The Consequences of Wood Cellular Structure and Rolling-Shear in Crossbanded Veneer Composites

by

Simo Koponen

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Abstract

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A hierarchical modelling path of wood and wood composites' properties is presented. First the calculation model (WOOD123) is developed for elastic and shrinkage behaviour based on the complex ultra-, micro- and macro-structure of wood, based on the properties of wood main constituents and their orientation. Then the results and the understanding obtained are utilised in the development of the calculation program for the analysis and design of transversely loaded layered wood composite plates (OptiPly).

The model (WOOD123) predicts the elastic and shrinkage properties of wood at the cell wall level and at the macro-level, where wood substances consist of earlywood, latewood and ray cells. The modelling of the cell wall properties and behaviour is based on the properties of cellulose, hemicellulose and lignin. At the cellular level wood substances consist of individual softwood cell types (earlywood, latewood and ray cells). Finally at the highest level of the cellular modelling, earlywood, latewood and ray cells are combined together to predict anisotropic elastic properties of wood, the effects of moisture content on the elastic properties and the nonlinear shrinkage in different directions.

WOOD123 model, developed by this author, has been the first model capable of building the full path from the ultra- and micro-scale material properties, polymer orientation and arrangement to the orthotropic behaviour of wood. Earlier models are limited only to the prediction of cell wall properties or the layered structure of cell wall is neglected and the behaviour of cellular wood substance is modelled using homogenous cell walls.

Due to the lack of suitable micro-scale testing devices and inadequate microscopy facilities and due to the large number of structural and material property parameters required in the model as input data, the development and verification of the model have been done mainly based on the material and structural parameters obtained from the literature. The elastic properties, the dependence of the elastic properties on the moisture content of wood and the complex shrinkage behaviour calculated by the model agreed well with the elastic constants and material behaviour presented in the literature.

Next step was the modelling of the behaviour of layered wood composites. For the development and verification of OptiPly-program large experimental work has been carried out. Tests contain plywood and LVL manufactured using birch and spruce veneers, different veneer thicknesses and special lay-ups, short- and long-term tests were performed and test methods varied from standard tests to more complex beam-type and point-loaded plate tests. The tests showed that the shear deformations in cross veneers have a strong effect on the deflections and the strength of wood composite plates. However, the conventional theory based on Love-Kirchoff hypothesis does not take into account pronounced shear deformations of cross layers.

The accuracy of the classical theory and the generalised Bernoulli's hypothesis is compared. The calculation based on the exact solution of the generalised Bernoulli's hypothesis by Heinisuo correlates well with the test results. The accuracy of prediction of the mid span deflection obtained using the generalised Bernoulli's hypothesis is –16%…+10%, and by the classical lamination theory is –26%…+13%, respectively. OptiPly-program was found to be reliable, slightly conservative and suitable for the practical design of plywood plates. At this moment Finnish plywood and LVL industry uses OptiPly-program in practice.

Key words: cellular structure, mechanical properties, model, plywood, veneer, wood

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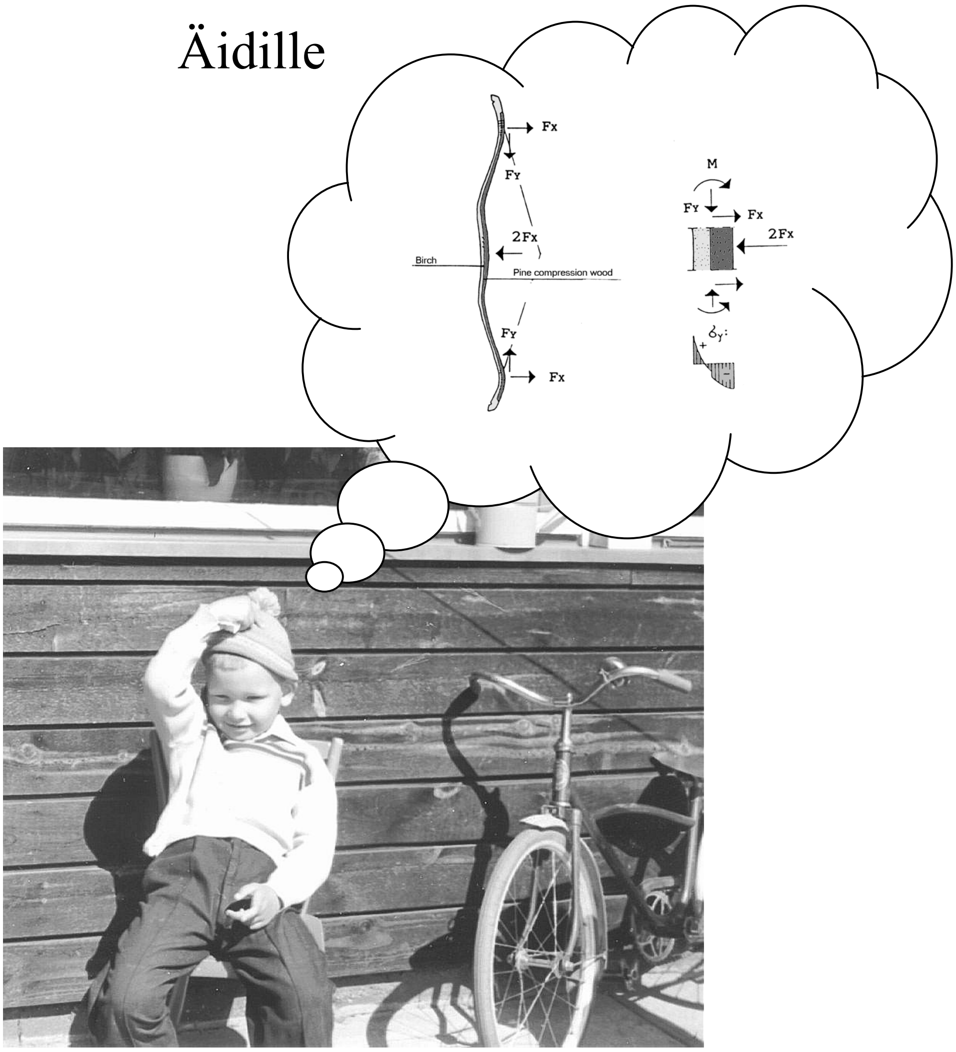

