MICROMECHANICAL MODELING OF WOOD FIBER COMPOSITES

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ABSTRACT

An analytical concentric cylinder model for an *N*-phase composite with orthotropic properties of constituents was previously presented by the authors. The model is a straightforward generalization of Hashin's concentric cylinder assembly model and Christensen's generalized self-consistent approach. With only minor modifications the model allows for including also free hygroexpansion terms in the elastic stress–strain relationship to deal with orthotropic phase swelling. Thus the effect of wood fiber ultrastructure and cell wall hygroelastic properties on wood fiber composite hygroexpansion can be analyzed. Using properties available from literature on the three main wood polymers, cellulose, hemicellulose and lignin multiscale modeling was performed to calculate the hygroexpansion coefficients of the fiber cell wall and an aligned wood fiber composite. The fiber cell wall was modeled regarding each individual layer S1, S2 and S3 as a balanced and symmetric laminate since it was assumed that the fiber will be restricted from bending and rotation within the composite.

Regarding the fiber cell wall as a balanced and symmetric laminate enables us to calculate "apparent" fiber properties when rotation is not allowed. In reality the fiber's helical structure leads to an extension-twist coupling and thus a free fiber will deform axially and also rotate upon loading in longitudinal fiber direction making the response more compliant. Within the composite the fiber rotation will be restricted however. Therefore, the decision was also to compare the two extreme cases (i) free rotation and (ii) no rotation of the fiber in the composite.

1. INTRODUCTION

The concern for nature and our environment has dramatically increased the interest in use of renewable and recyclable materials. Wood and other lignocellulosic fiber reinforced polymers have large potential as structural materials due to the high specific stiffness, high specific strength and high aspect ratio of the fibers [1]. Apart from the positive environmental aspects wood fiber composites are also interesting from an economical point of view. Although cellulosic fiber composites are certainly not new to mankind they are still considered relatively novel materials in terms of usefulness in structural design. The reason for this is that the fibers generally show highly variable mechanical properties, dimensions, shapes and low ability to adhere to common matrix materials for efficient stress transfer. Another drawback is the fibers susceptibility to moisture uptake. Cellulosic fiber composites tend to swell considerably at water uptake and as a consequence mechanical properties, such as stiffness and strength, are negatively influenced [2]. The fiber-matrix adhesion may be improved and the fiber swelling reduced by various modification techniques, but nevertheless, the mechanical properties and dimensional stability of cellulose fiber composites must be better understood if they are to reach their full potential. Furthermore, due to the fibers helical internal structure they will tend to rotate upon loading in axial direction. In most studies on the mechanical behavior of wood fiber composites this extension-twist coupling (which is an expression of the in-plane normal - shear stress coupling of the unbalanced cell wall) is overlooked since it is assumed that the fiber will be restricted from rotation within the composite. Therefore, the objectives of this paper are (i) to analyze the effect of constituent hygroelastic properties on fiber- and unidirectional (UD) composite properties and (ii) to examine the influence of helical fiber structure on composite elastic properties by examining two extreme cases: free rotation and no rotation of the composite assembly. In this paper we will consider micromechanical modeling of wood fiber composites, but keeping in mind that other natural fibers have the same basic features and constituents as wood fibers and, hence, the presented methods of analysis are applicable also for them.

2. MULTISCALE MODELING

Composites made of wood fiber reinforced resins have an utmost intricate hierarchical structure. Several length scales may be distinguished in this structure. The macro composite consists of resin and fibers which are of variable length and have some orientation distribution within the composite. The wood fiber (in this case the softwood tracheid) can be described as a multiphase system of concentric layers surrounding a cavity in the middle called lumen. The outermost layer is the primary wall (which we will pay no further attention since it is assumed that this layer is removed during the fiber extraction process) followed by the outer layer of the secondary wall (S1), the middle layer of the secondary wall (S2) and the inner layer of the secondary wall (S3). In a composite the lumen may be empty or filled with resin. Lumen is often filled when a low-viscosity thermosetting resin and the resin transfer molding technique (RTM) are used and empty lumen often occurs for thermoplastic based composites where lumen filling might not be achievable. At an even smaller scale, the so called ultrastructural level, the layered structure resembles that of a fiber reinforced composite with cellulose microfibrils acting as reinforcing elements embedded in a stress-transferring lignin and hemicellulose matrix. The most important ultrastructural feature that governs the fiber properties is the microfibril angle (MFA) which according to definition is the angular deviation of the microfibrils from longitudinal fiber axis. The MFA in the S2 layer is the key parameter since this layer constitutes about 70-90 % in thickness of the cell wall [3]. An advantage for modeling is that the length scales are sufficiently different and therefore multiscale analysis is possible instead of considering the whole complexity of the system included in one model. The approach used in this paper is to link the different length scales by utilization of the concentric cylinder (CC) micromechanical model. Figure 1 illustrates the flow when modeling the softwood fiber starting from the microfibril unit cell (UC).

