

# Virtual characterization of MDF fiber network

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**Abstract** A virtual design method for medium density fiberboards (MDF) is proposed with the aim to optimize the fiber orientation and lay-up of MDF. The new method estimates the stiffness and strength by using microstructure models of the MDF fiber network. The virtual design is used to improve the manufacturing technology of MDF plates with multilayer oriented fiber structure. Experimental investigations of the mechanical behavior of MDF microstructure for various fiber geometries, glue content and distribution are complicated, time consuming and expensive. On the other side, virtual microstructure design allows to develop a new wood fiber based material with less experimental work. Microstructure models help to better understand the non-linear damage mechanical behavior of a wood fiber network depending on fiber geometrical parameters. Such parameters as crack distribution and fiber deformation on micro-scale level are complicated to experimentally measure, but possible to model using computer simulations. The virtual design tool requires less empirical data. The model takes into account information on average wood fiber orientation, fiber diameter, fiber length and mechanical properties of wood fiber cell wall and glue. The numerical method for strength and stiffness analysis of MDF microstructure was calibrated using standard MDF with non-oriented fibers. It turned out that this method gives precise results for MDF

with oriented fibers and even with multilayer structure. The proposed virtual microstructure design tool can significantly improve and speed-up the optimization manufacturing technology of MDF and other wood fiber based composites.

## 1 Introduction

Medium density fiberboards (MDF) have become popular in the last two decades with wide applications in furniture industry, structural engineering and automotive industry. MDF is formed from defibrated wood fibers and glue, providing several advantages such as less material properties deviation, no knots, shape and size variety, less moisture and temperature caused expansion compared to wood. The virtual design of MDF microstructures can successfully be used to tailor material mechanical properties (strength, stiffness), moisture and temperature properties for specific needs (Sliseris et al. 2014). The contribution of this publication is the numerical method for strength and stiffness analysis of the MDF microstructure. The requirements of mechanical and physical properties have significantly increased in the last two decades for the purpose of carrying bigger loads with thinner plates and better resistance to humidity and temperature changes. The manufacturing process of MDF consists of log chipping, chip washing, thermo-mechanical pulping, defibrating, spraying of resin and wax, drying, mat forming, hot pressing, and sawing. MDF consists of a wood fiber network in which the fibers are joined together at several contact points. Wood fiber consists of lignin, cellulose, hemicellulose and extractives. The fiber diameter varies from 20 to 50  $\mu\text{m}$  depending on the species and type of wood (hardwood or softwood). The fiber joints as well as

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the resin have a large influence on the strength and stiffness (Eichhorn and Young 2003).

The experimental comparison of MDF with oriented and non-oriented fibers was done by Groom et al. (1999) and Woodson (1977).

Numerical simulations show that it is important to include the effects of elasto-plasticity, failure of the bond and frictional sliding of the fibers in the case of large deformations (Liu et al. 2011; Matsumoto and Nairn 2009; Wilbrink et al. 2013). An approach to model cellulose fibers was proposed by Heyden (2000). However, in her work the fibers are modeled using beam finite elements which do not consider the deformation of the cross section (Wriggers and Zavarise 1997). The direct simulation of 3D fiber network deformation and failure (under different humidity conditions) using beam elements was proposed by Kulachenko and Uesaka (2012). The crack growth in a cellulose fiber network was studied by Isaksson et al. (2012) using implicit gradient nonlocal theory.

Genetic algorithms can be used to predict the internal bond strength of MDF (Andre et al. 2008). The cell wall of wood fibers consists of a layered structure. However, the strength and stiffness is mainly governed by the secondary cell wall S2 layer (Deng et al. 2012). The layered structure is formed from cellulose microfibrils with a diameter of 4 nm. The thickness of the S2 layer is about 85 % of the total cell wall thickness and the microfibril angle (with respect to the fiber axis) in the S2 layer varies from 10° to 30° (Persson 2000). To approximate the microfibril angle in the S2 layer the log-normal probability distribution is suitable (Persson 2000; Sliseris et al. 2014). MDF is produced mainly with urea–formaldehyde resins (partly modified with melamine) and to a small part with PMDI (polymeric diisocyanate) (Osemeahon and Barminas 2007). The complexity of the wood fiber network leads to complex nonlinear material behavior (Sliseris and Rocens 2010, 2013a, b; Schirp et al. 2014). To calculate the strength of MDF, the nonlinearity of the material has to be considered. A non-uniform density profile leads to non-uniform strain–stress fields even for a simple tensile test. The experimental investigation of material constitutive behavior for complex strain–stress fields is time and resource consuming. To take the material complexity into account the two scale simulation method can be used effectively (Feyel and Chaboche 2000; Li et al. 2014; Somer et al. 2014; Rafsanjani et al. 2013).

