less than 3 % of the wood volume.

The rays in softwoods are narrow but numerous and are the cause of the higher stiffness in the radial direction of the tree as compared to its transverse direction.

At a finer scale, that of microns, the wood material is a fibre-reinforced composite. The cell walls are made up of “fibres” of crystalline cellulose embedded in a matrix of amorphous hemicellulose and lignin.

As a material formed by nature, wood has a complex mechanical behaviour. Natural differences in properties are caused by different structures due to genetics and dissimilar growth conditions such climate, type of soil and growth terrain. Also the density of the wood shows large variations depending on such factors. The annual ring structure also results in a large density variation affecting the properties. Earlywood has a density about 300 kg/m^3 and latewood a density about of 1000 kg/m^3 (see **figure 6**). The difference is due to the differences in cross-sectional cell wall thickness between earlywood and latewood fibres.

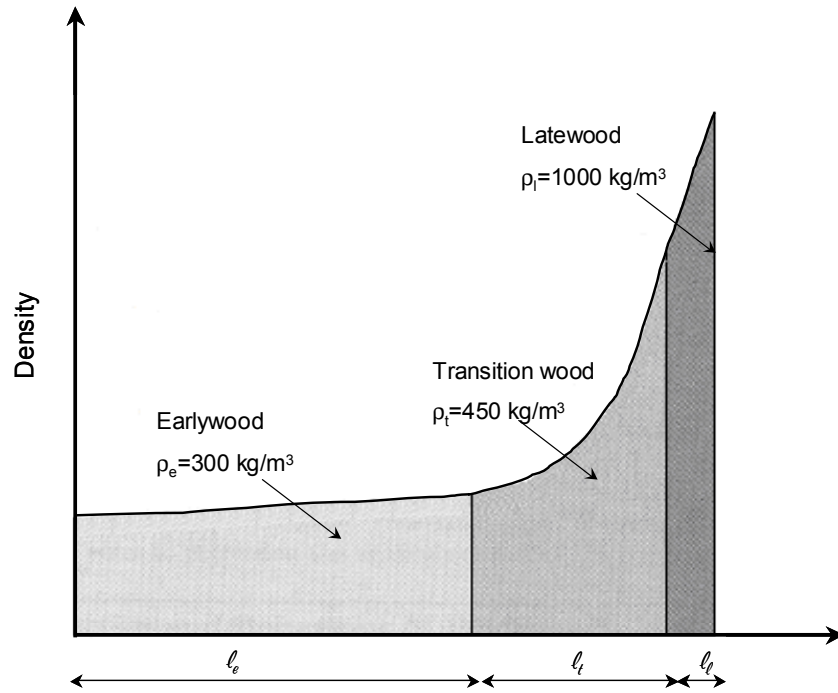


Figure 6 Illustration of the density variation from earlywood to latewood (Persson 2000).

2.3 Wood fibre structure

The structure of the wood cell is schematically illustrated in **figure 7**. The wood fibre is composed of several layers, outside is the primary wall (P) with the secondary walls (S) inside. This secondary wall is divided into three layers: the outer secondary wall (S₁), the main secondary wall (S₂) and the inner secondary wall (S₃).

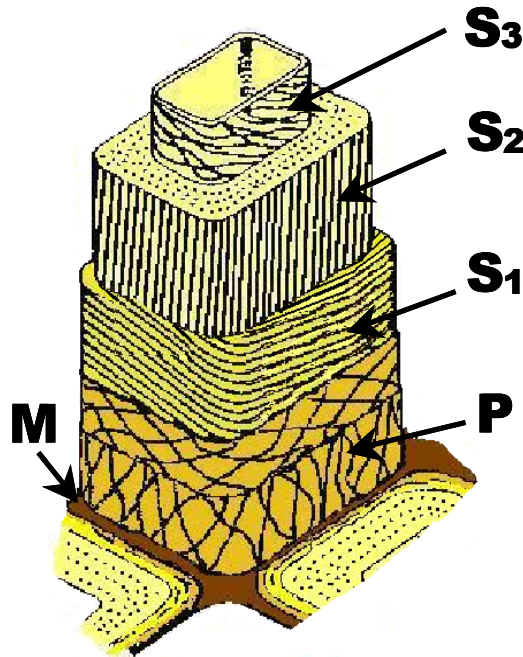


Figure 7 Schematic illustration of the cell wall layered structure of a softwood fibre. Due to the fact that the S₂ layer represents of about 80 % of the total cell wall thickness, the density and the microfibril angle of the S₂ layer dominate the mechanical properties of wood (Persson 2000).

The cell wall itself consists of the polymers cellulose, hemicellulose and lignin where the cellulose acts as reinforcement in a matrix of the other two polymers.

Cellulose is the most abundant biopolymer on earth. Around 40 % of the dry weight of wood consists of cellulose. It is a highly oriented semi-crystalline polymer and is in its unordered parts highly hydrophilic.

Hemicelluloses are amorphous carbohydrates made of a group of heterogeneous polymers. They make up about 20-30 % of the dry weight of wood. The hemicelluloses are highly hydrophilic. In Norway spruce hemicelluloses are of two different types: xylan and glucomannan.

Lignin is a heterogeneous three-dimensional polymer that constitutes approximately 30 % of the dry weight of wood. Lignin limits the penetration of water into the wood and makes the wood very compact.

Blocks of bundled cellulose chains form cellulose microfibrils. A number of these cellulose microfibrils with glucomannan in between make up a cellulose fibril aggregate or cellulose fibrils acting as reinforcement in the matrix of lignin and hemicelluloses (Fengel 1970, Fahlén and Salmén 2005). These aggregates are suggested to be surrounded also by glucomannan while xylan and lignin are more mixed in the matrix in between aggregates (Salmén and Olsson 1998).

The main difference between the cell layers is in the different orientation of the fibrils. The fibrils in the primary wall are oriented irregularly. The three layers of the secondary wall have different orientations of the cellulose fibril aggregates as well as differences in the polymer composition. The dominant layer is the S_2 , which makes up about 70-80 % of the thickness of the cell wall. In the S_1 layer, the angle of the fibrils is oriented from 70°-90° to the tracheid longitudinal axis (Brändström 2002). According to Brändström there is no evidence of a cross-ply in the S_1 layer, which was earlier commonly assumed. The S_2 layer begins where the S_1 layers microfibril angle gradually decreases. It has a fibril angle of 30° in juvenile earlywood, 10° in juvenile latewood and 2°-5° in mature wood (Bergander 2001). In the S_3 layer microfibrils are approximately oriented 50° to the longitudinal axis. These differences in fibril angle between the layers are responsible for the different properties in different layers of the fibre wall.

Outside the cells is the middle lamella (M), mostly composed of lignin, holding the fibres together. The hollow area inside the cell is called the lumen.

2.4 Behaviour of wood in compression

The stress-strain curves of wood subjected to normal loading can be divided into three regions: a linear elastic region, a plateau region and a rapidly increasing stress region. Compression, above the linear elastic level, gives a non-linear behaviour in all three directions. This is typical for cellular materials such as wood. The plateau region is a region of large deformation at almost constant force. This is due to elastic buckling of cell walls. The rapidly

increasing stress, at the end of the curve, follows from the fact that there is no cell structure left. This implies that the elastic modulus of the structure is close to the cell wall modulus (see **figure 8**).

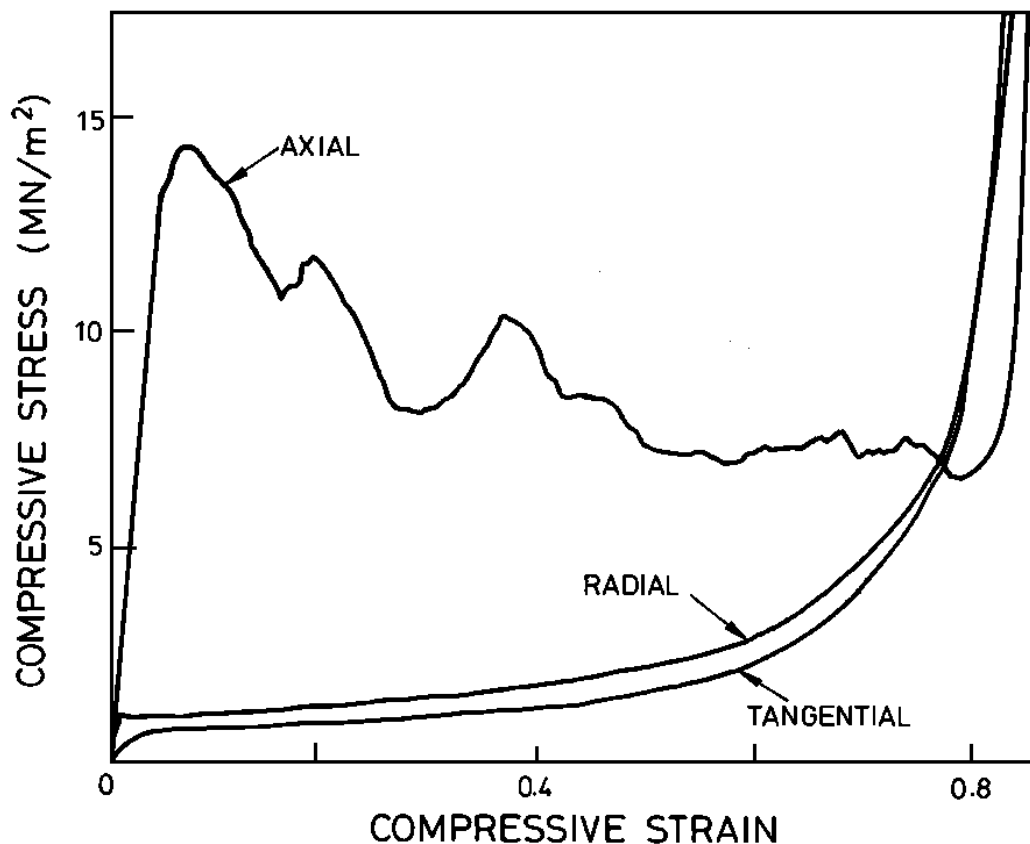


Figure 8 Non-linear behaviour for wood in compression in the longitudinal (axial), the radial and the tangential directions for a wood cell (Gibson and Ashby 1997).

The elastic modulus in the longitudinal, axial, direction is about 20 times larger than that in the other two directions. The difference in properties between the radial and tangential directions is probably due to differences between the structural arrangements of the wood fibres due to the fact that when wood cells are formed they divide in the radial direction thus forming regular rows of fibres (**figure 9**). In the transverse direction there is a large diversity between cells next to each other. Another structural difference between the radial and tangential direction are the ray cells, which are radially oriented thus increasing the stiffness of the wood in the radial direction (**figure 9**). These differences do not however alter the way the earlywood cell walls are deformed under compression, i.e. a buckling occurs in both the radial and tangential directions.

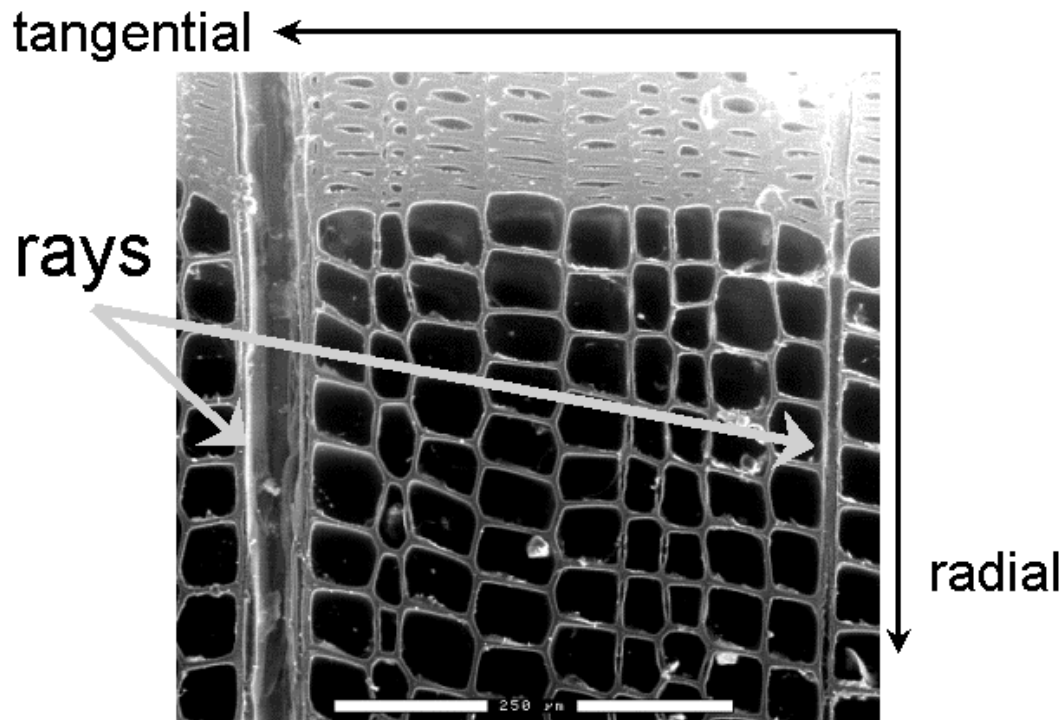


Figure 9 ESEM image of wood structure showing a cross section of an earlywood-latewood section.

2.5 Effect of rheology: temperature, moisture content and speed

Wood is a viscoelastic material made up of natural polymers. That it is a viscoelastic material means that its properties do not vary in a linear elastic way as in a spring or in a viscous liquid. The properties instead vary in relation to the variation of temperature, moisture content and duration and speed of the load applied. For that reason the mechanical properties of wood are also dependent on the frequency of the mechanical action.

With increasing moisture content and temperature the mechanical properties of spruce are reduced while an increase in the strain rate generally increases the strength and stiffness of the material. An increase in moisture content has the least effect on the longitudinal modulus but the largest on its compressive strength. At room temperature the effect of the moisture is highest above 10 to 15 % moisture content while when reaching above 30 % moisture content effects are negligible. The temperature generally has a larger effect at higher moisture contents. For wet specimens the largest influence occurs between 30 and 100 °C (Gerhards 1982). For softwood in the wet state the compression strength in the transverse direction is reduced with about 48 % at a low strain rate when the temperature is increased from 20 to 80 °C (Siimes 1967). The plateau stress in compression in the transverse direction also decreases with increasing temperature (**figure 10**) (Uhmeier et al. 1998) while increasing strain rate has the opposite effect. At low speeds the largest drop in plateau stress occurs between 50 and 100 °C, being rather unaffected at higher temperatures below degradation. At higher speeds it is expected that this region shifts to higher temperatures due to the viscoelastic nature of the wood.