ACKNOWLEDGEMENTS

The challenge to accumulate my understanding and fulfil my curiosity about the diverse material behaviour of wood has been started in 1986 at Helsinki University of Technology, Laboratory of Structural Engineering and Building Physics (HUT-LSEBP) under the guidance of Professor Pekka Kanerva, Dr. Tomi Toratti and Professor Ilmari Absetz. I wish to express my deep gratitude to Professor Pekka Kanerva, who had supervised the wood research group until 2004, for his consistent encouragement and support. My warm thanks are due to my dear friends and colleagues Tomi and Ilmari for pushing me into international wood science community and at the head of the mast, for challenging tasks, motivation, guidance and innovative discussions not only about wood but also sailing So Long, Vivace and skiing, among all.

In 1991 Mr. Vaito Rossi opened my eyes that I can see the world of plywood. With the introduction of Mr. Vaito Rossi (UPM-Kymmene Wood), Mr. Jouko Veistinen (Finnforest Oyj), Mr. Tero Nokelainen (Finnforest Oyj) and Mr. Erkki Meriluoto (Koskisen Oy), I have learned the importance of the end use requirements from the very beginning of my veneer products' (plywood and LVL) research. Professor Matti Kairi has also played an important role in the area of applied research and product development. They are all gratefully acknowledged.

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I hope that I have a talent to share the seeds of accumulateing wisdom and gaps in the knowledge with the ever lasting curiosity to support Mr. Jari Virta, Mr. Pekka Tukiainen and Ms. Susanna Peltola in their challenging research of cupping, fracture and intelligence.

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Espoo 1.5.2005, Simo Koponen

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1. INTRODUCTION

For mechanical wood processing industry, wood product and wood component manufacture it is a challenge to keep and to increase continuous competitiveness. In the case of plywood and laminated veneer lumber (LVL) products it is more and more important to manage efficiently the usage of raw material recourses and to optimise production and the products to the end use requirements. Deeper knowledge on the wood material behaviour in manufacture and in the end use is demanded.

It is important to know how wood's ultra-, micro- and macro-structures affect the strong anisotropy of wood, the mechanical behaviour and strength of wood products in end use applications. Particularly cellular structure has a strong effect when the load is applied in the transverse direction of wood. In several applications plywood and crossbanded LVL products (Kerto-Q) are used as transversely loaded plates. The longitudinal modulus of elasticity of spruce and birch wood is 12 000…18 000 MPa, while in the transverse direction the modulus of elasticity is 250…1 000 MPa due to cellulose orientation and cellular structure of wood. However, the lowest elastic constant is the shear rigidity in transverse direction, it is only 20…200 MPa. The ratio of the transverse modulus of rigidity versus the longitudinal modulus of elasticity can be as low as 1/500…1/100. In the case of isotropic materials, the modulus of rigidity is about 1/3 of the modulus of elasticity. In the case of wood, moisture reduces the value of transverse shear rigidity more than the longitudinal modulus of elasticity. In addition, the creep and especially the mechano-sorptive creep develops much faster in the case of transverse shear than in the case of normal loads in the grain direction.

To obtain more isotropic properties for plywood plates, normally 50…80 % of the veneers are orientated in the main direction and the rest in the cross-wise direction. Although the shear deformations in cross veneers can double the deflection of the transversely loaded plates, the effect of shear is commonly neglected. On the other hand, the classical plate theory is no more valid if there are layers that have very low shear rigidity. In the end use applications, such as concrete formworks and truck floors, those extremely optimistic assumptions can lead to shortening of the service life. To understand the shear behaviour in cross layers of plywood products is essential to know deformation mechanisms on the cell wall and cellular level in wood substance.

The macroscopic mechanical and physical behaviour and strong anisotropy of wood derive from the properties and arrangement of cell wall components and cellular structure of wood. Due to the complex structure of wood, the modelling of the macroscopic behaviour based on a several level hierarchical modelling approach, with simplifying assumptions and a homogenisation of lower level behaviour to reach next level, is necessary.