Since now, there has been no information on available virtual design tools (numerical method) for MDF microstructure with multi-layer structure and oriented fibers, where fiber length, diameter, shape and effect of fiber bundles can explicitly be taken into account. The goal of this study is to show and validate the virtual design tool which takes into account such microstructural properties and computes strength and stiffness for MDF with

necessary accuracy. The proposed simulation methodology performs Monte-Carlo simulations to estimate the stochastic nature of designed MDF.

## 2 Materials and methods

The present work consists of an experimental part, where MDF with multi-layer and single-layer structures are manufactured in a laboratory. 3D  $\mu$ CT images were analyzed to characterize the MDF fiber network. The distributions of the fiber length and diameter were obtained by using 2D images of fiber mat and image processing tools (Wirjadi et al. 2014). Furthermore, mechanical tests were carried out to compare the behavior of various MDF plates and to calibrate and validate the simulation tools. The simulations were done on micro-scale, where representative volume elements (RVEs) are homogenized and effective stiffness is calculated. These mechanical properties were used in macro-scale finite element simulations.

## 3 Materials

The MDF samples were made of pine fibers with urea-formaldehyde glue. The average solid volume fraction (SVF) was 40 %. The average density was 630 kg/m<sup>3</sup>. More details of the MDF manufacturing process are given in Table 1.

$\mu$ CT images with a resolution of 4  $\mu$ m and average volume of 500 mm<sup>3</sup> were made. More details of  $\mu$ CT images are specified in Table 2. The height of  $\mu$ CT samples was half of MDF thickness. The size of single voxel was 4.0  $\times$  4.0  $\times$  4.0  $\mu$ m.

$\mu$ CT images of cylindrical samples with 12 mm diameter and 6 mm height were obtained by hollow punch technique. The  $\mu$ CT images were obtained with the following X-ray parameters: voltage 60 kV, current 360  $\mu$ A and 0.1 mm Cu beam spectral filter are produced.

The material parameters (glue, glue content, paraffin content, temperature and press time) have been chosen similar to those used in the industrial MDF manufacturing process.

**Table 1** Materials used to manufacture MDF in laboratory

Parameter	Value
Wood species	Pine
Glue	UF-resin Kaurit <sup>®</sup> 337
Glue content	9 %
Paraffin content	1.5 %
Press temperature	200 °C
Press time	12 s/mm
Size of board	300 $\times$ 300 mm <sup>2</sup>

**Table 2** Material data and size of CT images

ID	Image size, voxels	Image size (mm <sup>3</sup> )	Density (kg/m <sup>3</sup> )	Layout
35924	2268 × 2207 × 1864	9.07 × 8.83 × 7.46	628.0	1 Layer, oriented fibers
35925	2256 × 2231 × 1832	9.02 × 8.92 × 7.33	620.0	1 Layer, non-oriented fibers
36498 <sup>a</sup>	2180 × 2165 × 1777	8.72 × 8.66 × 7.11	653.0	3 Layers, 90/non-orient/90
36503 <sup>a</sup>	2142 × 2136 × 1787	8.57 × 8.54 × 7.15	620.0	3 Layers, 90/0/90

<sup>a</sup> Thickness of first, second and third layer are 20, 60 and 20 % of total thickness, respectively

### 4 Methods

The full simulation cycle of MDF consisted of (1) image processing and analysis part, (2) generation of virtual RVEs, (3) micro-scale and macro-scale simulations (see Fig. 1). The image processing can be done once to calibrate the virtual fiber network generator.