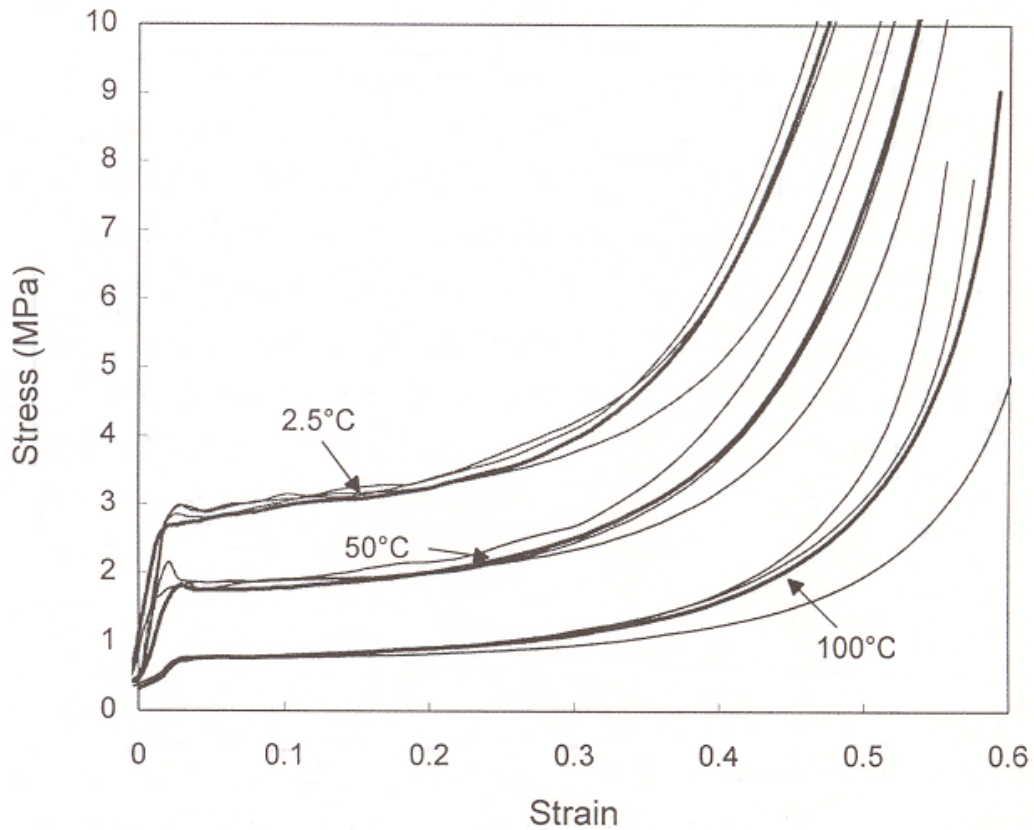


Figure 10 Stress-strain curves for wet spruce in radial compression at different temperatures (Uhmeier et al. 1998).

In radial compression of wet spruce, at low temperatures (25 °C), the very low strain rates of 10^{-1} to 10^{-3} only somewhat affect the stress in the plateau region. However, higher strain rates render a marked increase of the plateau stress which also depends on the moisture content of the wood (**figure 11**) (Uhmeier and Salmén 1996b). The presence of water in the lumen contributes to the stiffness of the wood at the higher strain rates. Due to the difficulties of pressing out the water through the pores of the fibre this water present in the lumen more and more contributes to the stiffness of the wood the more the wood is compressed if the speed of deformation is high.

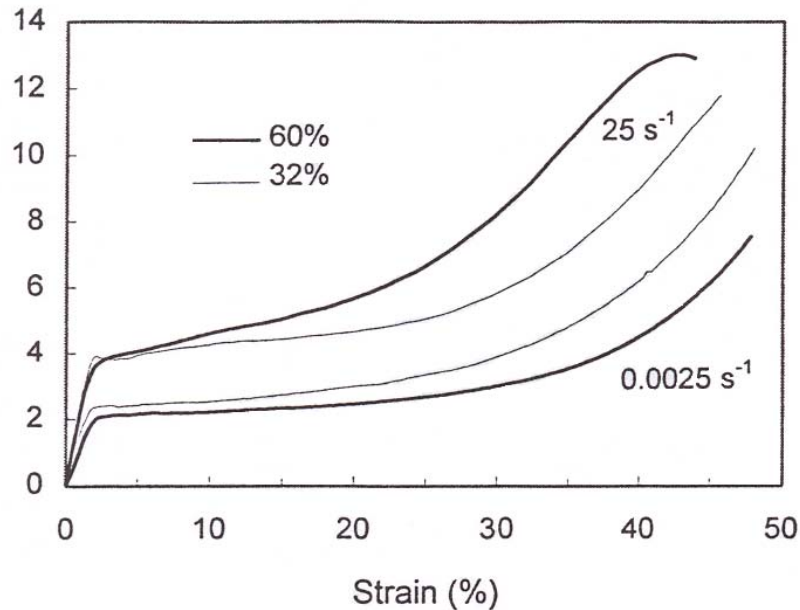


Figure 11 Stress-strain curves for wet spruce in radial compression at low and at high strain rate. The bold lines correspond to saturated specimens and the thin lines to drier specimens (32% weight of moisture based on total weight) (Uhmeier and Salmén 1996b).

2.6 Fatigue of wood

Fatigue is the accumulated damage occurring with repeated deformations. The fatigue properties of wet wood in the transverse direction are of interest as these are supposed to be similar to those occurring for the fibre fraction when producing a thermomechanical pulp, TMP (Salmén et al. 1985). Studies of fatigue in compression have also in the past been used to assess the effect of chemicals for thermomechanical pulping (Heitner and Salmén 1994, Mao et al. 2004).

Experimental data on the fatigue of wet wood show that the structural degradation due to mechanical deformation occurs faster at lower frequencies (Salmén 1987). This is also in line with grinding studies for mechanical pulp production where lower speed produces pulp of equal quality at lower energy demands (Lucander et al. 1985). With regard to temperature the higher the temperature the more rapid is the fatigue of the wood.

In repeated compression of wood the plastic strain increases and the plateau stress is reduced with the number of cycles of deformation (**figure 12**) (Uhmeier and Salmén 1996a). However the first cycle is by far the most effective, reducing the plateau strength by more than 50 %. This would suggest that a small number of large compressions across fibres would be an energy-efficient method to render collapsibility of the fibres. However for reaching the collapse levels necessary for paper production such a large number of large compressions has to be performed, as the incremental increase in plastic strain is small, resulting in an energy consumption that is immense and comparable to that of the mechanical pulping process (Uhmeier and Salmén 1996a).

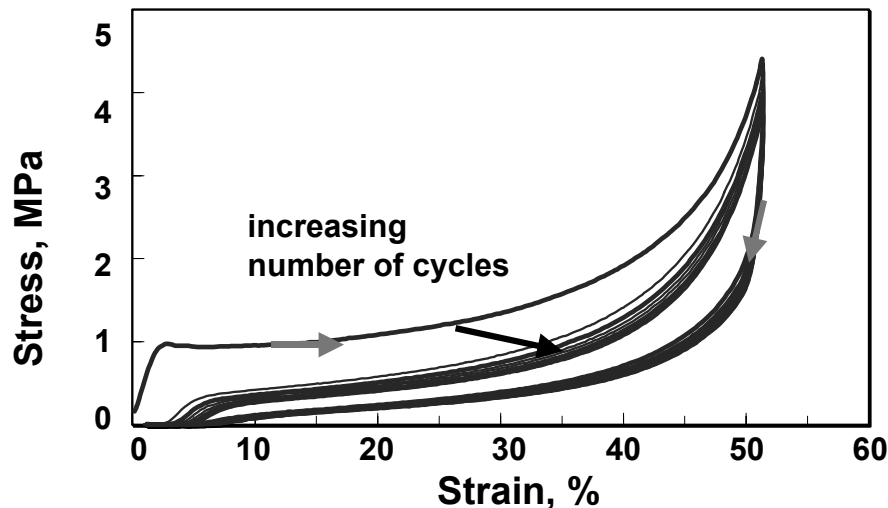


Figure 12 Stress versus strain for 10 consecutive compression cycles to 50 % strain of wet wood in the radial direction at 98 °C. The specimen of Norway spruce (*Picea abies*) was relaxed for 60 seconds between successive compressions (Uhmeier and Salmén 1996a).

About the same behaviour can be seen in fatigue of wood under shear (**figure 13**) (Dumail and Salmén 1999a); i.e. it is the first deformation cycle that seems to be the most beneficial one in giving a permanent deformation. However in the case of shearing there seems to be no appreciable reduction of the stiffness of the wood accompanying this permanent deformation.

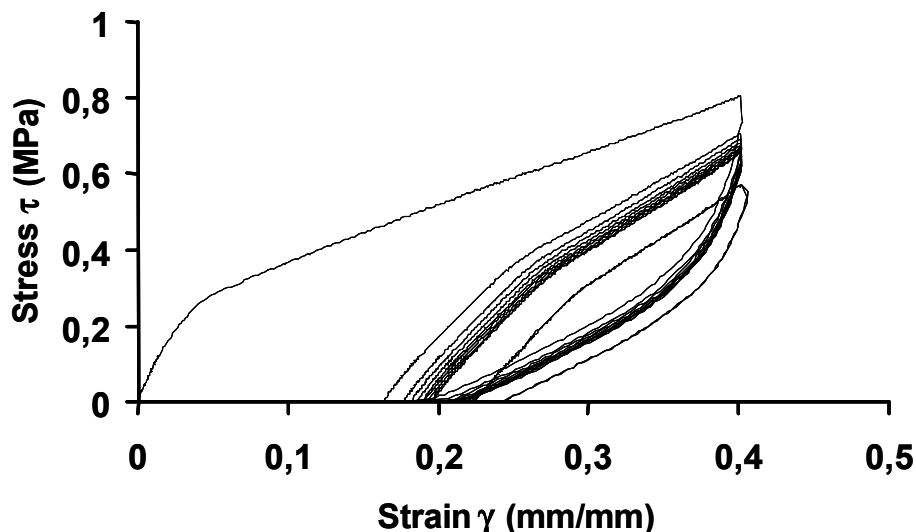


Figure 13 Cycling to 50 % strain for water-saturated wood sheared at 90 °C in water in the radial direction at 90 °C (Dumail and Salmén 1999a).

Both compression and shear deformation result in a permanent deformation of the wood fibres. With an increasing number of deformations this permanent deformation increases, a fatigue. However in both cases it is only the first cycle that has any substantial effect on the fibres while the subsequent cycles only contribute marginally to the increased permanent deformation.

3. SHEAR TEST DEVICES

3.1 Some existing shear test devices

Several shear test devices have been developed during the last fifty years. The number of different devices and subsequent modifications of these devices approved as standard test methods is a clear measure of the difficulties of testing in shear. The main difficulties in obtaining a simple shear force are caused by a relation always existing between shearing forces and bending moments.

There are several types of shear tests specially developed to test metals, wood or composites. The Notched beam shear test is a quite old method used for testing of wood (ASTM D-143, Radcliffe and Suddarth 1955), considered as the best method for nearly twenty years (**figure 14**).

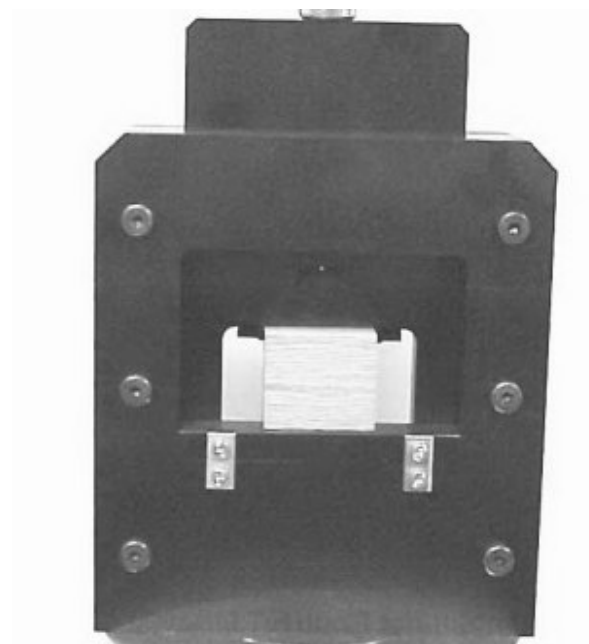


Figure 14 Shear parallel to grain fixture, ASTM.D-143.70

The Rail-test (**figure 15**) was developed to test composite laminates (ASTM D4255-83). It has been modified for testing shear strength of wood-based panels. The European and American standard method is to bond a specimen between two steel plates, which are loaded in compression (ASTM D1037). This test fixture causes problems in bonding the wood to the metal surfaces. A modification of this method solving the problem of insufficient bonding between wood and steel has been presented by Müller, Grindl, Sretenovic and Teischinger (2003). In this modification the test specimens are glued between two support blocks of beech wood using a phenolic resin, then two pairs of steel loading rails are fixed to the beech support blocks by means of rapidly hardening epoxy glue and additionally bolted together with four screws.



Figure 15 Two rail shear fixture tensile mode. ASTM.D4255.10

Another generally used shear test is the off-axis test (Liu 2002) but it implies the problem of using strain gauges and an advanced analysis based on theory of elasticity.

The Iosipescu shear method (Iosipescu 1967) was primarily developed to test metals, i.e. to test isotropic materials. It started from the consideration that one could obtain a pure shear loading by generating a simple shear force in the zero-moment section of a straight beam. This test method can provide results for both the shear modulus and the shear strength (Walrath and Adams 1983). The stress field is fairly uniform in the region between the notches. From the 70s this method has been applied to test ceramic material, composites, etc. The method was implemented, by way of a fixture and specimen design, for use on composite materials by Walrath and Adams (1983). This modification is called the Wyoming shear test fixture (**figure 16**). When testing orthotropic materials, off-axis effects have been seen and different developments of the Iosipescu shear test device have been proposed (Liu et al. 1999; Conant and Odom 1995). Odom et al (1994) pointed out how this device is sensible to misalignments and that the loading condition is not asymmetric as was originally assumed but non-asymmetric. The year after a new modification of the Iosipescu shear device was proposed (Conant and Odom 1995) to solve the problem of the twisting of the specimen. This twist gave different shear strains on the two sides of the specimen.

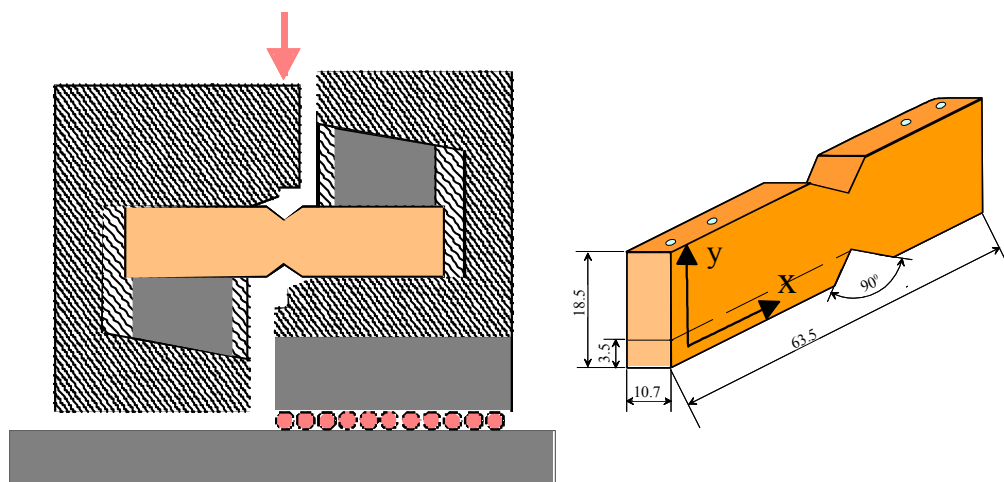


Figure 16 Schematic representation of the Iosipescu shear fixture (Wyoming version) and dimensions of the sample (in mm).

A few years after the development of the Iosipescu shear test device another important device was introduced: the Arcan shear test device (Arcan et al. 1978). The Arcan test device was designed to create a shear state as uniform as possible (**figure 17**). Liu (1984) tested this Arcan method on wood materials. It was found that this method may induce a pure shear state in the critical section of a butterfly-shaped specimen of either isotropic or orthotropic materials concluding that the method can be successfully used to test wood.