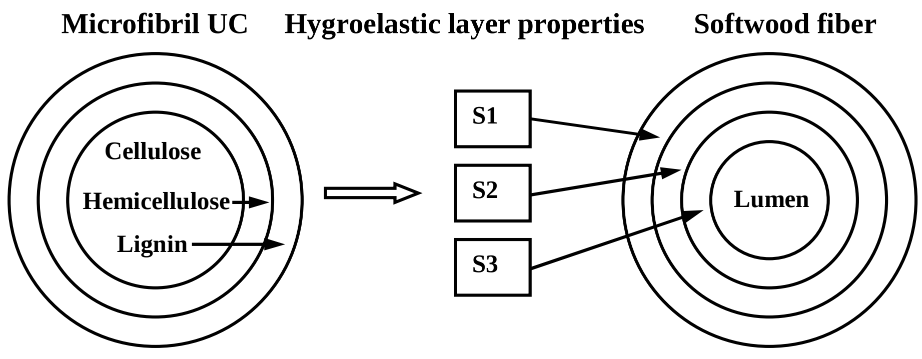

Fig. 1. Multiscale modeling of a softwood fiber using the concentric cylinder model

The fiber wall layer averaged properties will be modeled starting from cellulose, hemicellulose and lignin. The fiber wall averaged properties will be calculated using the layer properties calculated on the previous scale. The aligned wood fiber composite averaged properties will then be calculated by including an additional resin layer outside the S1 layer. The resin is taken as a typical isotropic thermoset with assumed elastic properties $E = 3.0$ GPa and $\nu = 0.35$. However, assigning "true" elastic properties to the wood polymers is unfortunately not a straightforward matter. There are many uncertainties regarding values on the wood polymers found in literature depending on the extraction procedures and experimental techniques used. After a literature review was conducted the decision was made to use the elastic properties as shown in Table 1.

Table 1. Assumed engineering constants of the wood polymers (dry condition).

Phase	Material behavior	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	ν_{23}
Cellulose	Transversely isotropic	150	17.5	4.5	0.1	0.5
Hemicellulose	Transversely isotropic	8	3.4	1.2	0.33	0.43
Lignin	Isotropic	6			0.33	

The wood fiber will be modeled as an assembly of long coaxial cylinders with high aspect ratio. This means that the stress transfer zone extends only over a small part of the interface and perturbation effects at fiber ends may be neglected. It is furthermore assumed that the bonding between fiber and matrix is perfect and the fiber is free from irregularities and defects. In a composite the lumen may be empty or filled with resin. In case of empty lumen the center phase will be modeled as a material with negligible stiffness compared to the stiffness of the other phases in the cylinder assembly. In this way the same analytical expressions are valid for both empty lumen and filled lumen case.

In the following analysis the composite structure under consideration is restricted to UD case. Although aligned wood fiber composites for obvious reasons are not often seen in reality, common models to describe the behavior of wood fiber composites are usually based on laminate analogy in which the key feature is determination of the UD layer properties [4]. A short-fiber composite with dispersed fibers with a certain orientation distribution is replaced by a laminate with many thin UD layers. The laminate is a stack of layers of different orientation and with a fixed layer volume fraction obtained from the fiber orientation distribution of the composite. In this way, inverse modeling (back-calculation) can be used to estimate fiber properties from macroscopic tests on composites. This is indeed a convenient way of determining fiber properties since tests on single fibers with minuscule dimensions are difficult, expensive and time consuming. A large amount of measurements on single fibers would also be necessary to ensure reliable statistics given the highly stochastic nature of their mechanical properties. However, it is emphasized that the back-calculation procedure only provides an indirect method of fiber properties determination. The fibers in the composite will have different properties than those in bulk wood (or for a free fiber for that matter). This is due to fiber damage during the extraction- and composite manufacturing process as well as additional constraints imposed on the fiber by (i) embedding it in the matrix material and by (ii) other neighboring fibers. Nevertheless, back-calculation of natural fiber properties from composite data may very well serve as a valuable and complementary tool to direct fiber testing and FEM calculations. Not to mention the future possibility of linking the apparent or "in-situ" fiber properties in the composite to actual or "true" fiber properties. In such case the success of the laminate analogy approach would depend on a reliable and robust micromechanical model.