Robert Hooke discovered plant cells with the help of microscope and sharp razor three hundred fifty years ago. Development of cellular models of wood has been started seventy-five years ago and today a large number of wood property models can be found from the literature. Some of the models can be found in: Price 1928, Schniewind [37], Boutelje [9], Mark [29], Perkins [32], Cave [10,11,12,13,14], Gillis [17], Tang [41], Bodig et al. [7], Salmén [35,36], Gibson et al. [16], Navi et al. [30], Koponen et al. [24,25,26,27,28], Steffanson [40], Persson [33] and Bergander et al.[5,6]. Microscopy observations are still today the most valuable tools in the development of theories and models related to the cellular properties of wood.

The advantage of the ultra and cellular level observations, theories and modelling is that it is not limited only to the elastic behaviour of wood, but it is also more universal with applications in creep [54,55], strength [22,23,41,43,59], heat [56] and moisture transfer [57,58], for example.

The development of these models requires accurate ultra and cellular level observations on the structure of wood, on the material properties of wood constituents as input parameters and also observations on the behaviour of cellular wood in different kinds of loading cases to verify models.

Often the disadvantage of detailed modelling is that, due to complex composite structure of wood, the number of microscopy scale material and structural parameters increases rapidly, which challenges the development of micro-scale testing methods.

2. EVOLUTION OF WOOD MODELS

The first structural model of wood was developed by Price in 1928 and it consisted of hollow tubular cells representing earlywood, latewood and ray cells. In this model cell walls were isotropic and Price concluded that the arrangement of the cellular units causes the anisotropy of the modulus of elasticity.

Schniewind [37] developed a model of shrinkage for black oak that contained earlywood, latewood and ray cells. Boutelje [9] modelled the relationship of the structure to transverse anisotropy with reference to shrinkage and elasticity. He discussed critically about different theories relating to the anisotropic behaviour and made references to experimental results.

Barber et al. [3] predicted mathematically the effect of microfibril angle on the longitudinal and transverse shrinkage of wood cells consisting of an isotropic matrix in which long cellulose microfibrils were embedded. Harris et al. [21] continued this work and using IBM 650 computer predicted the relationship between microfibril angle and longitudinal and tangential shrinkage. This work was successfully further developed by Cave [10,11,12,13,14] taking into account cell wall layers. In 1967 Mark published his book "Cell wall mechanics of tracheids" [29] which summarised biomechanics on cellular level, the observations and the modelling of elastic, shrinkage and strength properties of wood in details. Tang [41] studied stress distribution on each cell wall layer due to tension of single wood fibre and pointed out the importance of the twisting of the single fibre and its effect on internal stresses. In Tang's model the cell wall was layered and cell was assumed to be hollow cylinder. El-Hosseiny et al. [15] used flattened fibres and found that Hill's strength criterion of failure is applicable.

Bodig et al. [7] in their book "Mechanics of Wood and Wood Composites" dealt with modelling based on the layered composite theory and failure behaviour observations and failure modes in wood. Salmén et al. [35] studied the effect of cellulose stiffness, crystallite length, S1-, S2- and S3-layer microfibril angle and relative thickness of S2-layer on the longitudinal modulus of elasticity of wood fibre. In their studies the wood fibre was also flattened.

Gillis [17] extended Price's cellular model using double cell wall triple point elements representing the corner of three adjacent cells and calculated all the elastic constants of wood substance. He studied the geometrical effect of the direction of radial cell walls (rectangular or hexagonal cells) on elastic properties using isotropic material properties of cell walls.

Koponen's [25,26] hierarchical model was fully analytical combining modified Cave's layered cell wall model and Gillis's triple point elements. Triple point elements were improved to include bending, shear and axial deformations of cell walls, especially to increase the accuracy of the calculation of transverse deformations in latewood. At the highest level, the model combined earlywood, latewood and ray cells and predicted all the elastic constants and nonlinear shrinkage behaviour of wood in all directions. In addition, in 1993 Koponen [27] further studied the effect of irregular cell structure on the transverse elastic properties of one annual ring using homogenised cell wall in the finite element model (FEM) and cellular structure based on scanning electron microscope (SEM) study.

Stefansson [40] developed two dimensional FEM based model that contained middle lamella and S2-layer. Cell wall thickness and cell geometry were based on scanning electron microscope (SEM) photographs. Persson [33] continued his work and compared the effects of irregularity of cell structure (true irregular cell structure based on the microscopy, unsymmetrical hexagonal cells and symmetrical hexagonal cells) using FEM (3-D solid element, ABAQUS). Earlywood, transitionwood and latewood were added in the model accurately. At the same time Astley et al. [1,2,20] developed similar cellular FE-model (thick composite shell element, ANSYS) and studied also the effect of geometrical irregularity of cellular structure of softwood. The problems related with FEM modelling of irregular cell structure are the building up the geometrical model, the increasing size of the model, and how to apply boundary conditions to the model. Perré [31] modelled transverse elastic and shrinkage behaviour of ring porous hardwood and softwood with FEM-meshes built directly from the anatomical images.