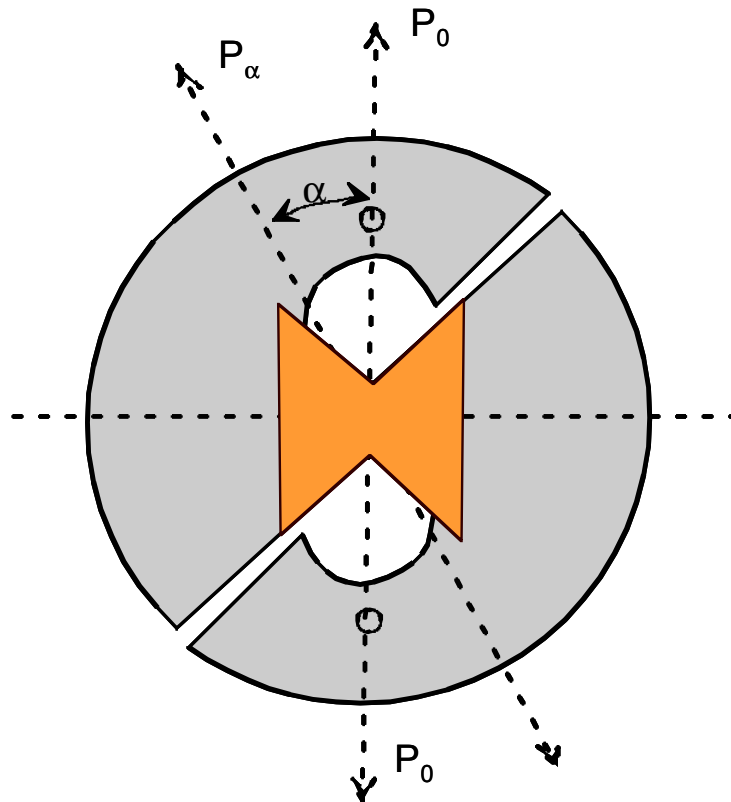


Figure 17 Test fixture and specimen according to Arcan et al. (1978).

Subsequent improvements of the Iosipescu shear test have been proposed by combining the principles of the Iosipescu and of the Arcan devices (Liu 2000).

There are few studies comparing different shear test methods (Swanson et al. 1985, Melin et al. 2000). This is probably due to each method being more or less adapted to its end scope (shear strain, shear failure) and the material studied. Thus to choose a shear test method several factors have to be taken in account and often the method has to be subjected to minor adjustments in order to fulfil the scope of each specific analysis.

3.2 Existing devices to test combined shear and compression loading

The Arcan test was primarily intended to induce pure shear stresses. However already two years after the first publication the test device was used by the team who developed it to test samples of reinforced composites under general biaxial stress states (Voloshin and Arcan 1980). Due to the geometry of the Arcan test, it comes natural to use it for testing in biaxial loading just by rotating the supporting tabs.

The Iosipescu shear device has also been further developed to be used for testing in biaxial loading (Bansal and Kumosa 1995) (**figure 18**). For the moment this modification and the one presented in this thesis (Papers I and II) are the only ones applying the Iosipescu shear test principle to test biaxial loading.

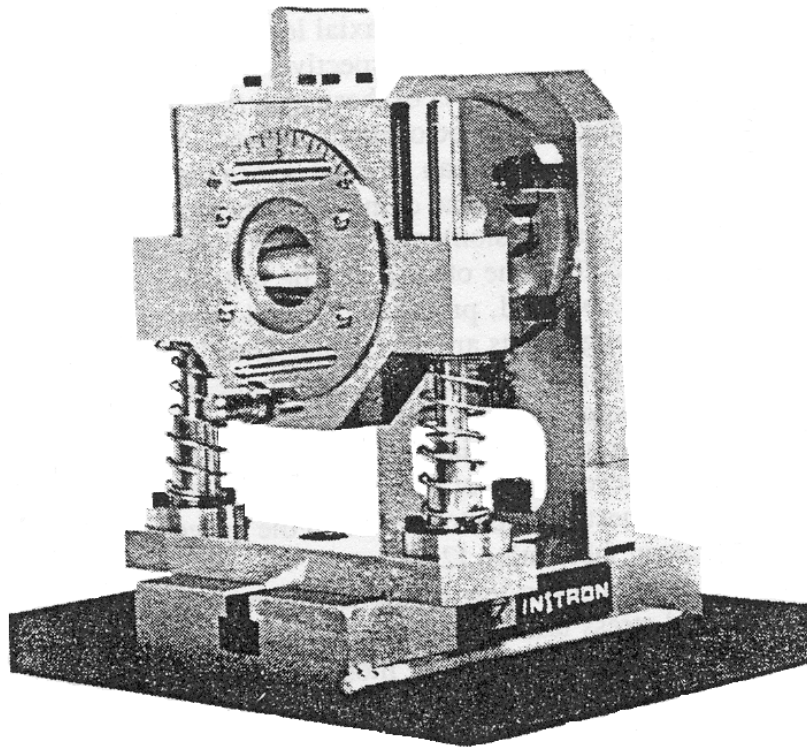


Figure 18 Iosipescu shear device modified to test in combined shear and compression (Bansal and Kumosa 1995).

A new biaxial test device to investigate the failure envelope for biaxially stressed wood has recently been presented (Müllner et al. 2004). This method uses a cruciform specimen loaded by applying the displacement by bars at the four edges of the specimen (**figure 19**). That means that the method needs a testing device with loading possibility on two perpendicular axes. This makes the method more expensive to use than the two methods previously listed.

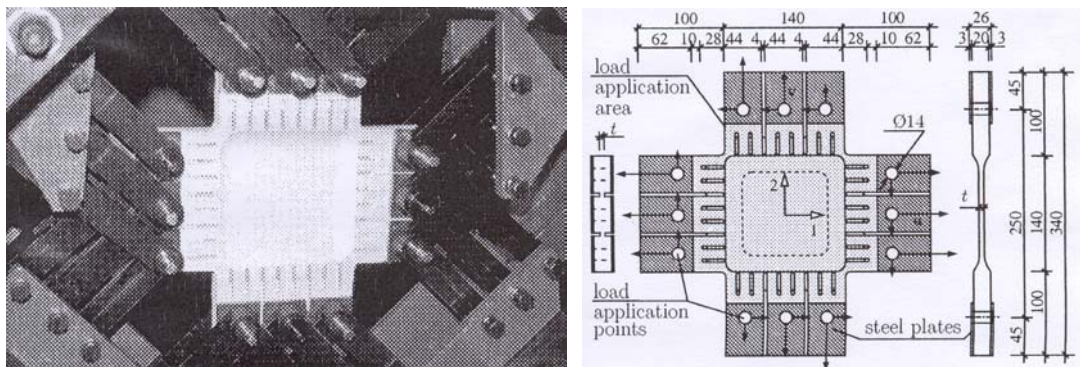


Figure 19 Biaxial testing device and cruciform sample (Müllner et al. 2004).

3.3 Equipment used here to test combined shear and compression loading

Two different shear test methods (Iosipescu and Arcan) were here modified to test wood in combined shear and compression loading.

Iosipescu

The Iosipescu shear device was in this thesis modified to make it possible to achieve both shear and compression forces with purely vertical movement of the piston of a hydraulic tensile testing machine (MTS Material Testing System) by rotating the jaws of the original device. Between the Iosipescu device and the rotating plates three spheres were introduced to assure the load being perpendicular to the lateral surfaces of the device itself. To maintain the contact between the jaws and the plates rubber rings were used on both sides of the device. Metal bars were screwed on the plates to maintain the plates and the Iosipescu jaws in the same plane (**figure 20**).

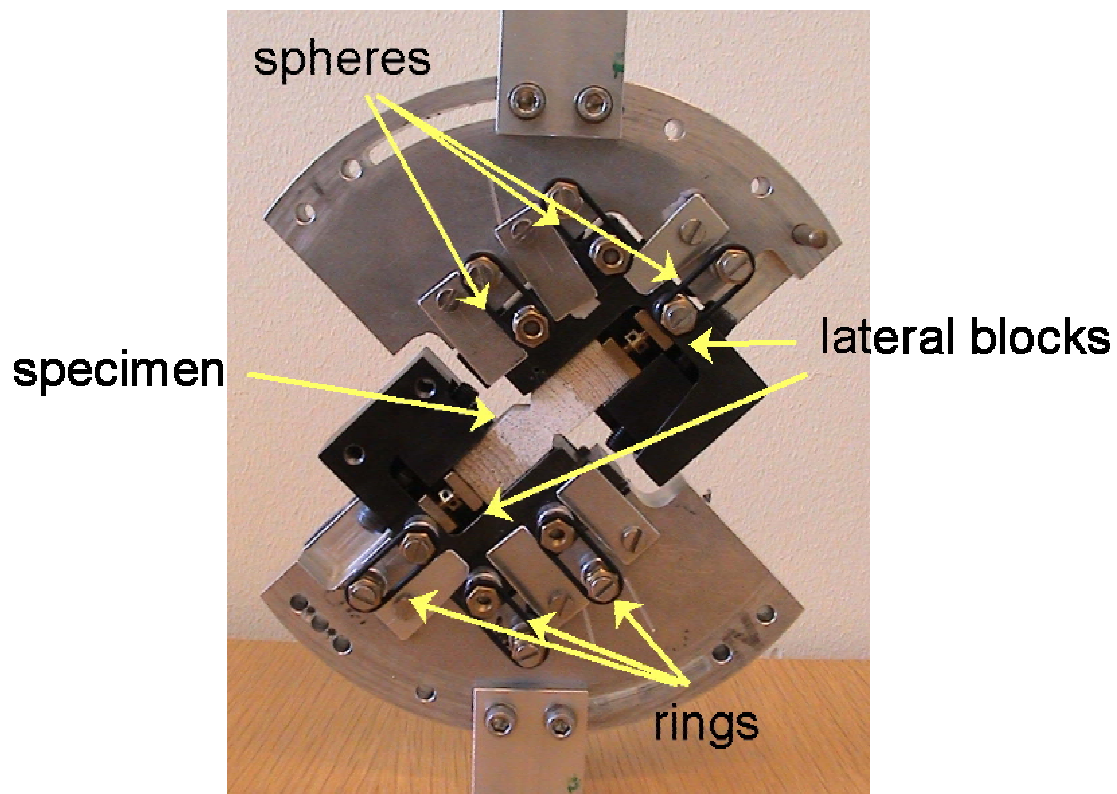


Figure 20 Modification of the Wyoming version of the Iosipescu shear fixture to test wood in combined shear and compression.

This modified Iosipescu shear and compression device was tested on an orthotropic material (Medium Density Fibreboard, MDF) with a mechanical behaviour considered comparable with that of wood but without the annual ring structure of wood. The analysis made both experimentally and analytically, with two different combinations of shear and compression loading, showed that the new test device was reliable for testing the MDF material in combined load (Paper I).

It was thus concluded that the modified Iosipescu apparatus was suitable for applying different combinations of shear and compression loading for tests on orthotropic materials. In combined shear and compression tests of wood, the values of the strain field in compression were however found to be ten times larger in the experimental test than in the finite element (FE) simulation (Paper II). The probable reason for this discrepancy is related to the deformation pattern of the honeycomb structure of the wood material. This means that a combined shear and compression load would be favourable to facilitate collapse of wood at low loads. The finite element analysis, with the material modelled as a linear elastic material, was thus not able to predict the deformation behaviour observed even when a variation of properties of the material in the annual ring structure was introduced. Thus the deformation of the cell structure must be fundamentally different from that of a homogeneous material as used in the FE model. To study what really happens to wood fibres, measurements at larger magnifications, i.e. at the fibre level, are necessary.

Arcan

The other method investigated in this thesis has been the Arcan device. Arcan and Weissberg (1988) found that a biaxial loading was easy to apply by changing the load application points. The biaxial loading is a single-parameter loading in this set-up since loading is applied only in one direction (**figure 17**). A modification of the Arcan test device has been developed at STFI-Packforsk (Stenberg 2002) to test through-thickness mechanical behaviour of paperboard. The modification consists of a U-shaped fixture attached to the Arcan device. The fixture allows movement of the Arcan device in the two directions in the plane of the device, but strongly restricts movements in the third direction as well as rotation of the device. In this thesis the equipment was further slightly modified to allow tests of thicker wood samples (**figure 21**). The modified device has also been equipped with an extensometer screwed close to the sample to measure the deformation of the sample under load.

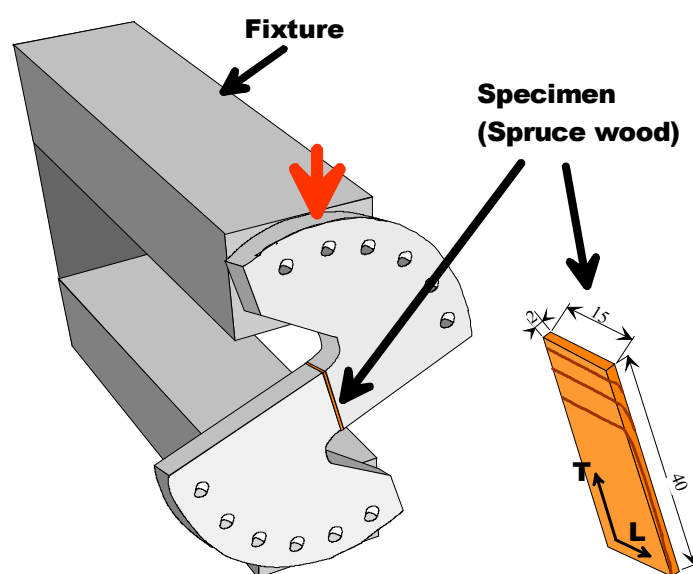


Figure 21 Modification of the Arcan shear fixture to test wood in combined shear and compression. Specimen dimensions in mm.

4. DEFORMATION OF WOOD FIBRES UNDER LOADING

The deformation of wet wood fibres at elevated temperatures under different loading cases, compression, shear and combined shear and compression is in this thesis investigated to simulate what happens to wood fibres in the refiner. In that way we may understand the mechanism that brings the fibres to collapse and possibly to use this knowledge to develop an effective process to obtain mechanical pulp of good quality at low energy cost.

4.1 Types of deformation under different load conditions

The deformation of wet wood fibres, in their transversal direction, is completely different in compression and in shear. Compression buckles the fibre walls (**figure 22**), and in this way gives a permanent deformation of the cell walls (Uhmeier and Salmén 1996a, Dumail and Salmén 1996). The deformation under compression is local, which means that when compressed in the radial direction subsequent rows of earlywood cells collapse one after the other as deformation proceeds. Usually the rows first collapse near the border to the latewood. This deformation type, typical for compression, is called “S” shape. The deformed shape of the cells under compression is strictly dependent on the aspect ratio of the cells. The first cell walls that bend are the thinnest ones, usually the first rows of the earlywood (Paper III).

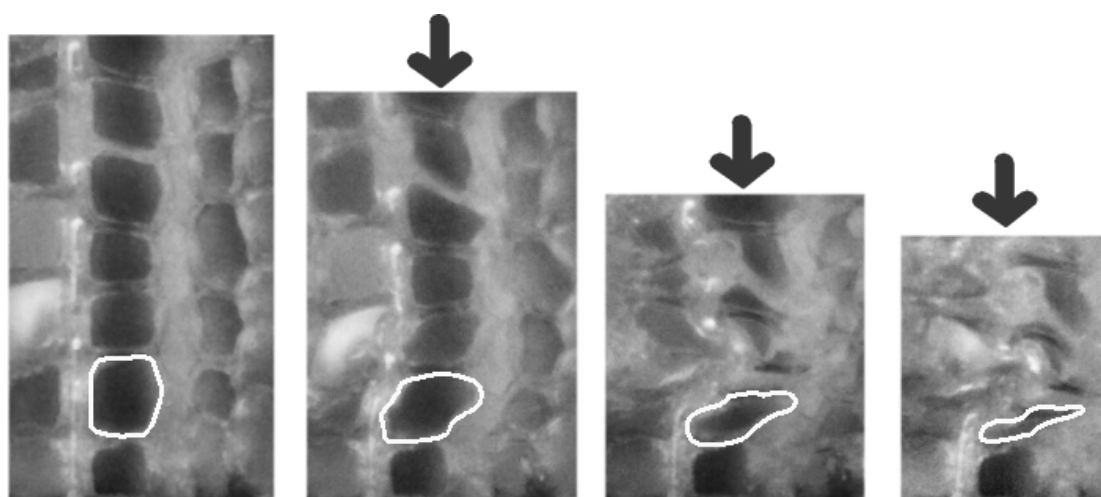


Figure 22 Deformation of spruce earlywood in radial compression. Samples immersed in water at 50 °C (Paper III).