3. THE CONCENTRIC CYLINDER MODEL

Micromechanical models for long fiber composites have been developed by Hashin and Rosen [5], Hashin [6] and Christensen and Lo [7] considering the constituents as concentric circular cylinders. In [5] the stiffness expressions for an isotropic hollow circular fiber composite were developed. The basic idea was that the entire cross-section of a composite material consists of many concentric pair cylinders (a hollow fiber surrounded by a concentric matrix layer) with different outer diameters, but all having the same fiber volume fraction. By assuming this random array of fibers explicit expressions were obtained for the plane-strain bulk modulus K_{23}, the shear modulus G_{12}, longitudinal modulus E_1 and Poisson's ratio ν_{12}. The limitation with Hashin's micromechanical model is that it renders only upper and lower bound for the transverse shear modulus. The limitation is related to the used homogenized boundary conditions in displacements or in tractions which do not exactly correspond to the conditions on the cylindrical boundary in a homogenized material. This problem was solved by Christensen and Lo [7] using a generalized self-consistent scheme. They considered an infinite effective composite with unknown shear modulus and a cylindrical sub-domain in it replaced by an equivalent fiber matrix microstructure.

Albeit proven very useful in many practical applications, these models may not be suitable for modeling natural fiber composites since they are limited to isotropic and transversely isotropic phase materials whereas natural fibers are at least orthotropic in cylindrical axes with different properties in the radial and in the hoop direction. Therefore, an analytical micromechanical model valid for orthotropic phase materials and for an arbitrary number of phases was developed to study the effect of various constituent stiffness properties on an aligned wood fiber composite [8]. The model is a straightforward generalization of Hashin's concentric cylinder assembly model and Christensen's generalized self-consistent approach. It was shown that all engineering constants for the composite cylinder may be calculated (with required accuracy) from knowledge of the constituent (phase) properties by setting up and solving a system of linear equations using appropriate continuity and interfacial conditions. Later this model was extended to include also the free hygroexpansion terms in the elastic stress-strain relationship [8].

4. DETERMINATION OF HYGROEXPANSION COEFFICIENTS

The free hygroexpansion of wood fibers is a well known phenomenon. Moisture absorption leads to an increase in moisture weight content and dimensional changes of the fiber as a consequence. In the linear elasticity of orthotropic materials these changes are assumed to be proportional to the moisture content change and three different constant coefficients of proportionality called hygroexpansion coefficients (β_j) characterize the relative dimensional changes in three directions of the material symmetry. As the result of phase swelling only normal stresses and strains develop, all shear components being zero, and the elastic stress-strain relationship may be written:

$$\sigma_i = C_{ij}\left(\varepsilon_j - \beta_j \Delta M\right) \tag{1}$$

C_{ij} is the stiffness matrix with usual notation and ΔM is the moisture weight content change. For an axi-symmetric problem in a particular case of loading when all shear stress components are equal to zero, the only non-trivial equilibrium equation is

$$\frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \tag{2}$$

By using Eq. (1), Eq. (2) and the strain to radial displacement relationship the displacement field equation for one cylinder may be set up and solved with following result:

$$u_r = A_1 r^{\alpha} + A_2 r^{-\alpha} + \frac{C_{13} - C_{12}}{\left(1-\alpha^2\right)C_{22}}\left(\varepsilon_1 r - \frac{H\Delta M}{C_{13} - C_{12}} r\right) \tag{3}$$

where

$$\alpha^2 = \frac{C_{33}}{C_{22}}, \quad H = \left(C_{13} - C_{12}\right)\beta_1 + \left(C_{23} - C_{22}\right)\beta_r + \left(C_{33} - C_{23}\right)\beta_\theta \tag{4}$$