Bergander et al. [4,5,6] studied the influence of S1-layer on the transverse modulus of elasticity of fibre cell wall and made the conclusion that S1- and S3- layer partly contribute to the value of transverse modulus of elasticity but they cannot be the only parameters affecting this property. Although S3-layer thickness is only 10% of S2-layer thickness, according to Koponen [28], it has an clear effect on the bending stiffness and bending strength of cell walls in transverse compression and shear.

In stepwise loading tests done by Stefansson [40] and Persson [33], the deformations in earlywood in radial compression and in shearing tests in RT-plane were very large. In latewood region no visible deformations occurred. Persson concluded that bending stiffness of earlywood cell walls is important for overall stiffness of softwood substance.

According to Persson [33] the number of tracheid cells between two adjacent ray cells is 7.1 on the average. In Persson's model the stiffness values were close to measured values with exception of the modelled radial stiffness being too high. The modelled shrinkage was also in good agreement with the experiential values except the difference between the radial and tangential was too low. Persson concluded that differences are probably due to the different microfibril angle in radial and tangential cell walls or due to the pores in radial cell walls.

3. STRUCTURE OF WOOD

Softwood consists of hollow tubular cells organised in sequential earlywood, transitionwood and latewood tracheids. In addition to longitudinally orientated tracheids there are radially orientated ray cells. The main components in cell walls are cellulose, hemicellulose and lignin. Cell walls are layered (M, P, S1, S2, S3) composite structures with varying composition and orientation of structural units (elementary fibrils, microfibrils). In the middle of two adjacent cell walls there is a middle lamella gluing cells together and forming a double cell wall. Especially the arrangement of cellulose in different layers has a strong impact on the mechanical and physical properties of wood. In transverse direction the cell structure and its variation are important. Ray cells have also an important effect on mechanical behaviour of wood substance. Pit pores are mainly located in the radially orientated cell walls and they are essential to control liquid flow between tracheids and ray cells but pits may also affect the strength properties.

3.1 Cellulose

The crystalline cellulose is common in all lignified plant cell walls and the cellulose content in wood is 40…55%. The longitudinal elastic constant of cellulose has been theoretically estimated based on the molecular structure by several researchers. The theoretical values have a large scattering from 56.5 GPa to 319 GPa. Sakurada et al. [35] has measured the value 137 GPa for ramie fibres. Mark's theoretical value 111.3 GPa is the closest (17% lower) to the Sakurada's value. The measurements and theoretical analysis of Page et al. (1977) on black spruce fibres, Preston's data (1960) as a function of S2-fibril angle for sisal fibres and Cave's [13,14] modelling indicated that the Sakurada's experimental value fits best to the modelling purposes. Salmén's [35] calculation results verified that the longitudinal modulus of cellulose is close to data presented by Sakurada.

The only values available for the transverse stiffness (Ey, Ez) and shear modulus (G) are theoretical ones. Most of the cell wall models are based on Mark's [29] values (Ey =27.2 GPa, Gxy=Gyz=4.4 GPa, Gxz=6.6 GPa).

The crystallinity of wood cellulose is 67…90% [35]. Between well-ordered regions there are disordered cellulose zones, which are called amorphous regions. These regions are not fully amorphous and properties of hemicellulose have been used to estimate elastic properties at these zones [37]. Generally it is noted that the amorphous regions have only a limited effect on the elastic properties of native wood and in the modelling disordered regions are generally ignored. However, these zones may affect the failure behaviour and strength of wood, if the amorphous regions are located in the same cross-section of the elementary fibrils and microfibrils. Especially in the pulping of wood fibres the reduction of crystallinity of cellulose has decreased the stiffness and strength. If the crystallinity decreases beyond 300 (due to irradiation for example), the strength of solid wood can also be reduced.

The theoretical tensile strength of crystalline cellulose is 19280 MPa, and shear strength is 326.6 MPa [30]. The experimental tensile strength of wood cell walls has varied from 190 MPa to 1480 MPa depending on S2-layer microfibril angle among all. According to Koponen [24] the longitudinal tensile stress in cellulose is about 3000 MPa, when latewood cell wall is loaded by 1500 MPa average tensile load and S2-layer microfibril angle is 0…15 degrees. Mark [29] obtained similar calculation results. Thus, the strength of wood in tension is not limited by the tensile strength of crystalline regions of S2-layer cellulose. Mark concluded that the shear strength is more critical one, but it should be kept in mind that fracture behaviour is very complex and diverse in wood.

3.2 Hemicellulose

Although cellulose is a dominating constituent (amount and orientation) affecting longitudinal modulus of elasticity and strength of wood, hemicellulose and lignin are important in the transverse behaviour. Hemicellulose content of wood is 20…25 %. According to Bergander et al. [6] properties of hemicellulose are dominating the transverse cell wall modulus. In the most of the cell wall models the value of 8 GPa in longitudinal (Ex) and value of 4 GPa for transverse (Ey, Ez) modulus of elasticity have been used in dry conditions. The longitudinal value and the effect of moisture are taken into account based on Cousin's [19] measurements. Transverse value is estimated probably based on the lignin properties. Glass transition temperature of dry hemicellulose is about 200°C and at room temperature it becomes rubbery at moisture content of 25 % [19].