Shearing of wood in the same direction does not buckle the fibre walls but just give them a sort of “rotation” as can be seen in **figure 23** (Dumail and Salmén 1999b).

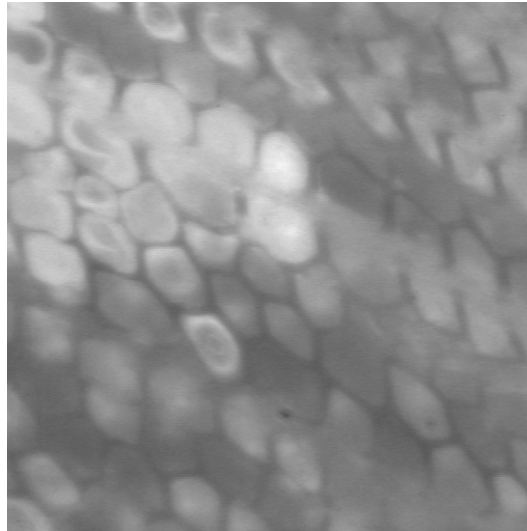


Figure 23 Deformation of earlywood cells during shearing of a water-saturated specimen in the transversal direction at 90 °C in water. The shearing strain is about 50 % (Dumail and Salmén 1999b).

Under a combined shear and compression loading, the fibre cells show yet another type of deformed cell shape: the cell walls do not bend as under compression but instead the corners deform in a macroscopic way (**figure 24**). All the cells start to deform at the same time to a “brick” shaped pattern. This is probably due to the lower stiffness in the tangential direction of the material. The deformation mechanism under combined load affects the corners as well as the cell walls because all the cells have the same probability to deform (Paper III).

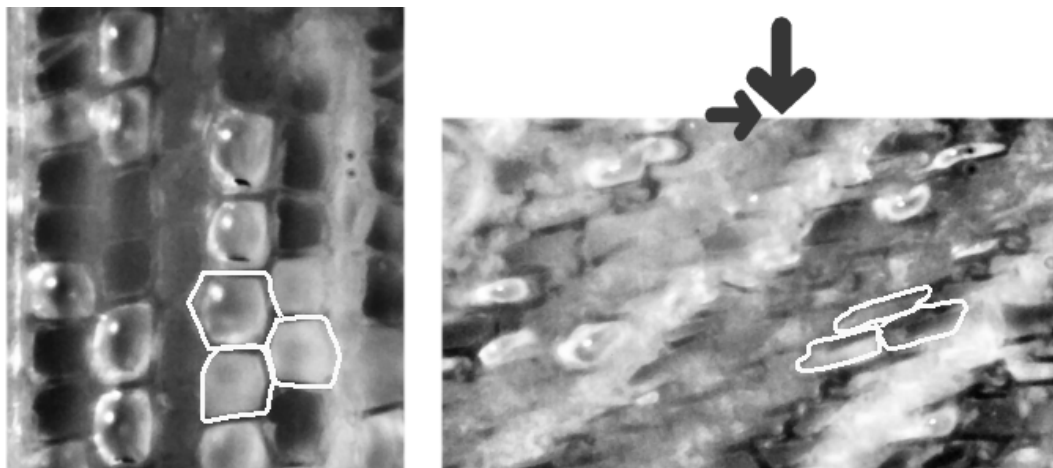


Figure 24 Deformation of earlywood in combined shear and compression loading in the radial direction for samples tested immersed in water at 50 °C (Paper III).

Schematic drawings of the different deformation types obtained under the three different loading cases of compression, shear and combined shear and compression are shown in **figure 25**.

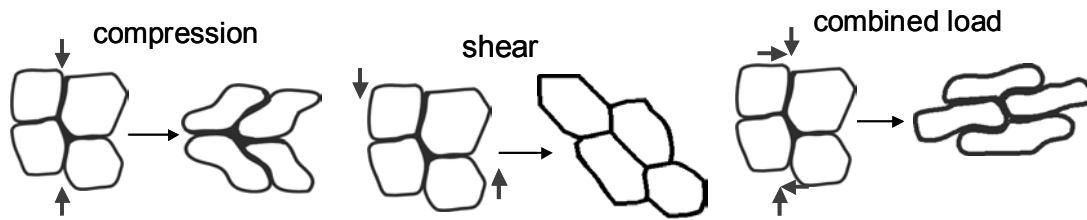


Figure 25 Schematic drawing of deformation modes of softwood fibres in the transverse direction in compression (*left*), in shear (*centre*) and in combined shear and compression load (*right*).

4.2 Energy consumption under different loading conditions

The energy used during a deformation process is equal to the area under the stress/strain curve ($\sigma_{12} - \varepsilon_{12}$) assuming that none of the energy stored is recoverable; in fact the energy absorbed during deformation is the same as the work required for such a deformation and that corresponds to the integral of the stress σ over the strain ε . That integer is equal to the area below the stress-strain curve.

Compression

The stress-strain curve of wood subjected to compression loading can be divided into three regions a linear elastic region, a plateau region and a rapidly increasing stress region as previously described, **figure 8**. The plateau region is a region of large deformation at almost constant force due to the successive elastic buckling of the rows of cell walls. This is the region where the “S” shape deformations of the cell walls appear. The rapidly increasing tangential stiffness, at the end of the stress-strain curve, follows from the fact that there is no cell structure left. This implies that the elastic modulus of the structure approaches the cell wall modulus. Due to the fact that the deformation is successive, row by row of earlywood fibres, it is possible to compare the stress-strain curve in compression with the stress-strain curves of the other deformations loads only if the cells are fully compressed in a single cycle. A reloading of a sample not fully compressed will have a first plateau, due to the previously collapsed fibres, at the same level of stress as after a full first cycle and a second plateau stress, due to the previously non compressed cells, at a higher stress level. Thus the stress/strain curve will show two different plateau regions (Uhmeier and Salmén 1996a).

The deformation in compression requires the highest load and thus the largest energy as compared to loading in pure shear or under combined load to reach the same strain level (**figure 26**).

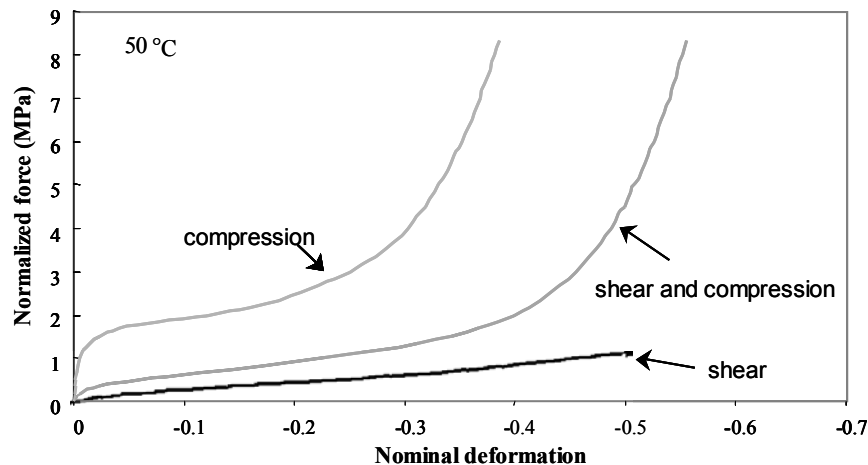


Figure 26 Nominal force versus nominal deformation for softwood in the transverse direction in the three loading cases: compression, shear and combined shear and compression. Tests performed in water at 50 °C.

Shear

The stress-strain curve in the case of pure shear load does not show any plateau, as all the cells deform at the same time. No buckling of cell walls occurs but just a “rotation” of the cells. Of the deformation types here tested, this deformation type requires the least load for a given deformation (**figure 26**). In this type of deformation the wood deforms to a large degree before reaching the state of wall touch requiring larger forces.

Combined shear and compression

The stress-strain curve of wood subjected to combined shear and compression loading does not either show the plateau region typical of the curve obtained in compression (**figure 26**), as the sample is homogeneously deformed in the earlywood region.

The load required to reach a certain strain level in the combined load case is much inferior to the load to reach the same strain in compression (Paper III). The energy needed to deform samples to a specific strain in combined shear and compression is only about half as much as that needed to deform samples in pure compression.

4.3 Types of deformation under repeated load

Compression + compression

During a second cycle in compression, the cells seem to have lost their characteristics of instability. This means that instead of collapsing row by row, the deformation is more general and spread out over the entire earlywood section, but still deforming in the “S”-type manner (**figure 27**). Thus during this second cycle in compression the fibres deform following the same pattern as in the first compression cycle.

The loss of unstable buckling is probably due to an introduced permanent damage in the cell walls. This is also probably the reason for a lower load required in this second deformation cycle.

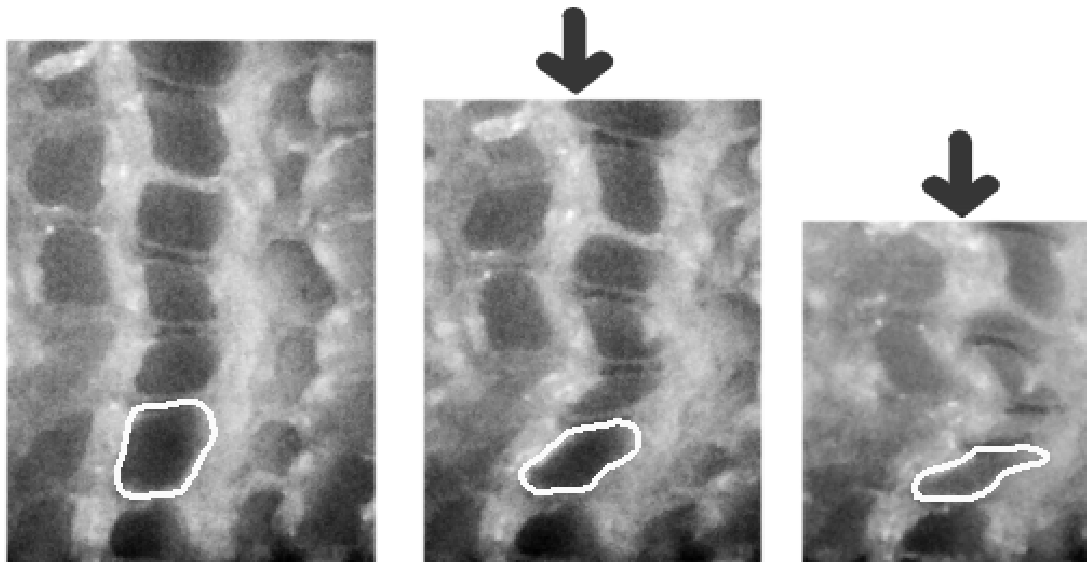


Figure 27 Images of deformation in the second cycle of compression of six rows of earlywood fibres, saturated with water at 50 °C. The arrows show the direction of loading. The height of the picture represents the actual strain of the sample (Paper III).

Shear + shear

During a second cycle in shear it is likely to assume that the fibres deform following the same pattern as in the first cycle in shear (**figure 23**). There is no appreciable reduction of the stiffness of the wood accompanying this permanent deformation although it decreases (Dumail and Salmén 1999a).

Combined load + compression

When samples are tested in compression after a cycle in combined shear and compression load, the cells deform with the “brick” shape instead of the “S” shape typical of compression (**figure 28**). Thus the cells deform in the same manner as in the preceding cycle. This indicates that also here the deformation level of the first cycle has introduced a permanent damage in the cell walls or cell corners. The stress level reached in the first cycle is enough to introduce damage so that the type of deformation in the second cycle follows the same pattern, the “brick” type as in the first deformation. The fibres deform all at the same time and the radial direction changes from vertical to circa 45°.

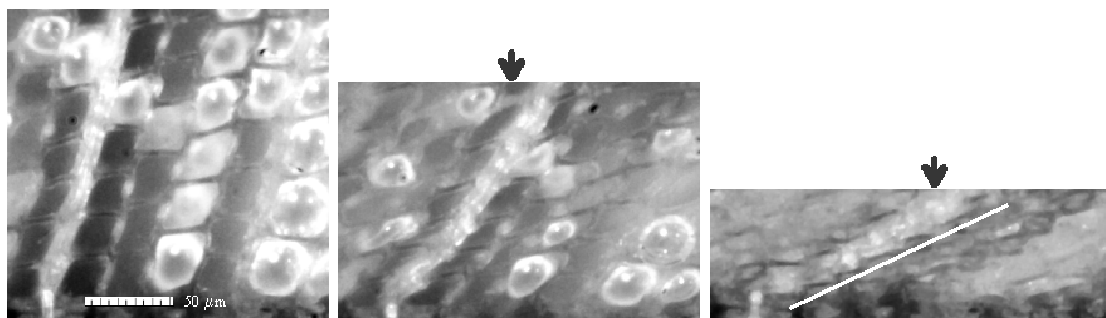


Figure 28 Image of the first rows of earlywood fibres from a cycle in compression after a cycle in combined load. The sample, saturated with water, was tested at 50 °C. The arrows show the direction of loading. The height of the picture represents the actual deformation of the fibres (Paper IV).

Compression + combined load

If the first cycle of loading is that of a compression the deformation in a following cycle of combined compression and shear load is different at low and high temperature, i.e. 50 and 90 °C. At 50 °C the deformation in the combined load cycle follows that of an “S” shape of the cell walls, and a horizontal orientation of the rows is maintained (**figure 29, left**); while at 90 °C instead the cells deform more with a “brick” shape however with highly deformed cells walls (**figure 29, right**).

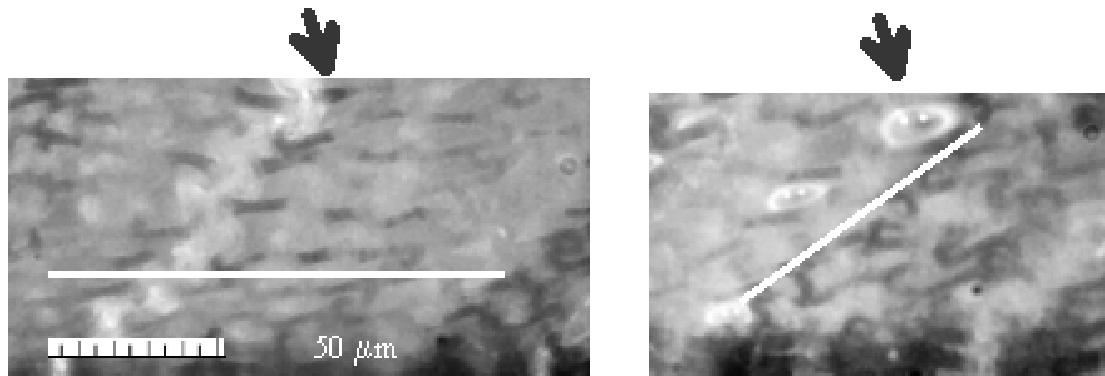


Figure 29 Image of the first rows of earlywood fibres from a combined shear and compression test. The sample, saturated with water, was tested at 50 °C, *left*, and at 90 °C, *right*. The arrow shows the direction of loading. The height of the picture represents the actual deformation of the fibres (Paper IV).