A_1 and A_2 are unknown constants and ε_1 is the constant strain in axial direction as a result of phase swelling. For a composite cylinder Eq. (3) is generalized to N-phases with the requirement that the displacement and stress expressions have to satisfy continuity conditions on all interfaces, i.e. the solutions obtained for each phase separately must satisfy the following conditions: (*i*) Radial displacement must be zero on the symmetry axis; (*ii*) Displacement and radial stress continuity conditions at all interfaces; (*iii*) Zero radial stress at the outer boundary $r = r_N$ of the cylinder assembly. In case of free swelling the constant strain in axial direction must result in zero average stress in that direction. It is then realized that the unknown constants A_1^k and A_2^k for $k = 1,...,N$ can be determined by setting up and solving a system of linear algebraic equations. The problem is conveniently solved by using ε_1 as a numerical parameter for the requirement of zero axial stress. For every value of ε_1 the system of linear equations is solved and checked whether zero average stress in axial direction (with required accuracy) is obtained. When ε_1 have been determined the hygroexpansion coefficients in longitudinal direction β_L and transverse direction β_T of the cylinder assembly may be calculated from

$$\beta_L = \frac{\varepsilon_1}{\Delta M_{avg}} \qquad \beta_T = \frac{\varepsilon_r^{avg}}{\Delta M_{avg}} = \frac{u_r\left(r_N\right)}{r_N \Delta M_{avg}} \tag{5}$$

The average moisture content of the analyzed assembly ΔM_{avg} is determined using the rule of mixtures. For further detail regarding derivations and explicit expression for solving the hygroexpansion coefficients the reader is advised to [8].

5. HELICAL FIBER STRUCTURE

In reality a softwood cell wall layer is at least an orthotropic material in its local system of coordinates. However, if the concentric cylinder assembly model is used to calculate its properties using the multiscale approach starting from the properties of the wood polymers cellulose, hemicellulose and lignin the cell wall layer will be transversely isotropic in the local coordinate system. The theory presented in this section is valid for more general materials with orthotropic layer properties in their corresponding local coordinate systems. Notation and orientation of local and global axes is shown in Fig. 2.

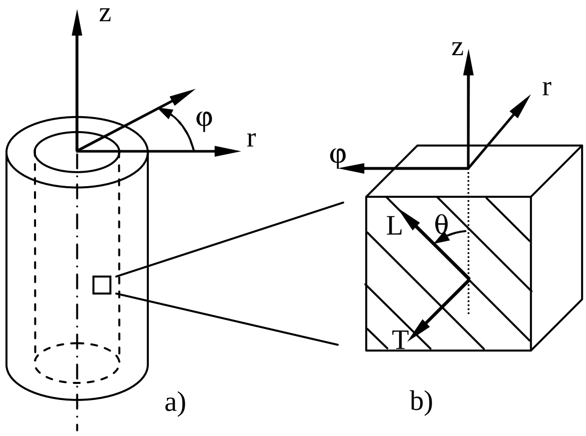

Fig. 2. Schematic drawing of a cylindrical cell wall layer in a) global view, b) detail of the layer showing the relationship between local (L,T,r) and global coordinates (z,φ,r).

In the global system of coordinates the layer has only one symmetry plane, which is the (z,φ)-plane, and the material has a monoclinic symmetry in these coordinates. Expressions for radial displacement and the relevant stresses and strains are given in detail in [8]. The radial displacement for the *k*-th sub-cylinder is

$$u_0^k = A_1^k r^{\alpha_k} + A_2^k r^{-\alpha_k} + \varepsilon_1 a_1^k r + D_1 a_2^k r^2 \tag{6}$$

A_1^k and A_2^k are unknown constants, α_k, a_1^k and a_2^k are known functions of the *k*-th phase elastic constants. ε_1 is the strain in z-direction and is coordinate independent (constant). D_1 is related to the rotation of the cylinder assembly due to monoclinic material properties. As in the previous discussion regarding determination of the hygroexpansion coefficients displacement and stress continuity conditions have to be satisfied at the interface between two sub-cylinders (layers) with indexes k and $k+1$. In addition the center phase must be either isotropic or transversely isotropic. It can be shown that using the appropriate displacement and stress continuity conditions will lead to the following relationships between constants to be determined:

$$A_1^k r_k^{\alpha_k} + A_2^k r_k^{-\alpha_k} - A_1^{k+1} r_k^{\alpha_{k+1}} - A_2^{k+1} r_k^{-\alpha_{k+1}} = \varepsilon_1 r_k \left(a_1^{k+1} - a_1^k\right) + D_1 r_k^2 \left(a_2^{k+1} - a_2^k\right) \tag{7}$$

$$A_1^k \beta_1^k r_k^{\alpha_k - 1} + A_2^k \beta_2^k r_k^{-\alpha_k - 1} - A_1^{k+1} \beta_1^{k+1} r_k^{\alpha_{k+1} - 1} - A_2^{k+1} \beta_2^{k+1} r_k^{-\alpha_{k+1} - 1} = \varepsilon_1 \left(\beta_3^{k+1} - \beta_3^k\right) + D_1 r_k \left(\beta_4^{k+1} - \beta_4^k\right) \tag{8}$$