To obtain the  $\mu$ CT images, 2000 projection images were taken. The  $\mu$ CT uses the Feldkamp algorithm (filtered backprojections) to reconstruct the volume data.

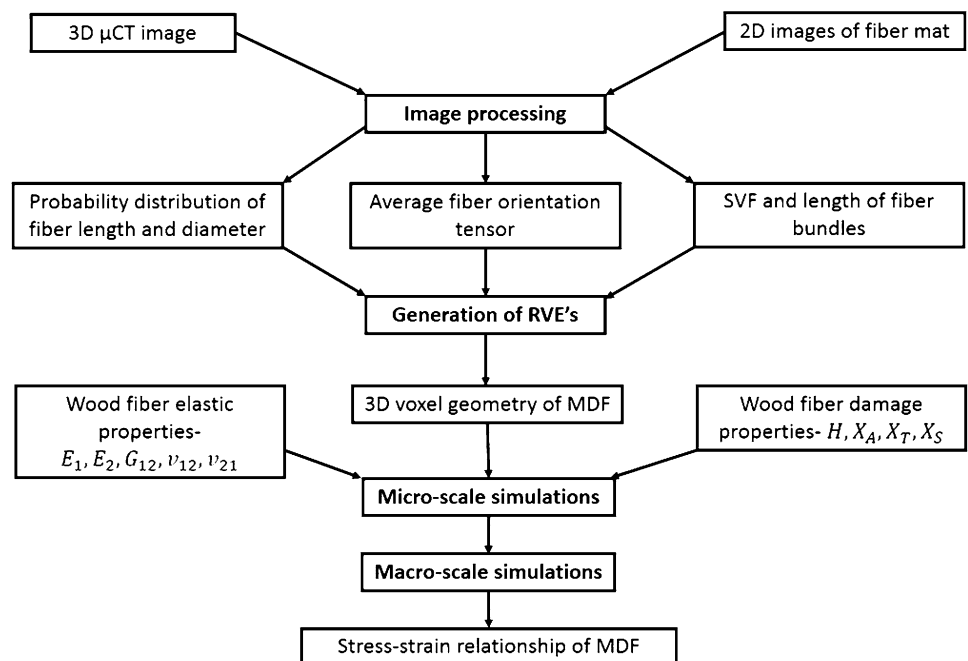
$\mu$ CT reconstructions of the specimens were processed using the MAVI software package (Fraunhofer ITWM, Kaiserslautern). The image processing consisted of simple noise-reduction filtering followed by a thresholding step, yielding a finite element model in the form of a binary volume image. This means, the model consisted of a segmentation of the fiber system, represented as the foreground pixels. These pixels are arranged on a cubical grid, where the distance between two neighboring grid points corresponds to the nominal resolution of the  $\mu$ CT scan.

The output (fiber length, diameter, orientation, fiber bundle SVF) of image analysis was used as input for virtual

RVEs generation tool. The fiber network parameters, which can be technologically modified, like fiber orientation or amount of fiber bundles, can be optimized to design better MDF plates. This method simulates a fiber lay-down process and a compression of MDF to obtain the fiber network with needed properties.

The input parameters of micro-scale simulations are voxel discretization of a fiber network, modulus of elasticity, shear modulus and Poisson’s ratio of wood fiber cell wall. In addition, the damage properties, such as ultimate stress in axial and transversal direction of wood fiber cell wall have to be specified. Experiments for single wood fiber are complicated and not well documented in present literature. Only tensile test experiments of single fibers could be found (Joffe et al. 2009). As a result of micro-scale simulation, stress–strain relationships for virtually designed fiber networks were obtained. These relationships were used to compute modulus of elasticity and shear modulus of MDF by performing macro-scale finite element simulations. The constitutive law for macro-scale simulations is an explicitly defined stress–strain function (obtained by micro-scale simulations) in user defined constitutive model (e.g. UMAT in Abaqus software).