3.3 Lignin

The lignin properties are based on the measurements by Cousins [18]. The modulus of elasticity at dry state is 4 GPa and lignin is assumed to be isotropic. Bodig et al. [7] have used value of 2 GPa. Commonly amorphous lignin is assumed to behave as an isotropic material but according to Åkerholm et al. [49] aromatic units of lignin are not distributed in the structure in an isotropic way. The properties of lignin depend on the moisture and temperature. Glass transition temperature of dry lignin is about 200°C and in wet condition it is 80-90°C.

3.4 Cell wall layers

Cell wall consists of primary wall (P) and secondary layers (S1, S2, S3), (Figure 1). In the middle of the two adjacent cells (double cell wall) there is also a middle lamella (M). Thicknesses of cell walls (2…10 μm) and sizes of cells (porosity) affect the wood density. The thickness of double cell wall affects also bending behaviour and buckling resistance in transverse and longitudinal compression. S2-layer (thickness and micro-fibril orientation) has strong effect on longitudinal properties. Differences between S1- and S2-layer structure have been related to the failure modes observed in longitudinal tension tests. Middle lamella and primary wall affect the transverse tension strength especially at high moisture content and elevated temperature. The shear strength of softwood in LR-direction is often limited by the properties of the middle lamella between latewood-earlywood boundary. This might be due to the sudden change in the density of wood causing more brittle failure type or due to the freezing defects.

According to Brooker [8] there are not clear borders between cell wall layers and he pointed out that it is commonly accepted that the change from one layer to another is smooth and there is intermediate layers S12 and S23. In these layers microfibril orientation is between those of main layers. Brooker referred to work done by Abe et al. [8] and noted that in S1-layer the microfibril orientation changes stepwise in a counter clockwise direction from the outside to the inside, from roughly –45° to about +70° at S12 boundary. S2 has microfibril angle from 20° to 0°. In S2-layer microfibrils are closely packed, but not in the other layers. S2 forms 80…90 % of the double cell wall thickness. Sell et al. [61] and Gu et al. [62] observed that in S2-layer agglomerations of microfibrils are orientated radially. Tangential thickness of agglomerations is 0.1…1 μm. However, according to the most of the earlier and current studies S2 is layered tangentially.

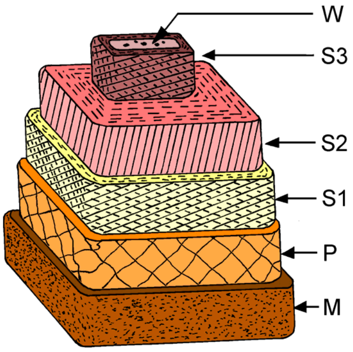

Figure 1: *Illustration of the cell wall layers in latewood*

3.5 Rays

Ray cells have important contribution in anisotropy of broad-rayed timber, such as oak and beech, Boutelje [9]. Pine, however, seems to have similar anisotropic in the rayless regions as has tissue in which rays are present. Boutelje's conclusion is that rays have no appreciable influence on the shrinkage anisotropy in conifers. The shrinkage and elastic anisotropy in transverse plane are due to the differences between radial and tangential cell walls of tracheids. Figure 2 shows the simplified arrangement of the cellular structure of wood used in model WOOD123.

According to Reiterer et al. [34], based on the test performed using oak and ash, one can conclude that the rays play an important role not only in the anisotropy of transverse stiffness and strength but also in the fracture mechanical properties. Their results indicate that even when microcracks have been developed already, the occurrence of a propagating macrocrack in the tangential plane is hindered by the ray tissue.

In addition to strengthening effect of ray cells, rays may be potential fracture propagation paths in the radial plane especially in tangential tension.

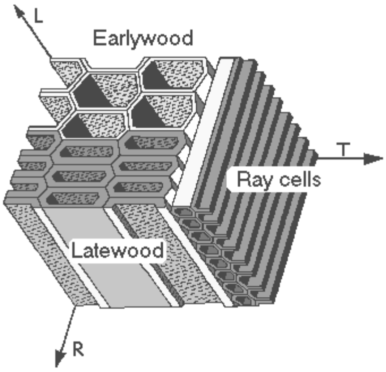

Figure 2: *Illustration of the cellular structure of wood used in model WOOD123*

3.6 Earlywood, transitionwood and latewood

In softwoods the density, cell dimensions and the composition of cell walls are different. Thus, the behaviour and failure modes differ as a function of location in an annual ring. The density of earlywood is about 300 kg/m^3 and in latewood it can be more than 1000 kg/m^3. From mechanical point of view, earlywood is clearly cellular solid material but latewood is closer to the composite continuum with small pores. The change from earlywood to latewood is smooth and this transition region is called as transitionwood. When the annual growth starts, there is a sharp change from dense latewood to light earlywood, which clearly affects the failure behaviour of wood.