4.4 Permanent deformation of wood under repeated load

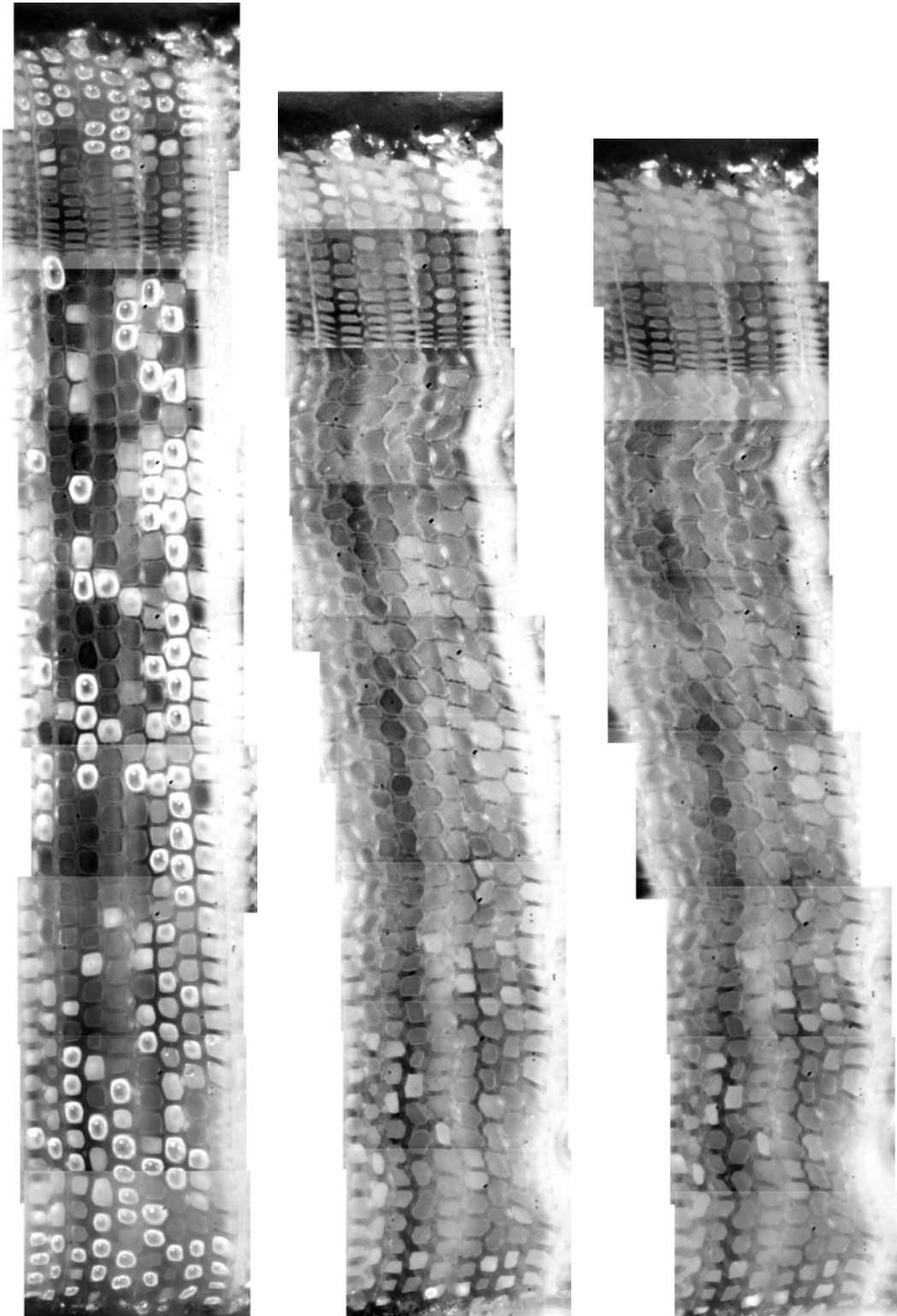


Figure 30 Permanent deformation of a wood sample under repeated compression at 50 °C. Before testing (*left*), after first cycle in compression (*centre*) and after second cycle in compression (*right*). The height of the picture represents the actual deformation of the fibres. The initial height was about two millimetres.

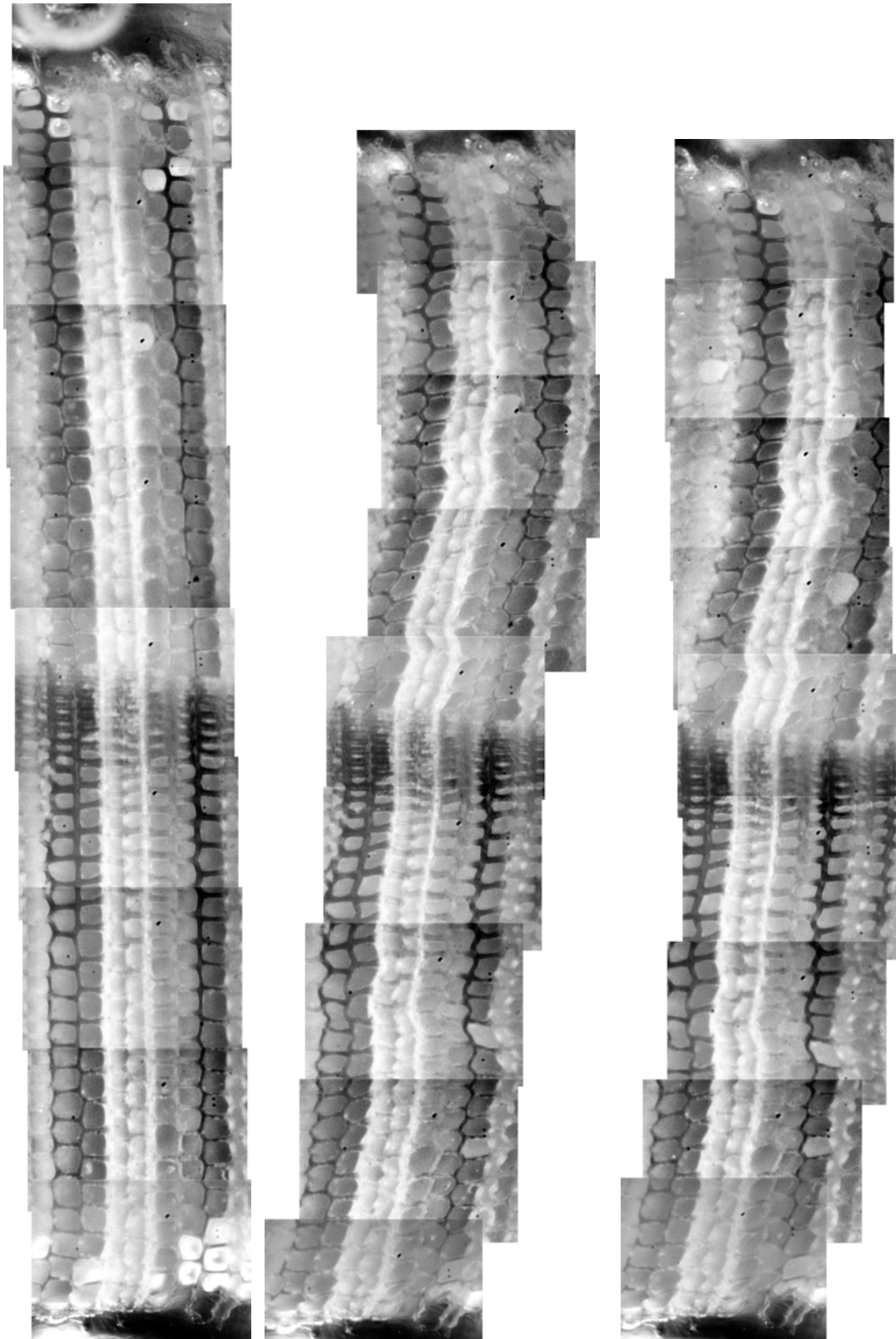


Figure 31 Permanent deformation of a wood sample under repeated compression at 90 °C. Before testing (*left*), after first cycle in compression (*centre*) and after second cycle in compression (*right*). The height of the picture represents the actual deformation of the fibres. The initial height was about two millimetres.

For a sample tested in compression the permanent deformation for a first compression cycle at 50 °C to a strain level of 30 %, was about 8 % as seen from the cross section of a sample of a total high of two millimetres (**figure 30**). The sample springs back directly after loading to almost the same height as that of the untested sample. The second cycle in compression, uses less energy but does not render any substantial increase in the permanent deformation, totalling about 9 % (**figure 30**).

The same can be seen for the tests performed at 90 °C (**figure 31**). The permanent deformation after the first cycle in compression was about 6.5 % while after the second cycle it reached about 8.5 %.

Both at 50 °C and a 90 °C it is obvious that the whole sample has been deformed and not only the most thin-walled earlywood cells close to the latewood-earlywood transition. All cells, except perhaps for the latewood cells, have got a buckling of the fibre walls. The permanent deformation obtained is thus not localized to some particular area of earlywood fibres but is an average over the whole earlywood and transition wood region. When the wood is compressed beyond the plateau region also buckling of latewood fibres may occur (Dumail and Salmén 1996).

4.5 Energy consumption under repeated load

Compression + compression

Both at high and at low temperature the second deformation cycle requires, as seen in **figure 32**, much less energy to deform to a specific strain level. This is due to the permanent deformation achieved in the first cycle as a consequence of the buckling of the cell walls. The energy needed for this second cycle is about 0.9 kWh/t at 50 °C and 0.3 kWh/t at 90 °C to deform to 30 % strain compared to the energy of the first cycle of 1.3 kWh/t at 50 °C and 0.6 kWh/t at 90 °C (see **table 1**, page 32).

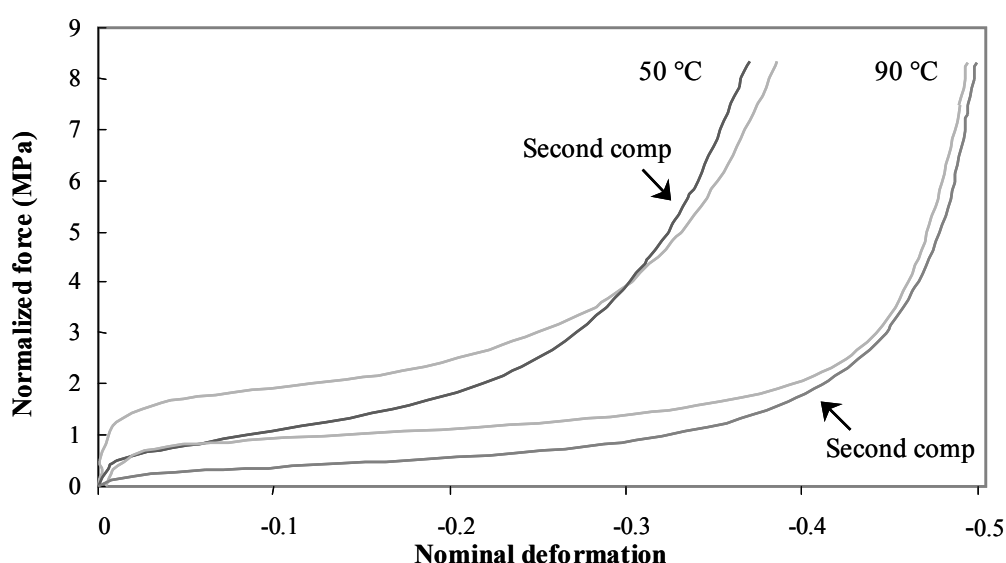


Figure 32 Comparison of the loading curves in repeated compression tests, in transverse direction, of wet samples tested in water at two different temperatures.

Shear + shear

A second test in pure shear requires about the same energy as is needed in the first cycle of shear (**figure 13**). Note that the second cycle was only deformed to 22 %. The stress/strain curve in shear does not show any plateau due to the fact that all the fibres deform together.

Shear + compression

For samples subjected to pure shear a second cycle in pure compression shows no significant lowering of the plateau region; i.e., no substantial reduction in energy demand as compared to an original compression curve (**figure 33**). This is probably due to the fact that the load in shear does not buckle the fibre walls during the deformation. As the deformation appears at the same time in all the cells the load is more evenly distributed. The rotation of the cells occurring during shear does not seem to introduce any visible damage to the cell wall themselves, although a permanent shear deformation occurs. Thus when loaded in the direction of the fibre wall, i.e. when subjected to transverse compression, they still appear as columns withstanding buckling.

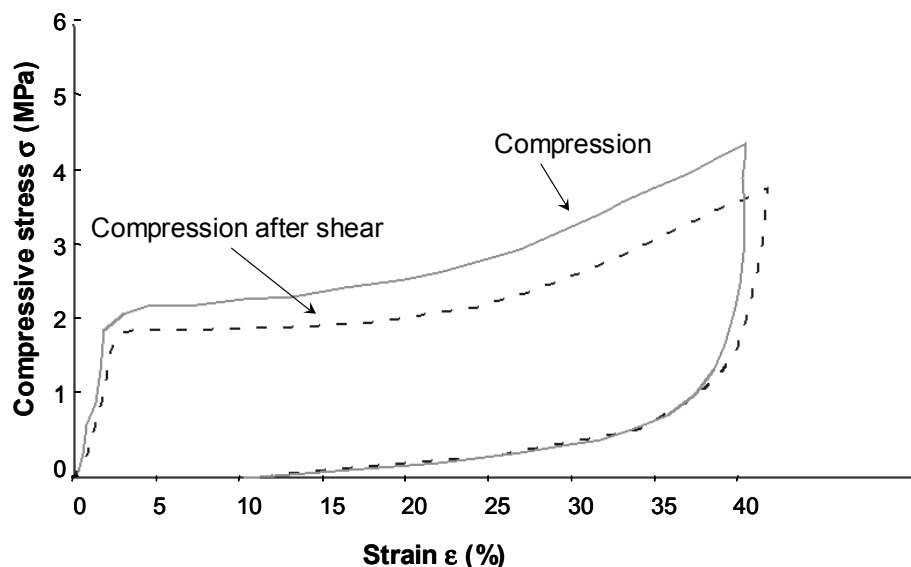


Figure 33 Stress-strain curves during the first loading in compression for intact specimens and during a compression loading of previously sheared specimens (Dumail and Salmén unpublished material).

Combined load + compression

The load required during a second deformation, in compression after a preceding one in combined shear and compression load, is much lower than that needed in a second cycle in compression after a compression cycle (**figure 34**). Moreover the first deformation in combined shear and compression utilizes less energy than the first deformation in compression.