**Fig. 1** Scheme of MDF simulation methodology



This approach is less computationally demanding than coupled micro–macro scale simulation and FE<sup>2</sup> method. Therefore it is more relevant for practical applications.

#### 4.1 Image processing and analysis

Fiber orientation, length, diameter and fiber bundles were analyzed using 3D image analysis. Fiber length and diameter were obtained by segmenting fibers in 2D images of fiber mat.

A method based on Hessian matrix (Redenbach et al. 2012) was used to obtain the averaged fiber orientation tensor in each MDF layer. The current resolution of  $\mu$ CT images does not allow to segment single fibers. However, this resolution gives a possibility to analyze relative large volumes of the MDF—namely around 0.5 cm<sup>3</sup> with the height of half thickness of MDF.

Fiber orientations were estimated by calculating the local fiber direction in each voxel and applying volume averaging technique (Schmid and Schmid 2006). Here, a method based on the Hessian matrix was used, having as elements the second order partial derivatives of gray value 3D  $\mu$ CT image. This has proved to be robust in many applications (Wirjadi et al. 2014). The eigenvectors of the Hessian matrix carry information of the fiber orientation. For a fibrous structure, the smallest gray value variation is expected along the fiber. Thus the eigenvector corresponding to the smallest eigenvalue of the Hessian matrix is interpreted as the local fiber direction. Cumulation of these local directions yields the volume-weighted direction distribution. An estimator for the components is obtained by averaging the components of the local direction over small sub-volumes (Wirjadi et al. 2014).

#### 4.2 Segmentation of fiber bundles

Digital  $\mu$ CT images of MDF microstructure show the presence of a significant amount of non-separated fibers- fiber bundles. To investigate the influence of fiber bundles on strength and stiffness, the amount, orientation and size of fiber bundles has to be known. A method to segment the fiber bundles was proposed. Furthermore, the method was used to estimate SVF and length of the fiber bundles. A microstructure region with fiber bundles was characterized as a region where all fibers are aligned parallel. Hence, the fiber bundle can be defined as a region in the fiber network where in each solid phase voxel exists a similar fiber orientation vector. For every solid phase voxel in a 3D image, a local fiber direction  $v(x, y, z)$  was computed. Then, a “sliding” orientation tensor was computed by averaging the tensor products  $v^T v$  in  $N \times N \times N$  voxel window around every voxel. For every voxel, an eigenvalue decomposition of Hessian matrix was computed, where  $e_1 \geq e_2 \geq e_3$  are the (sorted) eigenvalues of  $T(x; y; z)$ . Using the eigenvalues, the measurement was

reduced to one scalar number in every voxel, the so-called strength parameter  $\xi = \log(e_1/e_3)$  of the orientation distribution (Wirjadi et al. 2014). This number was high at points with very strong orientation. Since in the fiber bundles there are a bunch of parallel fibers, this strength measure was assumed to become large in regions of fiber bundles. This strength measure was threshold to detect the fiber bundles. This method uses information on a local orientation tensor in each solid phase voxel.

#### 4.3 Solution of elasticity problem

The nonlinear mechanical behavior of the MDF results from the highly nonlinear-anisotropic nature of a wood fiber. Wood fibers are brittle under short term tension loads. Damage of fiber joints, fiber tensile breakage or fiber buckling typically occur. A new continuum damage model was introduced to capture the nonlinear behavior. The homogenization was performed by assuming small strain theory (strain does not exceed 3 %). The computation of the stress–strain fields of the RVE leads to a boundary value problem in elasticity (Sliseris 2013):

$$\begin{aligned} \operatorname{div} \sigma(x) &= 0, \quad x \in \omega, \\ \sigma(x) &= C(\epsilon, d, k)(x) : \epsilon(x), \quad x \in \omega, \\ \epsilon(x) &= E + \frac{1}{2}(\nabla u(x) + \nabla u^T(x)), \quad x \in \omega, \\ u(x) &- \text{periodic}, \quad x \in \delta\omega, \\ \sigma(x) * n(x) &- \text{anti-periodic}, \quad x \in \delta\omega. \end{aligned} \quad (1)$$

This problem was transformed to equal Lippmann–Schwinger type integral equations (Moulinec and Suquet 1998):

$$\epsilon(x) = E - \int_{\Omega} \Gamma^0(x-y) : ((C(\epsilon, d, k)(x) - C^0) : \epsilon(x)) d\Omega \quad (2)$$

It was solved iteratively by using Fast Fourier Transformation (FFT) method (Moulinec and Suquet 1998; Merkert 2013).