$\beta_1 - \beta_4$ are known functions of the *k*-th phase elastic constants [8]. The external boundary of the *N*-cylinder assembly is free of radial tractions:

$$\sigma_r(r_N) = A_1^N \beta_1^N r_N^{\alpha_N - 1} + A_2^N \beta_2^N r_N^{-\alpha_N - 1} + \varepsilon_1 \beta_3^N + D_1 \beta_4^N r_N = 0 \tag{9}$$

The unknown constants A_1^k and A_2^k for $k = 1,...,N$ can be determined by setting up and solving a system of linear algebraic equations using Eq. (7-9). If no rotation of the cylinder assembly is allowed then $D_1 = 0$ and the system of linear algebraic equations is readily solved using a constant ε_1. If the assembly is allowed to rotate freely then D_1 is unknown and must be determined from the requirement of zero average torque according to

$$T_{z\varphi}^{av} = 2\pi \sum_{k=1}^{N} \int_{r_{k-1}}^{r_k} r^2 \sigma_{z\varphi}^k dr = 0 \tag{10}$$

Insertion of the expression for $\sigma_{z\varphi}^k$ in Eq. (10) give the condition needed to determine D_1. The problem is conveniently solved by using D_1 as a numerical parameter. For every value of D_1 the system of linear equations is solved and Eq. (10) used to check whether zero average torque (with required accuracy) is obtained. Poisson's ratio may be calculated from the displacement of the outer cylinder boundary, and the associated z-axis force can be used to define the apparent elastic modulus of the assembly:

$$E_z = \frac{\sigma_z^{av}}{\varepsilon_1} = \frac{2}{\varepsilon_1 r_N^2} \sum_{k=1}^{N} \int_{r_{k-1}}^{r_k} r \sigma_z^k dr \qquad \nu_{zr} = -\frac{u_0(r_N)}{r_N \varepsilon_1} \tag{11}$$

6. RESULTS AND DISCUSSION

6.1 Hygroelastic properties

Firstly the microfibril UC hygroelastic properties were calculated. The assumed volume fractions of the wood polymers were: S2 and S3 layers 49% volume fraction of cellulose, 27% hemicellulose and 24% lignin. The S1 layer had 20% volume fraction of cellulose, 15% hemicellulose and 65% lignin. These values are for dry material, but since hemicellulose and lignin will absorb moisture and swell for some given relative humidity (RH) their volume fractions will change. The stiffness of hemicellulose and lignin will also change. By using the data on moisture absorption and the stiffness-moisture dependence presented by Cousins [9] the hygroelastic properties and the new volume fractions for the microfibril UC were determined. Table 2 shows the obtained result for 80% RH calculated using the CC-model. It is emphasized that the presented results for the hygroexpansion coefficients shown in Table 2 are calculated in relation to the zero RH state. In other words, the result for 80 % RH reflects a change from zero to 80% RH only.

Table 2. Calculated microfibril UC properties for 80% RH (stiffness in GPa).

Layer	E_1	E_2	G_{12}	G_{23}	ν_{12}	ν_{23}	V_{CE}	V_{HC}	V_{LI}	β_1	β_2
S2/S3	69.35	2.88	0.99	1.01	0.218	0.430	0.182	0.165	0.653	0.023	0.438
S1	29.58	2.95	1.01	1.02	0.288	0.452	0.453	0.302	0.245	0.005	0.436

The hygroexpansion coefficients β_1 and β_2 were determined based on the assumptions made by Cave [10] that β_{CE} = 0 in all directions and β_{HC} = 0.5 in transverse directions and β_{LI} = 0.33 in all directions. Thus cellulose is believed to stay unaffected by moisture and the swelling in longitudinal direction for hemicellulose is considered to be insignificant. These are rather crude assumptions. However, due to lack of other data at hand these values will suffice for modeling purposes at time being.