4. MODELING OF ROLLING-SHEAR

Transversely loaded laminated composites, including plywood, are often theoretically analysed and dimensioned assuming that the classical plate theory (CPT) is valid with reasonable accuracy. In this theory following assumptions are made:

- lines perpendicular to the middle plane of the plate remain straight and at right angle to the middle plane (neutral axis),
- no out-of-plane shear deformations occur through the thickness of the plate.

These basic simplified assumptions involve the approximation of the linear distribution of strain through the thickness of the plate and shear deformations are neglected. To consider shear behaviour, the first order shear deformation theory (FSDT) has been added to the CPT. In FSDT shear deformations are assumed to be constant through the thickness of the laminate and a shear correction factor is used to compute shear strain energy accurately [50,51,52]. Globally, a good accuracy in the prediction of the deflections can be achieved using FSDT, but locally the stress distributions are not so accurate [43].

In the case of reinforced laminates and sandwich panels calculation models have been developed during last two decades [47], which take into account transverse shear deformations more accurately. Liao et al. [45], Barbero [43], Choi et al. [48] have studied the transverse shear effect in fibre reinforced laminates, when the ratio of longitudinal modulus of elasticity and transverse shear rigidity is 50. Unfortunately for plywood type wood composites these theories have not been yet adopted, although the phenomenon is more pronounced.

Higher order shear deformation theories (HSDT) have been used to improve the prediction of the shear stress distribution through the thickness of plate. Third order theories are capable of presenting quadratic shear distribution through the thickness of homogeneous plate and satisfying traction-free boundary conditions at the top and bottom surface of plate. Here, the shear correction factor is not needed. The application of these theories is however limited to single layer plates, thus the out-of-plane shear strains are continuous across the material interfaces. In the case of multi-layer plates, this assumption will result in discontinuous out-of-plane stress components, thus violate the equilibrium of stresses.

Layer-wise theories are based on continuous displacement distribution through the thickness, but the derivatives of the displacements are not necessarily continuous at the interfaces between layers. Chen et al. [46] have presented a piecewise hierarchical axisymmetric solid element for laminated composites, for example. The finite element formulation of these theories leads to the elements with large number of degrees of freedom (being close to conventional 3-D continuum elements stacked in the thickness direction), which makes them laborious to use. Therefore most studies presented in literature are limited to three-layer laminates. Layer-wise constant shear theories (LCST) are believed to be the best compromise between computational cost and the accuracy [43]. In wood composites, the number of layers often ranges 10-20. Thus conventional or modified 3D-elements require enormous calculation capacity.

Plenty of model development and analysis work dealing with the behaviour of layered beams has been done. The application of layered beam theories is among all sandwich structures, concrete-steel composites, nailed wood beams and shear walls [44]. The solution for the layered beams based on the generalised Bernoulli's hypothesis solved by Heinisuo [44] can be regarded as LCST.

The solution of layered beams can be directly adopted in the model of layered plate structures, if the plate is assumed to consist of a raft girder with layered rectangular beams in x- and y-direction. The advantage of this model is that only five degrees of freedom (DOF) are needed at each node regardless of the number of the layers in the plate. The disadvantage is that the twisting of the plate is not considered.

5. SUMMARY OF THE THESIS

5.1 Paper I and II

Koponen S., Toratti T., Kanerva P.: Modelling Longitudinal Elastic and Shrinkage Properties of Wood. Wood Sci. Technol. 23:55-63, 1989.

Koponen S., Toratti T., Kanerva P.: Modelling Elastic and Shrinkage Properties of Wood Based on Cell Structure. Wood Sci. Technol. 25:25-32, 1991.

The model (WOOD123) to predict elastic and shrinkage properties of softwood is presented in Paper I and II. Paper I deals with the modelling of cell wall properties and behaviour based on the properties of the wood main polymeric constituents: cellulose, hemicellulose and lignin. In Paper II the behaviour of the wood substance concerning individual softwood cell types (earlywood, latewood and ray cells) is modelled. Further effort is that earlywood, latewood and ray cells are combined together to predict softwood elastic properties and shrinkage.

Model WOOD123 developed by the author is the first model capable of building the full path from the micro-scale material properties, polymer orientation and arrangement to orthotropic behaviour of softwood. Earlier models are limited only to the prediction of cell wall properties (Cave [10,11,12,13,14], Tang [41], Salmén [35]) or to the behaviour cellular substance with homogenous cell walls (Gillis [17], Gibson [16]).

Due to the lack of suitable micro scale testing devices and inadequate microscopy facilities and due to the large number of structural and material property parameters required in the model as input data, the development and verification of the model have been done mainly based on the values obtained in literature. The elastic properties, the dependence of the elastic properties on the moisture content of wood and the complex shrinkage behaviour calculated using the model agreed well with the values and behaviour presented in literature.

5.2 Paper III

MFA International Workshop, New Zealand 21-26.11.1997. Effect of Wood Micro-Structure on Mechanical and Moisture Physical Properties. Koponen S.

Paper III builds the link between the microstructure of wood as a raw material (Paper I and II) in wood composites and the mechanical properties of layered wood composites manufactured using veneers (plywood and laminated veneer lumber, LVL). Traditionally the bulk density of wood has been the main parameter used to explain the elastic, strength and moisture properties (sorption, elastic and strength properties and shrinkage). However, more detailed knowledge of the suitability of the specific wood species or an individual stem and the part of the stem (distance from the pith, height) could be obtained, if the wood composition and its variation were known at the annular ring level, at the cellular level (earlywood, transitionwood, latewood and ray cells) and at the cell wall level (M-,P-,S1-,S2-,S3-layers).