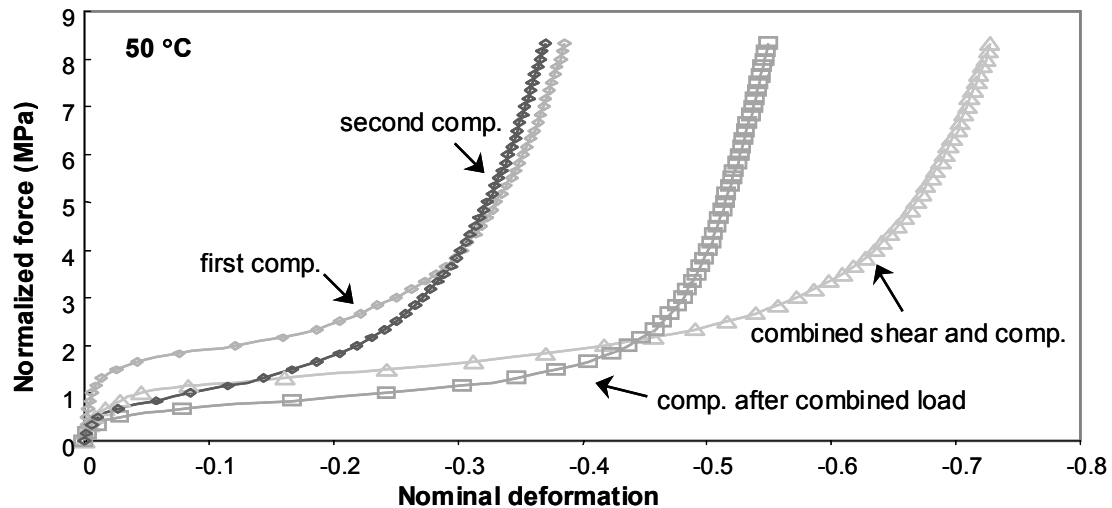


Figure 34 Comparison of stress-strain curves in compression repeated loading tests. Samples were tested in water at 50 °C.

Thus, these data suggest that in order to obtain a high degree of collapse with low energy demand a combination of a compression with a low shear followed by a compression load is more beneficial than only a repeated compression cycling. The different energy requirement for the different cycles are summarized in **table 1**, page 32.

It is well known that subjecting a material to a loading in the same way does not progress the breakdown to the same extent as when altering the loading mode or loading path (Steenberg 1980). Thus for the purposes of energy savings a sequence of different loading of the fibres of wood is an interesting option.

4.6 Energy consumption under loading sequences

To further explore the effect of sequential loading test combinations of shear and compression load together with a pure compression load were tested; the first sequence had a first cycle in combined load then a cycle in compression and the last cycle in combined load and the second sequence had the first cycle in compression followed by a cycle in combined load and a last cycle in compression, see **table 1**, page 32. Both sequences were tested at the temperatures of 50 and 90 °C.

The energy used under the different loading conditions indicated that the first deformation required the largest amount of energy, for all loading conditions and temperatures tested. A compression cycle after a cycle in combined load required less energy than the compression cycle after a cycle in compression. The third cycle in compression had a lower energy demand than the cycle in compression after a combined load, especially in the case of tests performed at 50 °C (**figure 35**).

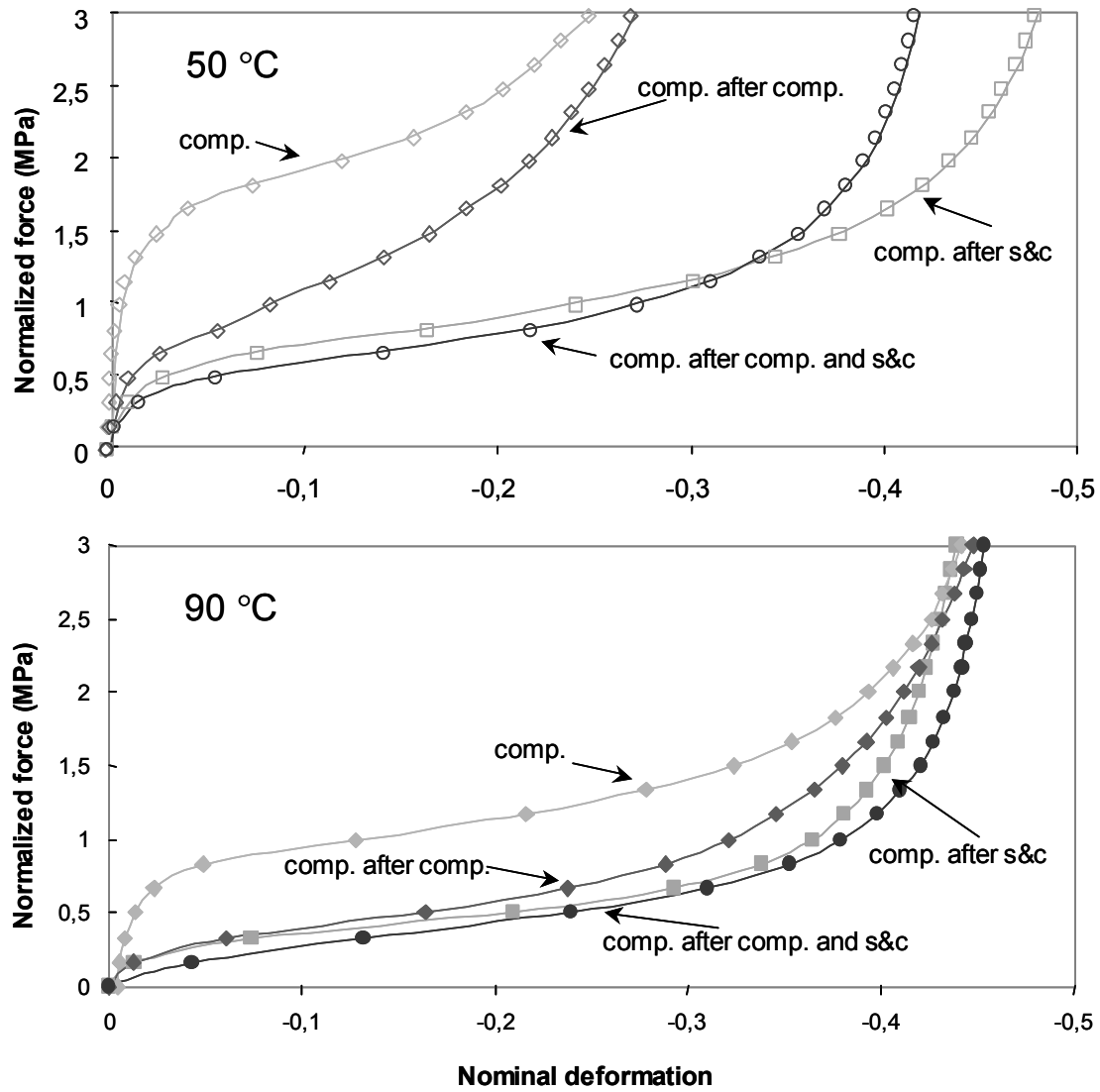


Figure 35 Normalized force versus nominal deformation curves for tests in compression performed in varies steps of the two sequences at the two temperatures of 50 °C (top) and 90 °C (bottom).

In **table 1** the average energies needed in the different loading cycles to reach a strain level of 30 % are listed for the tests at low and high temperature. The strain level of 30 % has been chosen to compare the curves at their stress plateau values. The two cycles in compression at 50 °C are more in the densification area, as their plateau region is much shorter than in the other loading curves. The energy in the second cycle of pure shear is calculated just to a strain of 22 % due to the limited data available for this deformation cycle (Dumail and Salmén 1999a). The curves can be compared also at a given stress level, in that case the strain reached is much larger under the combined load deformations. In that a case the energy levels will be more similar.

Table1 Energy consumption, in kWh/t, for the different loading cases calculated for a strain level of 30 %. The curve for the shear energy is taken from **figure 13** where the second cycle only reached a maximum strain level of 22 % (Dumail and Salmén 1999a).

	1 st cycle		2 nd cycle		3 rd cycle	
	load	energy	load	energy	load	energy
50 °C	comp	1.3	comp	0.9		
			s&c	0.44	comp	0.39
	s&c	0.72	comp	0.45	s&c	0.34
90 °C			comp	0.28		
	comp	0.57	s&c	0.24	comp	0.22
	s&c	0.43	comp	0.25	s&c	0.17
			shear	0.15 (22 % strain)		
	shear	0.26	comp	1.09		

As can be seen from the values listed in **table 1**, the deformations at high temperature always use less energy than the corresponding cycles at lower temperature.

The overall conclusion is that for subsequent deformations less energy is needed for compression if a combined load has preceded it. The deformation in compression requires larger amounts of energy than the deformation in combined loads.

Due to the fact that less energy is needed to start to deform wood in combined load than under compression load, the application of a combined load as a first cycle may thus be a way to permanently deform fibres using less energy.

5. MODEL OF WOOD CELL DEFORMATIONS (Paper V)

5.1 Background

Modelling of structural deformations of a material has the ability to test how different parameters, as here the wood constants or the load application points, affect the resulting behaviour. Once a model has been shown to work well enough to reproduce the real behaviour it is both easy and economical to study variations of the model itself and in that way obtain information on the principles ruling some given behaviour.

Modelling of wet wood under compression and combined shear and compression load was in this thesis performed to better understand the key factors effecting the collapse of wood fibres under conditions of mechanical pulping of wood chips in refiners. Experiments under these loads have shown that the wet fibre network exhibits two different deformation modes; an “S” shape mode associated with compression and a “brick” shape mode associated with combined shear and compression. To study the factors governing these mechanical behaviours of the fibre network a material model with the characteristics originating from the properties of the wood polymers was developed. The model was developed from a two-dimensional nine cell model to a three-dimensional twelve cell model.

A number of different FE models of wood at different structural levels have been developed in the last years to simulate the behaviour of the wood material at different levels of organization, from the behaviour of wood (Ormarsson et al. 1998) to annual rings (Jernkvist and Thuvander 2001) to fibres (Holmberg 1998, Persson 2000, Astley et al. 1998) and to fibre walls (Koponen et al. 1989, Koponen et al. 1991). These models were developed more to derive the elastic properties of softwood from its cellular structure than to study the deformation behaviour of the cells themselves.

As none of the previous models were considered suitable for predicting single fibre deformation behaviour under diffuse stresses a new model, at the level of a few fibres, was developed in this thesis. The global loading in combined shear and compression of a wood test sample gives each individual wood fibre a complex loading influenced by the surrounding fibres. A cell wall model of twelve fibres was thus developed to be able to capture the influence of neighbouring cells while still reaching results in reasonable computing times. The deformation pattern of this model was studied with respect to different material properties.

5.2 Material model

Wood can accurately be treated as an orthotropic material with three perpendicular principal material directions.

To model the deformation of the wood cells under load some knowledge of the ultrastructure is needed (see Section 2.3). At the fibre level the cell walls can be seen as a laminate with three thin unidirectional orthotropic layers of lamina, representing the secondary wall (S_1 , S_2 , S_3) and one layer of randomly oriented fibres representing the primary wall (the P layer). The

lamina of the secondary wall, **figure 36**, was assumed to be transversely isotropic. The analysis was based on the assumption that for these thin layers plane stress conditions prevail.

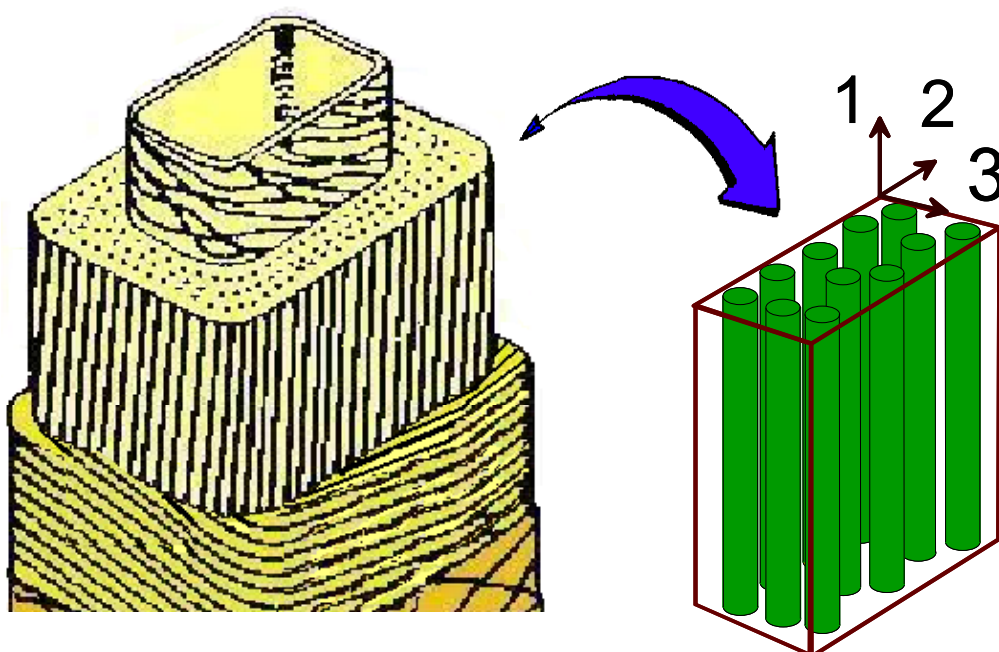


Figure 36 Schematic illustration of the structure of a lamella in the secondary wall of a softwood fibre.

The influence of the material properties on the deformation of the fibre network was studied by starting from the wood polymer properties, building up the lamella of the cell wall to the final cell shape. The material properties of the cell walls were calculated from data of the component polymers and by the orientation of the cellulose aggregates, the fibrils. The cellulose fibrils were assumed to be perfectly aligned and evenly distributed in each layer. The hemicellulose and lignin matrix was assumed to have complete bonding with the cellulose fibrils and to be aligned in the same direction as these. The matrix was also assumed to be homogeneous. The properties were so calculated for the local 1, 2 and 3-direction for the cell layers. In the model for each layer the properties were applied to local cylindrical reference systems oriented along the fibrils. This means that the main axis in the local coordinate system (the first principal material directions) was oriented along the fibrils.

5.3 Models of a wood cell

All the FE models previously developed to predict the elastic properties of wood start from determining the shape of the wood cells. One of the first models of wood (Price 1928) was based on tubular cells arranged in a two-dimensional lattice. In more recent times a honeycomb model, still two-dimensional, was developed. This model had hexagonal cells (Gillis 1972) to capture some of the irregularities of the wood structure (**figure 37**).

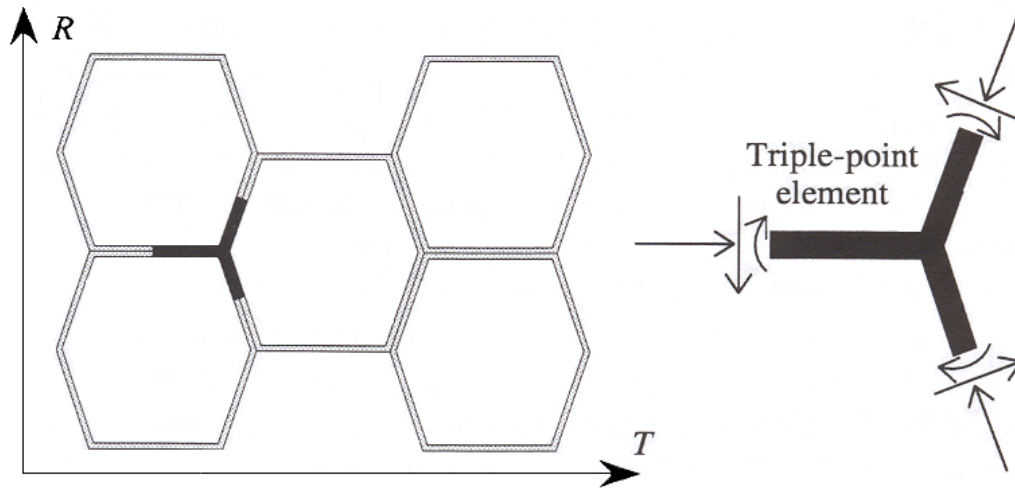


Figure 37 The model of the cellular structure developed by Gillis (1972).

Most of the models that have been developed in the last years have started from the hexagonal model considering non-uniform thickness of the fibre walls (Watanabe et al. 2000) or considering irregular shapes (Jernkvist 2000 and Persson 2000) (**figure 38**).