The hygroexpansion coefficients in a wood fiber are strongly dependent on the MFA in the S2 layer. Therefore, the hygroexpansion coefficients for a wood fiber at 80% RH as a function of microfibril angle in the S2 layer were calculated. The lumen volume fraction was 36% and each layer was individually included in the analysis. Since the cylinder assembly representing the composite has to be transversely isotropic two hygroexpansion coefficients, longitudinal and transverse, are defined. The MFA in S1 is assumed 80° and constituting 10% of the cell wall thickness. S3 MFA is 45° with a cell wall thickness fraction of 5%. S2 MFA is varied 0-90° for modeling purpose and its cell wall thickness fraction is 85%. The hygroelastic properties of each layer in a global z-r-φ coordinate system are obtained by transformation of the microfibril UC properties using the corresponding MFA. Furthermore, each layer is also modeled as a balanced and symmetric angle-ply laminate. Fig. 3a shows the result of the simulation. This may be compared with an alternative calculation routine also shown in Fig. 3a, where first a homogenization over all cell wall layers is performed (the cell wall layers are lumped together using classical laminate theory) and then the cell wall is modeled as a single layer in the CC-model. This routine should be considered as less accurate. Fig. 3b shows the hygroexpansion coefficients for the aligned composite. The hygroexpansion coefficient $\beta = 0.7$ and moisture content $\Delta M = 0.02$ have been used together with the aforementioned engineering constants for the resin. Also here each layer was individually included in the analysis.

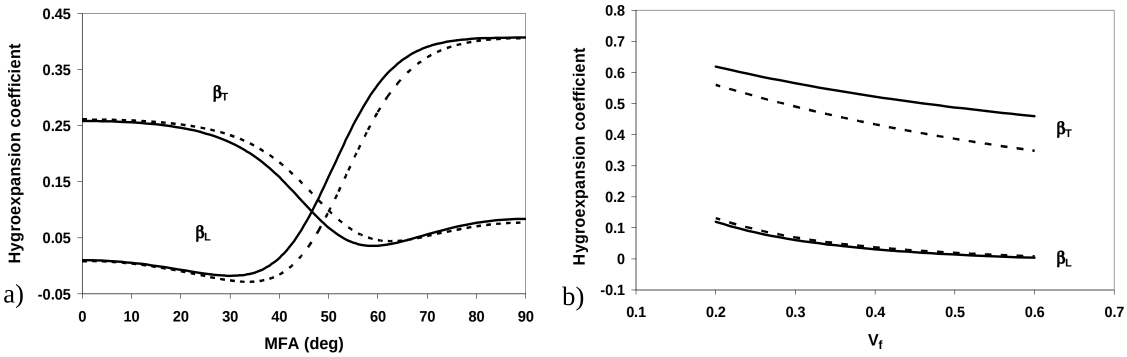

Fig. 3. a) The hygroexpansion coefficients for a wood fiber at 80% RH depending on microfibril angle in the S2 layer. The results are for layered cell wall (solid line) and homogenized cell wall (dashed line). b) Hygroexpansion coefficients at 80% RH depending on fiber volume fraction in the composite for filled lumen (solid line) and empty lumen (dashed line).

From Fig. 3a it is clear that the longitudinal hygroexpansion coefficient β_L increases abruptly for MFA higher than 40°. Experimental results on wood also support this phenomenon. The transverse hygroexpansion coefficient β_T decreases with increasing MFA which is reasonable since β_L and β_T must be inversely related. The hygroexpansion coefficients of a typical softwood fiber were also modeled by Neagu and Gamstedt [11]. They used a state space formalism modeling the wood fiber as an assembly of coaxial hollow cylinders made of orthotropic material with helical structure. The model was employed to investigate the effect of the fibers helical structure on its hygroelastic properties and it was found that the model could capture experimentally determined hygroelastic behavior of wood fibers.