The importance of S2-layer on the elastic and shrinkage properties of wood is already well known based on the several experimental and theoretical studies performed by the author and the other scientists. In this paper, more focus is on the transverse properties of wood. Paper shows that the layered cell wall structure in details, bending, compression and shear deformations of cell walls occurring in the transverse loading cases should be known to obtain full understanding of the material behaviour.

Attention is also paid for the effect of S3-layer composition, orientation and thickness in this paper. In practice the transverse behaviour of wood substance is important in cross layered wood composites produced using veneers like in plywood plates. This is due to the large shear deformations (rolling-shear) occurring in the cross veneers.

5.3 Paper IV

COST 508 Final Conference. Stuttgart, Germany. 1996: Shear properties and behaviour of plywood and LVL. Koponen S.

Different test methods used to determine the planar shear (rolling shear) strength and the shear rigidity of plywood and LVL are compared. Analysis is made for birch and spruce veneers. It is based on the test results obtained from literature and the experimental work. It was found out that the standard test method according to EN 789 gives 20% lower shear strength than 4-point bending test at short span analysed using classical lamination theory. In the short span bending tests the span length (the span to panel thickness ratio) and the loading configuration (3-, 4-, and 5-point bending) both affect the rolling shear strength value. Moreover, the density of veneers, rotary peeling cracks, stacking sequence and moisture content have also effects on the shear strength and shear rigidity.

5.4 Paper V

IUFRO S5.02 Timber Engineering Group Meeting, Sydney 5-7.7.1994. Shear analysis of cross veneered wood composites. Koponen S.

In this paper the shear behaviour in flatwise bending of cross veneered wood composites is studied theoretically and experimentally. The paper shows that the classical lamination theory (Love-Kirchhoff law) is not accurate due to the large shear deformations (rolling-shear) in cross veneers. The generalised Bernoulli's hypothesis and its exact solution derived by Heinisuo [44] are adopted to overcome this problem. A computer program based on Heinisuo's theoretical work was developed for the analysis of layered wood composites.

The experimental part consists of 336 tests of birch plywood specimens having different lay-ups, spans and loading configurations. The material parameters for the developed calculation program are determined accordingly. The accuracy of the classical theory and the generalised Bernoulli's hypothesis is compared. The calculation model based on the exact solution of the generalised Bernoulli's hypothesis was in a good agreement with the test results. The accuracy of the prediction of the mid span deflection obtained using the generalised Bernoulli's hypothesis falls –16%…+10%, and the classical lamination theory –26%…+13%, respectively.

5.5 Paper VI

COST 508 - Wood Mechanics, Workshop on service life assessment of wooden structures, Espoo 18-19.5.1994. Long-term behaviour of wood composites - shear creep and crack formation in cross veneered structures. Koponen S.

In this paper the shear behaviour of cross layers are studied. Both short-term and long-term tests have been performed and analysed. In long-term loading the damaging process at compression side, opening of rotary peeling cracks at cross layers, the effects of knots and the density variation on creep and shear deformations were observed.

5.6 Paper VII

COST 508 Wood Mechanics Workshop on Mechanical Properties of Panel Products, 22-23 March 1995 in WATFORD, UK. Effect of Moisture on Short-term properties, Creep and Long-term Strength of Plywood Slabs. Koponen S., Saavalainen I.

The effect of rolling shear behaviour in transverse loading of plywood plates are studied. The applicability of different theories is discussed (classical plate theory, first order shear theory and higher order shear theories) and shear stress distributions are compared. Both the short-term and long- term test results are presented. The results show that under high moisture content and varying environmental humidity rolling-shear is pronounced.

The experimental and theoretical analyses of point loaded plywood plates were also conducted in this paper. The applicability and the accuracy of the developed layered plate raft-model (later versions of the calculation program is named as OptiPly) based on Heinisuo's solution were analysed.

5.7 Paper VIII

IUFRO S5.02 Timber Engineering Group Meeting, Copenhagen 18-20.6.1997. Moisture deformations and creep of plywood. Koponen S., Saavalainen I., Lehtinen M.S.

This paper deals with the warping and creep behaviour of plywood subjected to varying environmental humidity. In the case when both faces of the plywood are exposed to surrounding moisture (two sided wetting), the warping is due to the material property variation between individual veneers used in plywood lay-up. Thus, the theoretical analysis is made using Monte-Carlo simulation and classical lamination theory.

The mechano-sorptive creep was mainly caused by the rolling-shear creep of cross veneers and compression creep at the compression side (longitudinal veneers) of the specimen. The creep at compression side was found to be larger in birch veneers than in spruce, leading to the different type of shear behaviour. The mechano-sorptive creep analysis is made using model developed by Ranta-Maunus [53], which was found to be accurate although it does not take into account the moisture content distribution trough the thickness, instead, it is based on the average moisture content of specimen.