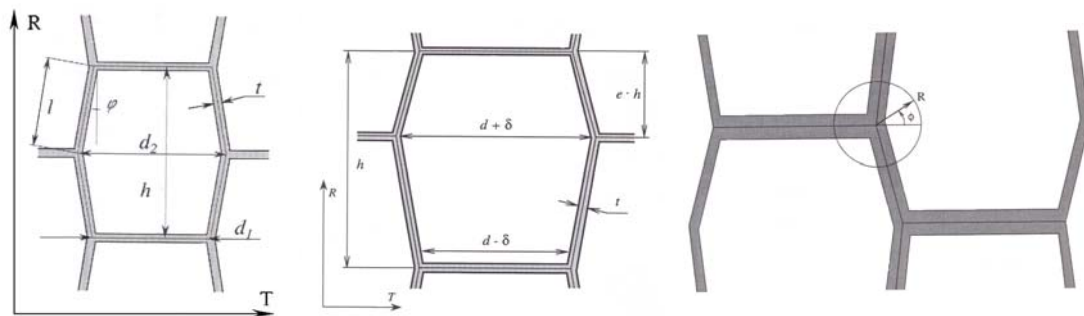


Figure 38 The models of the cellular structure developed by Jernkvist (2000), *left and centre*, and Persson (2000), *right*.

Some authors (Perré 1997, Persson 2000) use homogenisation to predict macroscopic properties from the microscopic description of a non-homogeneous medium. This method works under the hypothesis that the medium is periodic and that the material is composed of subcells of equal shape. A material is periodic if its properties have a variation that follows a repetitive pattern. The homogenisation, when applicable, reduces to solve the problem over a unit cell. Both Perré and Persson use a square cell to calculate the homogenisation properties of the cell wall which are then applied to a geometry of square fibre cross section in the case of Perré (**figure 39**) while Persson uses the hexagonal fibre cross section show in **figure 38**.

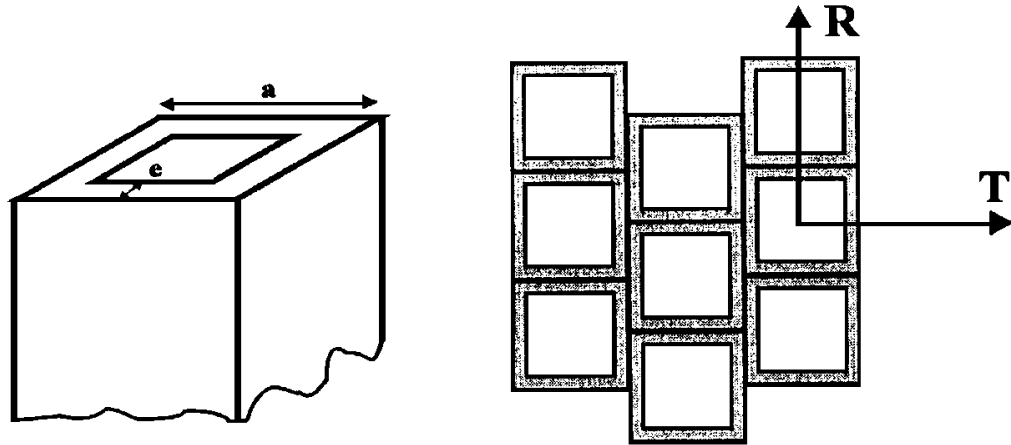


Figure 39 The model of the cellular wood structure and geometry developed by Perré (1997) applying homogenisation procedure.

In reality wood cells are hexagonal, pentagonal or square with large variations in the length of the sides and the symmetry or asymmetry of the cells themselves. When examining the cell structure of the spruce wood studied, in general the cells are more of a square type than hexagonal. Images of cells of the spruce samples tested did not show any preference in the shape of the cells (Paper III). Thus the cell model was in this thesis assumed to be square. The dimensions were taken as an average for wood fibres. In fact, with the thickness of the wall of one fifth of the diameter of the cells they are more compact than the average earlywood cells being more close to dimensions of transition wood fibres. The cell wall was divided into four layers (see **figure 40**).

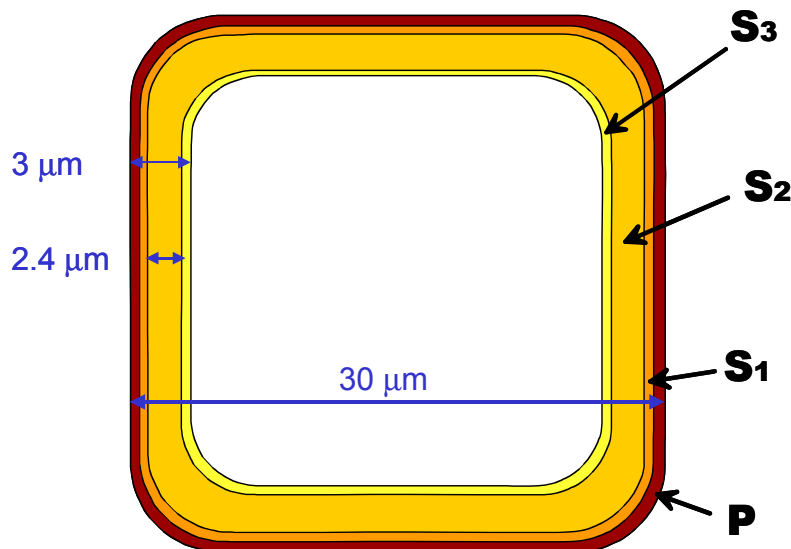


Figure 40 Geometry of the cell wall model in cross section representing a softwood fibre.

5.4 Two-dimensional modelling of a network of nine cells

The network models were designed in the first case as a 2-D model to study the effects on the middle cell surrounded by cells simulating different structural environments. In this case eight similar cells flanked the cell for

which the deformation behaviour was to be modelled. Connecting the nine cells together is the middle lamella. To decrease the model size, the cells of the upper and lower rows were modelled to consist of just one layer. The elastic modulus used for these layers was 6500 MPa with a Poisson ratio of 0.2. Those values were calculated to represent the material properties in 2-D where no orientation of the fibril angle could be introduced into the model and the material was supposed to be isotropic (Palmlblad 2004). The values represent a rather stiff cell wall. Two cell configuration models were tested to model different structural variations in the wood: model 1 (**figure 41, left**) with perfect symmetry and model 2 with the lateral columns of cells placed one third of a cell length vertically lower (**figure 41, right**).

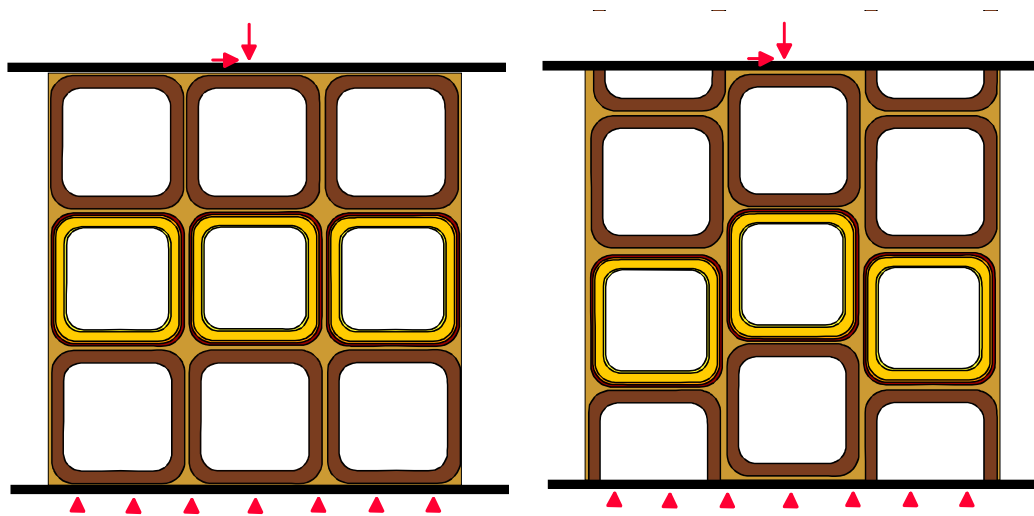


Figure 41 Geometries of the softwood structure in the radial tangential plane in the 2-D models with nine cells.

Buckling analysis

To make the model behave more like in reality during deformation in compression, small geometric imperfections were introduced in the structure, which makes buckling possible. The first two eigenmodes of the two models are shown in **figure 42**. It is clear that the different geometries, even if the difference is small, affect the deformation type. The model on the right has a deformation that is closer to the ones from the experiments. This is probably due to the geometry of the asymmetric model that better represents the structure of the wood cell organization. The model on the left in fact has a shape that is closer to the theoretical shape of a homogeneous material subjected to compression but a honeycomb structure with an irregular geometry will change direction of the slope (about $\pm 45^\circ$) in several places. The model on the right give a more general deformation having the cell walls inclined in two directions.

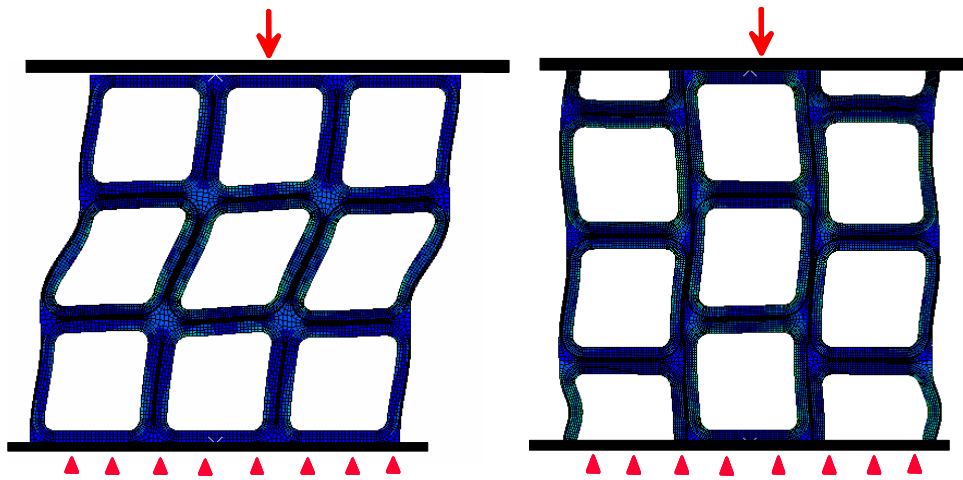
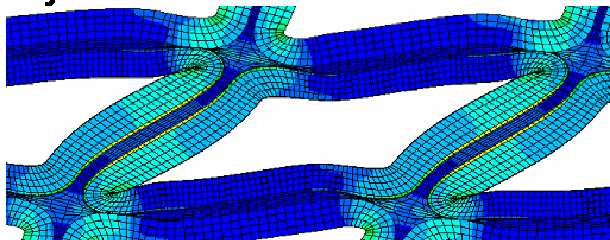


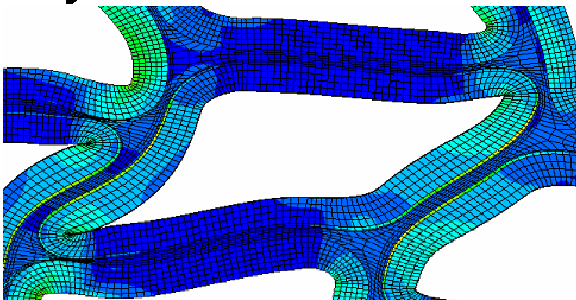
Figure 42 Eigenmodes resulting from the buckling analysis for the symmetric model (*left*) and the asymmetric model (*right*) of the 2-D model.

Still comparing the compression behaviour of the 2-D model configurations on the cell level it is clear that the deformation in the asymmetric model is closer to the one found experimentally than the symmetric one (**figure 43**). However the deformations of both models show a collapse of the lower left hand corners. In the symmetric model both the lower left and the upper right hand corner collapse a fact that is not observed experimentally.

Symmetric Model



Asymmetric Model



Experiments

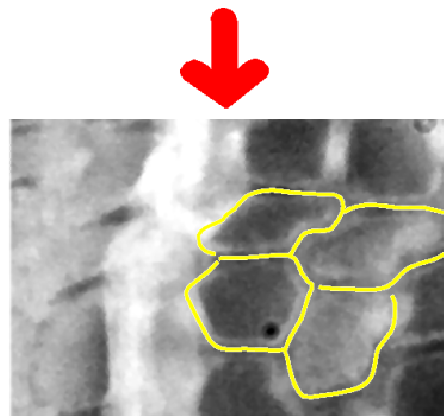


Figure 43 Comparison of the results of the compression analysis of a symmetric model (*left, top*) and an asymmetric model (*left, bottom*) with an image of deformation of wood in compression (*right*).

In this 2-D model the transverse isotropic assumption makes the cell model isotropic in the R-T plane. This means that the elastic modulus along the cell wall, E_T , equals the elastic modulus transverse to the cell wall, E_R . Taking into consideration that in reality E_R is lower than E_T may change the deformation form. The use of a full orthotropic material could thus affect the cell deforming shape. However, in order to have an orthotropic material in a coordinate

system out of the plane of the cross section of the cell requires a model in 3-D to be used.

5.5 Three-dimensional modelling of a network of twelve cells

To simulate the deformation of a fibre in the wood material a row of four fibres was modelled surrounded on top and bottom by two other rows of four cells (see **figure 44**). The enlargement of the cell model as compared to the 2-D analysis was found necessary in order to not obtain too large boundary effects on the edges. As the 2-D analysis indicated a better resemble with reality for the asymmetric cell arrangement such a model was here chosen. All the resulting twelve cells were connected to a frame modelling the middle lamella that separates two cells with a distance of $0.9\text{ }\mu\text{m}$. To decrease the model size for computation, the cells of the upper and lower rows were assumed to only consist of one layer. The material properties for this layer were chosen to be isotropic linear elastic and slightly stiffer than the S_2 layer in the R and T directions: $E=3500\text{ MPa}$ and $\nu=0.2$. The lower stiffness of these cells was chosen as the upper and lower rows were mainly thought to distribute the load to the cells in the middle row.

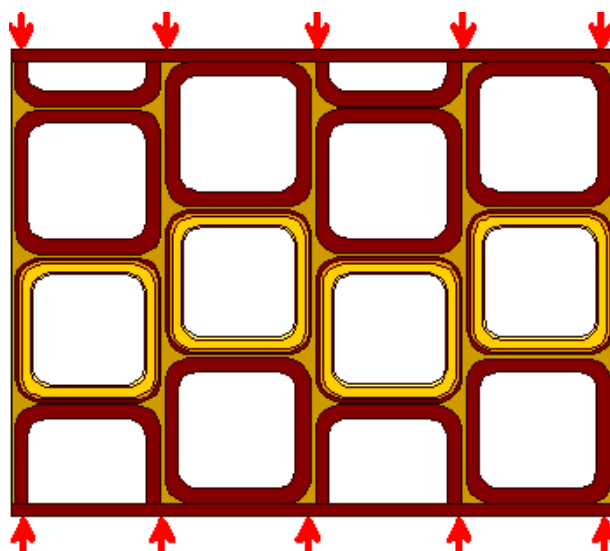


Figure 44 3-D model of the network of cells.

Two plates were modelled on top and bottom of the cell network to apply vertical displacement to the cells. The top and bottom plates were subjected to a controlled vertical movement in the case of compression and a vertical movement and a rotation or a vertical and horizontal movement in the case of the combined load.