6.2 The influence of helical fiber structure on composite stiffness

The helical orientation of the microfibrils in the cell wall layers implies that axial deformation is coupled with torsion. In the previous example, and as in most other studies concerning wood fibers, this twist-extension coupling is not accounted for. The question is then how much this will affect the modeled elastic properties of a UD wood fiber composite. Lekhnitskii developed the elasticity theory of materials with cylindrical anisotropy and presented the method of solution based on two stress functions. Analytical solutions for infinite tubes subjected to uniform radial pressure, axial force and torque were presented. The elasticity problem concerning multilayered cylindrical tubes with anisotropic material properties has also been studied by several authors. In [8] a straightforward and transparent exact solution for the above elasticity problem was presented, and given in brief in this paper. This CC-model is valid for an arbitrary number of layers with monoclinic material properties in a global coordinate system and here used to analyze two extreme cases modeling the fiber in the composite: (i) free rotation and (ii) no rotation of the cylinder assembly. It is not clear exactly how much the fiber will be restricted from bending and rotation in a composite when surrounded by other fibers, but we suspect that this restriction will be significant. Thus when discussing the possible reinforcing effect of wood fibers in a composite the (ii)-case should be regarded as the most probable one. Following the theory outlined previously and using the same fiber layer properties as in section 6.1 the longitudinal modulus and major Poisson's ratio were calculated. Figure 4 shows the result of the simulation.

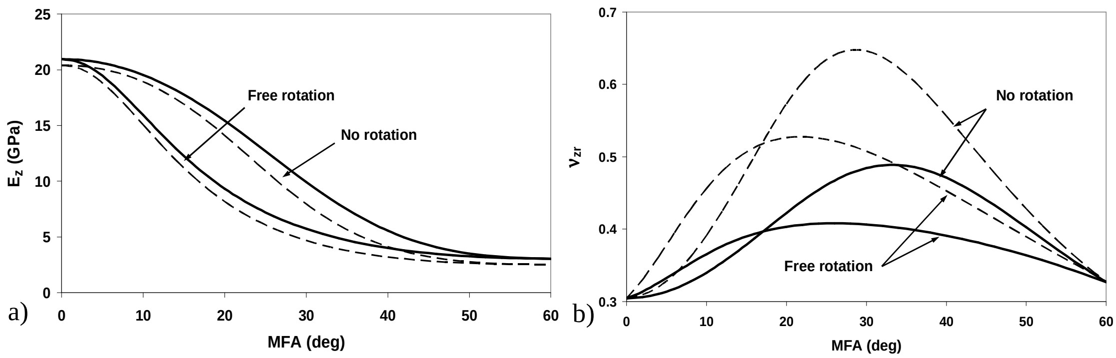

Figure 4. Longitudinal modulus a) and Poisson's ratio b) for a wood fiber composite depending on MFA in the S2 layer using the CC-model for filled lumen (solid line) and empty lumen (dashed line). Fiber volume fraction is 50 % and lumen volume fraction of fiber 36 %.

Clearly the longitudinal modulus depends highly upon MFA in S2 layer when modeling normal wood fiber reinforced composites (MFA 10-30°). Poisson's ratio is roughly equally sensitive to whether it is restricted from rotation or not, or if the fiber has an empty lumen.

7. CONCLUSIONS

The breakthrough for natural fiber composites in terms of usefulness in structural load bearing applications is yet to come. Some of the problem areas have been identified as: fiber-matrix adhesion properties, dimensional instability, fiber property variability and ultrastructural- and microstructural changes during the fiber extraction process and composite manufacturing. Currently many researchers are involved in the efforts to understand and solve these very challenging tasks with the future goal to develop high performance "green" composites. Parallel to these efforts there is clear and distinct need for a broader knowledge-based understanding of the mechanical performance of natural fiber composites on several length scales. The objective of this paper was to present micromechanical models that are suitable for parametric studies of fiber properties and their influence on composite properties.

Multiscale modeling of hygroelastic properties has been performed for a wood fiber composite. The cell wall was modeled regarding each individual layer as a symmetric angle-ply laminate to reflect the fact that the fiber will be restricted from bending and rotation within the composite. The hygroelastic properties presented herein must therefore be regarded as in situ properties and not be compared to the properties of a free unrestricted fiber. The cell wall longitudinal hygroexpansion coefficient was determined depending on microfibril angle in the S2 layer at 80% relative humidity and was found to correlate rather well with experimental values on wood. It could be seen that the transverse hygroexpansion coefficient had the correct functional form and was indeed inversely related to the longitudinal hygroexpansion coefficient as expected, even though it cannot be directly compared to experimental values on wood. Finally an analytical concentric cylinder model valid for orthotropic phase materials with helical structure and for an arbitrary number of phases was presented. It was found that the composite longitudinal modulus depending on the microfibril angle in S2 layer was heavily affected depending on restrictions to fiber rotation.

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