5.8 Paper IX

IWEC '96 New Orleans, Louisiana, USA. October 28-31 1996: Point Loaded Plywood Plates, Koponen S.

In this paper program OptiPly is introduced and its accuracy is analysed. It is based on the generalised Bernoulli's hypothesis [44] and plate raft-girder model. OptiPly has a user friendly pre- and post-processing interface and it is developed for the design of plywood plates in different end use applications. At this moment OptiPly program is used by UPM-Kymmene Wood and Finnforest for the design and optimisation of plywood and LVL plates.

Tests using double span point loaded plywood plates were performed. In the prediction of the linear part of deflections of point loaded plywood plates, an accuracy of ±15% was obtained when the material parameters used in the calculation model are derived from 3-, 4-, and 5-point bending test of beam specimens. However, the strength values were 20% higher in point loaded case than that in the beam tests. This is due to the stress redistribution occurred in non-linear part of the loading. Thus OptiPly was found to be reliable, slightly conservative and suitable for the practical design of plywood plates.

6. CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

A hierarchical modelling path of wood and wood composites' properties is presented. First the calculation model (WOOD123) is developed for elastic and shrinkage behaviour based on the complex ultra-, micro- and macro-structure of wood and based on the properties of wood main constituents and their orientation. Then results are further utilised in the development of calculation program (OptiPly) for the analysis and design of transversely loaded layered wood composite plates.

The model (WOOD123) predicts the elastic and shrinkage properties of wood at cell wall level and macro level, where wood substances consist of earlywood, latewood and ray cells.

The modelling of cell wall properties and behaviour is based on the properties of wood main polymeric constituents: cellulose, hemicellulose and lignin. At the cellular level wood substances consist of individual softwood cell types (earlywood, latewood and ray cells). Finally at the highest level of the cellular modelling, earlywood, latewood and ray cells are combined together to predict anisotropic elastic properties of wood, the effects of moisture content on elastic properties and nonlinear shrinkage in different directions.

Model WOOD123, developed by the author, is the first model capable of building the full path from the ultra- and micro-scale material properties, polymer orientation and arrangement to the orthotropic behaviour of wood. Earlier models are limited only to the prediction of cell wall properties or the layered structure of cell wall is neglected and the behaviour of cellular wood substance is modelled using homogenous cell walls.

For the development and verification of program OptiPly large amount of experimental work has been carried out. Tests contain plywood and LVL manufactured using birch and spruce veneers, special lay-ups, short- and long-term tests were all performed and test methods varied from the standard tests to the more complex beam-type and point loaded plate tests. The results indicate that the shear deformations in cross veneers have a strong effect on the deflections and strength of wood composite plates. The conventional theory based on Love-Kirchoff hypothesis does not take into account pronounced shear deformations of cross layers.

The accuracy of the classical theory and generalised Bernoulli's hypothesis is compared. The calculation based on the exact solution of generalised Bernoulli's hypothesis was in a good agreement with the test results. The accuracy of the prediction of the mid span deflection obtained using generalised Bernoulli's hypothesis varies –16%…+10%, and by the classical lamination theory –26%…+13%, respectively. Program OptiPly was found to be reliable, slightly conservative and suitable for the practical design of plywood plates. At this moment Finnish plywood and LVL industry uses OptiPly-program in the design of plywood structures in practice.

Although the elastic behaviour of wood can be fully understood simply based on the longitudinal properties of cellulose, layered structure of cell walls and cellular structure of wood substances, the wisdom of the strength of wood is more challengeable and more laborious to achieve.

To get deeper insight into the strength behaviour, the first step is to understand elastic behaviour of wood. At the macroscopic level, the elasticity is more or less averaged value of the ultra- and micro-scale movements of the substance or structural elements and the modelling itself stands imperfections but without loosing its moderate accuracy. It is known that strength and fracture initiation are very local. Nevertheless, the prediction of the local stress field, place of the critical point, the mode of failure and the direction of the fracture propagation demand lots of experiences achieved on the *in-situ* microscope observations [38,39]. Even if we can make the necessary observations and the correct assumptions of the mode of failure, the prediction is sensitive to numerous parameters. We should be aware that several of these are obtained using indirect methods or based on empirical calculations. Also some of parameters which might be important is still being ignored to obtain simpler model.

In the hierarchical modelling with several levels of representative material elements, each combines and transfers necessary information from lower level to higher level models.

Currently, single model that contains all the levels of the material hierarchy and can accurately predict the ultra-level response to the macroscopic loads is beyond our skills and resources. In practice, on each step of the model, some of the lower level detailed information is lost. The wisdom is how to simplify and how to focus accuracy on the critical points.

It should be kept in mind that the process of the damaging of wood is divided to several stages: the elastic behaviour of wood, pre-crack initiation stage (plastic, viscose and buckling processes), initiation of crack and damage zone and fracture and damage zone propagation. Wood may contain cell wall level or intercellular damages for example due to drying or specimen's preparation, which can affect the crack and damage propagation in our test or in practice. Wood is three-dimensional structure and the limited observations at the surface of the specimen or testing using thin specimen may not reflect real life situation.

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