All layers were connected to each other with a “tie” constraint. This constraint means that the nodes on the surfaces between the layers were tied together. This initial contact between two surfaces was set to persist during any loading history and no sliding between surfaces was allowed. With this constraint possible delamination between the different layers of the cell walls was excluded. This may to some extent have affected the modelled deformation of the cells as such a mechanism could be relevant for large deformation. In

micrographs taken by ESEM on dried wood samples delaminations between the cell walls may be seen (**figure 45**). Those delaminations occur due to the drying of the microscope sample but are not present in similarly prepared samples that have not been mechanically deformed (Salmén and Pettersson 1995). Thus these delaminations indicate that the bonding between the layers to some extent has been weakened, i.e. some damage has been introduced by the deformation imposed during tests.

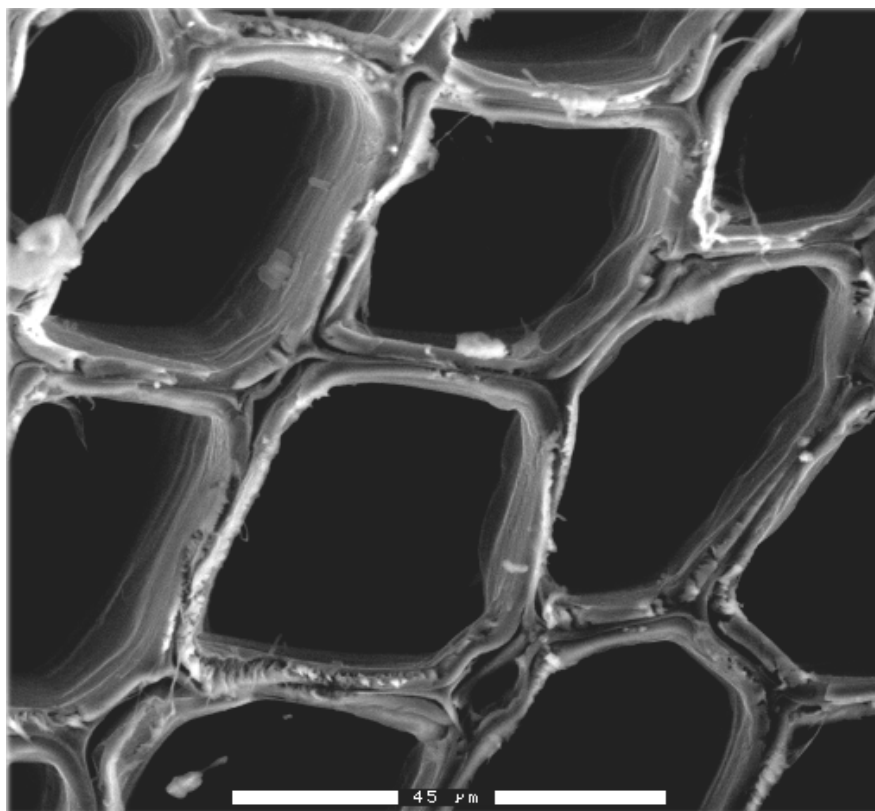


Figure 45 ESEM image of a sample tested in combined load followed by a compression cycle, in water at 50 °C.

Buckling analysis

A buckling analysis was made for each material and geometry. **Figure 46** shows the first two buckling modes obtained in such an analysis. As the difference in eigenmode was small between the different models only the eigenmode from the model made of single cell walls with isotropic material are shown. The second eigenmode was chosen for the further analysis as it was closer, as in the two-dimensional model, to the actual deformed shape observed in the experimental studies (Papers III and IV). The resulting geometry with these geometric imperfections, from the chosen buckling mode, was the starting geometry in compression of the model.

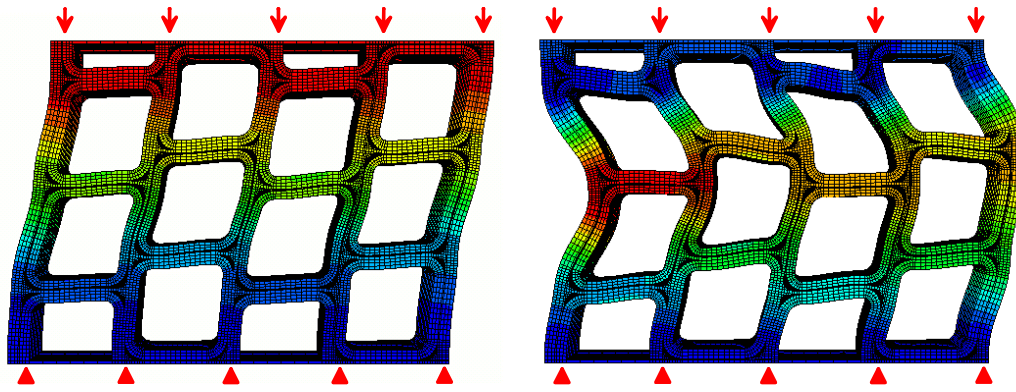


Figure 46 First (*left*) and second eigenmode (*right*) obtained from buckling analysis of the 3-D wood cell wall model.

Model in compression

Figure 47 shows the deformation in compression of the model of twelve cells all made up by a single cell wall layer and with isotropic elastic material. In this case the same material has been used also for the middle lamella. Each cell deformed with a different shape. It is apparent that many of the cells deformed in the typical “S” shape observed experimentally.

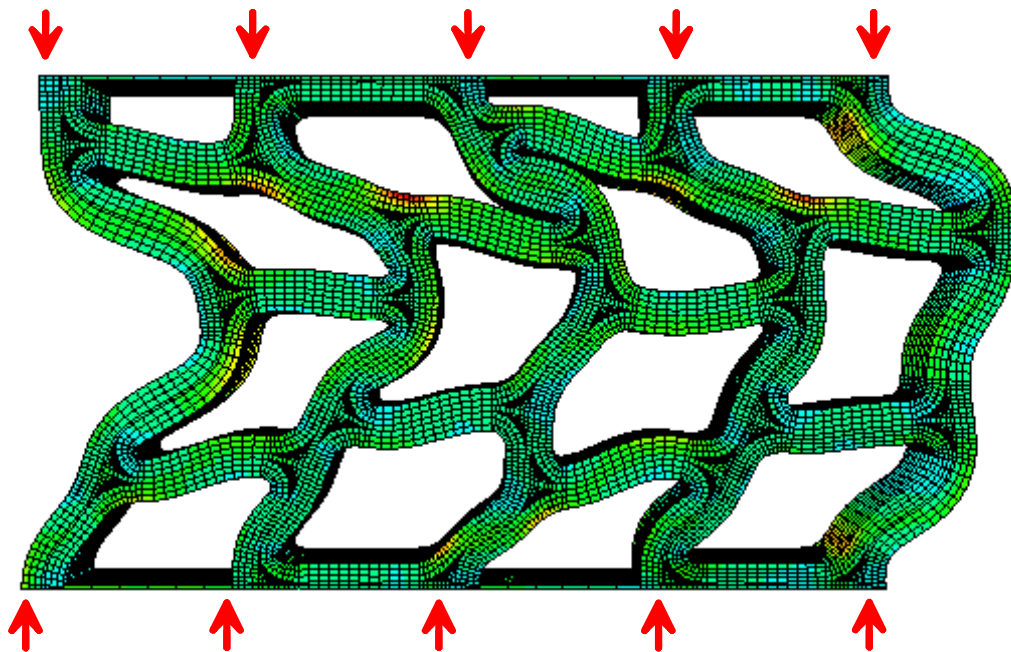


Figure 47 Deformation obtained in compression with a model made of single layered cells with isotropic elastic properties.

When an orthotropic material was introduced in the cell walls of the middle row the deformation was very similar to the deformation of the model with isotropic material for all the cells. Also when introducing cells made of layers of different material to the cells, representing the middle lamella, the P and the S layers, the deformation was similar although some additional bending of the walls of the middle row cells could be seen.

Model in combined shear and compression

To model the loading in combined shear and compression load it was necessary not just to introduce displacements in the vertical and in the horizontal direction but to apply a vertical displacement together with a rotation to model the loading conditions. In fact the wood cells in the experimental combined load tests are subjected to this kind of loading. The resulting loading field from the sum of the displacement and the rotation can be seen in **figure 48**.

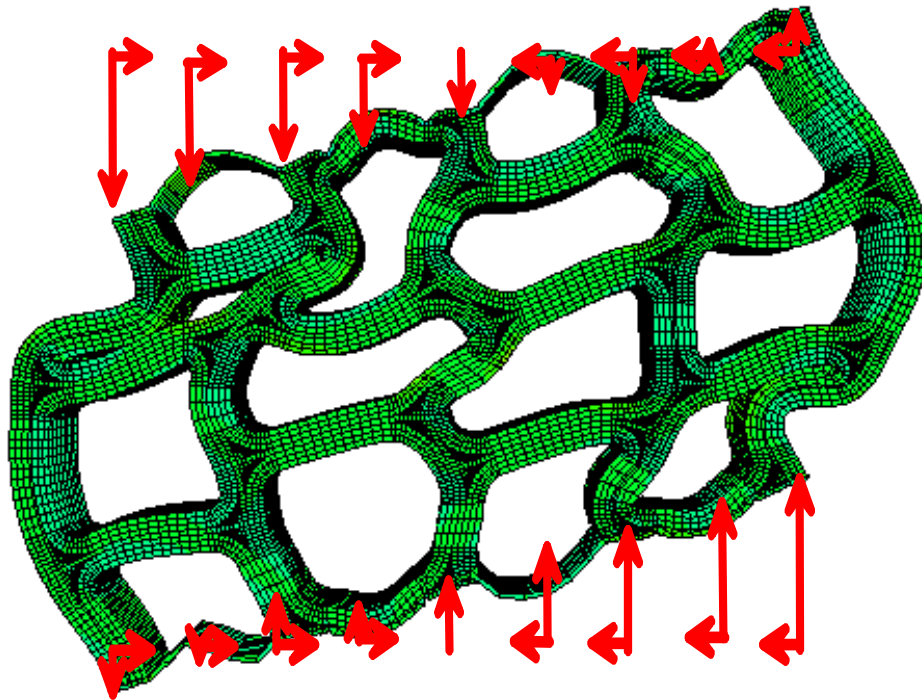


Figure 48 Deformation obtained in combined shear and compression with a model made with single layer cells modelled with isotropic elastic material.

Also in this case the further refinement of the model on the cell wall level with material orthotropy and layered structure did not affect the outcome of the simulations.

Comparing the FE simulation of the deformation with the two deformation types analysed within the previous experimental work (Papers III and IV) it is obvious that some of the cells of the middle rows of the model here developed deform as observed experimentally both under compression (**figure 49**) and under combined shear and compression (**figure 50**).

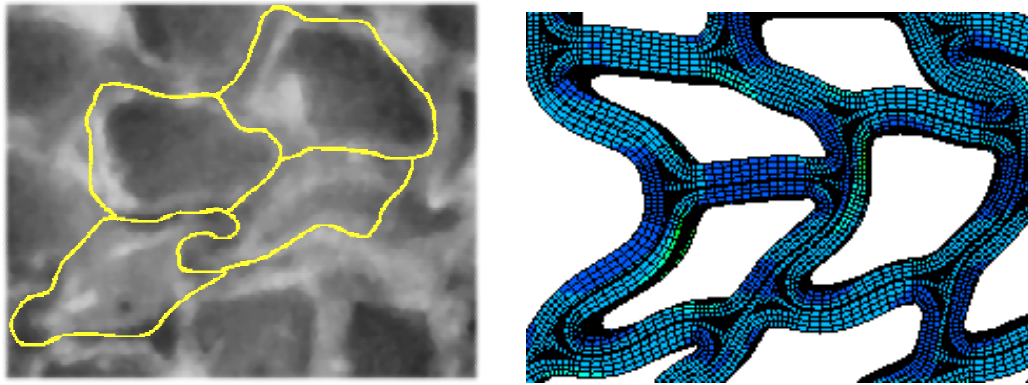


Figure 49 Comparison of the deformed shape obtained in compression: experimentally, *left*, and by numerical analysis, *right*.

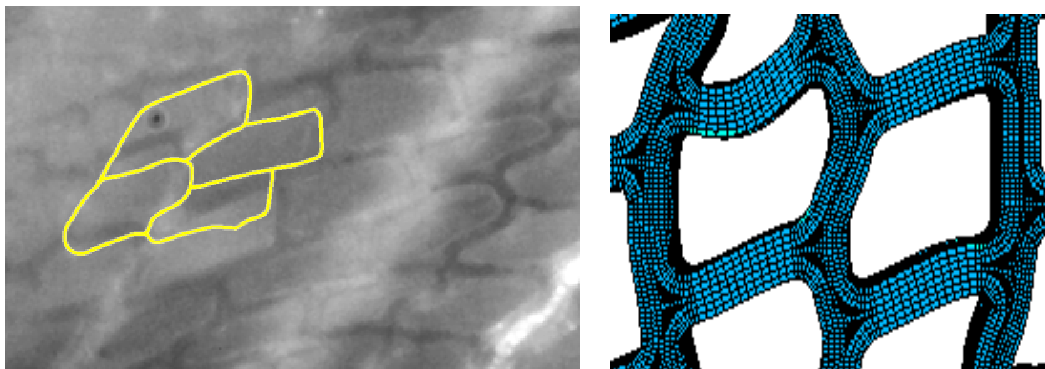


Figure 50 Comparison of the deformed shape obtained in combined shear and compression load: experimentally, *left*, and by numerical analysis, *right*.

It is important to stress that the material properties used in this model are linear elastic, while wet fibres may also exhibit some plastic type of material behaviour during mechanical loading which could be a reason for the discrepancies seen.

The analysis here made shows that it is possible to model the complex deformation patterns of wet wood in its transverse direction both in compression and in combined shear and compression load. However this requires the use of a 3-D model, as a simple 2-D model was not able to represent the cell shapes obtained experimentally in a suitable manner.

The deformation achieved both under compression and under combined shear and compression was found to be similar independent of the material constants used or the numbers of layers of the cells walls that the model was composed of. This implies that the most important factor governing the deformation pattern of the fibre network is the cell structure itself. This might also be the reason why the deformed shape of the water-saturated wood cells are very similar at low and high temperatures where materials properties are largely affected by the softening of the lignin.

6. CONCLUSIONS AND FUTURE ASPECTS

The modification of the Arcan test device here developed has been shown to be a useful method for testing repeated deformation of wet wood samples in different combination of loading conditions. This gives new possibility to study wood fibre deformations under conditions simulating mechanical pulping. Moreover, to combine energy curves and images of fibre deformation has given a new understanding of the behaviour of wood under different loading conditions and combinations thereof.

Test of spruce under other loading situations such as pure shear or under other combinations of compression and shear than used here could make this study more complete, although the combinations with a small component of shear have so far seemed to be the more promising deformation type for deforming wood with low energy levels.

Different wood species as well as wood from differently grown trees of the same species could also be easily tested and the results compared concerning both deformation type and energy used for a better understanding of how wood quality affects refining.

The finite element method has proved to be a versatile method that well complements any experimental work. The model developed in this thesis could be improved by changing the geometry of the cells to one taken from a real image from an experiment on wood. In that case a larger number of cells should be modelled but the material used could be of isotropic elasticity. Another possibility should be to look at the concentration of stresses in the present model and to introduce a fracture mechanism in those areas to simulate delaminations between layers.

The results from this work will be used to try to develop an alternative way of producing mechanical pulp. A laboratory device has already been built on the principle of applying shear and compression loading to wood fibres and is running at STFI-Packforsk. The possibility of replacing the refiner with such a new a process requires however more thoughts and many practical experiments before being a reality.

7. ACKNOWLEDGEMENTS

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