Cell wall of the wood fiber was modelled as a transversal isotropic material. The continuum damage approach was used to predict the strength (Souza et al. 2011). Three damage variables and three maximal stress criteria were used (Sliseris et al. 2014; Qing and Mishnaevsky 2010). The damage variables  $d_i$  were computed by using exponential expression:

$$d_i(x, \epsilon) = 1 - e^{-H_i \sqrt{\epsilon : C : \epsilon}}, \quad d_i \in [0, 1), \quad i = 1, 2, 3 \quad (3)$$

Stiffness coefficients of fiber cell wall were reduced proportionally to values of damage variables: where  $k$  is

$$C(\epsilon, d, k)(x)^{-1} = \frac{1}{k} \begin{bmatrix} \frac{1}{(1-d_1)E_1} & -\frac{\nu_{21}}{(1-d_2)E_2} & -\frac{\nu_{31}}{(1-d_1)E_1} & 0 & 0 & 0 \\ sym & \frac{1}{(1-d_2)E_2} & -\frac{\nu_{31}}{(1-d_1)E_1} & 0 & 0 & 0 \\ sym & sym & \frac{1}{(1-d_1)E_2} & 0 & 0 & 0 \\ & 0 & 0 & 0 & \frac{1}{(1-d_3)G_{23}} & 0 \\ & 0 & 0 & 0 & 0 & \frac{1}{(1-d_3)G_{23}} \\ & 0 & 0 & 0 & 0 & \frac{2(1+\nu_{12})}{(1-d_2)E_2} \end{bmatrix}, \tag{4}$$

solid volume fraction in mixed phase voxel (for details see Sliseris et al. 2014),  $E_1$  is the modulus of elasticity of fiber cell wall in fiber axial direction,  $E_2$  is the modulus of elasticity of fiber cell wall in fiber transversal direction,  $G_{ik}$  is the shear modulus,  $\nu_{31}$  is the Poisson’s ratio.

Other details of the constitutive model are described in Sliseris et al. (2014).

## 5 Results

### 5.1 Fiber bundle effect on strength and stiffness

Computational simulations were performed to study the fiber bundle effect on the strength and stiffness of MDF. The numerical results were validated with experimental measurements. The mechanical properties of cell wall of wood fiber are described in Table 3. Virtually generated RVE was discretized in  $200 \times 200 \times 200$  voxels. Size of voxel was  $2 \times 2 \times 2 \mu\text{m}$ . A fiber laydown process was simulated to obtain density in the range of  $280\text{--}380 \text{ kg/m}^3$ . The simulation of the fiber network compression was performed to obtain typical density of MDF. The compressive strain is in the range of  $50\text{--}60 \%$ . Large strain

theory was used to accurately simulate the compression. Average density of RVEs with fiber bundles and without fiber bundles are  $613$  and  $606 \text{ kg/m}^3$ , respectively. After compression and crop,  $190 \times 190 \times 80$  voxel model was obtained. Visualization of voxel model is shown in Fig. 2.

Fiber bundles were segmented in five  $\mu\text{CT}$  images by using the proposed method and also manually. A slice of a  $\mu\text{CT}$  image is shown in Fig. 3. It can be clearly seen that fiber bundles occupy significant parts of this cross section. Therefore, fiber bundles cannot be neglected.

Solid volume fraction of standard MDF varies from  $5$  to  $15 \%$ . In the  $\mu\text{CT}$  images it can be seen that the fiber bundle distribution is not uniform.

A tensile test of MDF microstructure was simulated. It turned out that fiber bundles have significant effect on the stress–strain curves of MDF. The simulations show a lower strength and stiffness for microstructures with fiber bundles (see Figs. 4, 5).

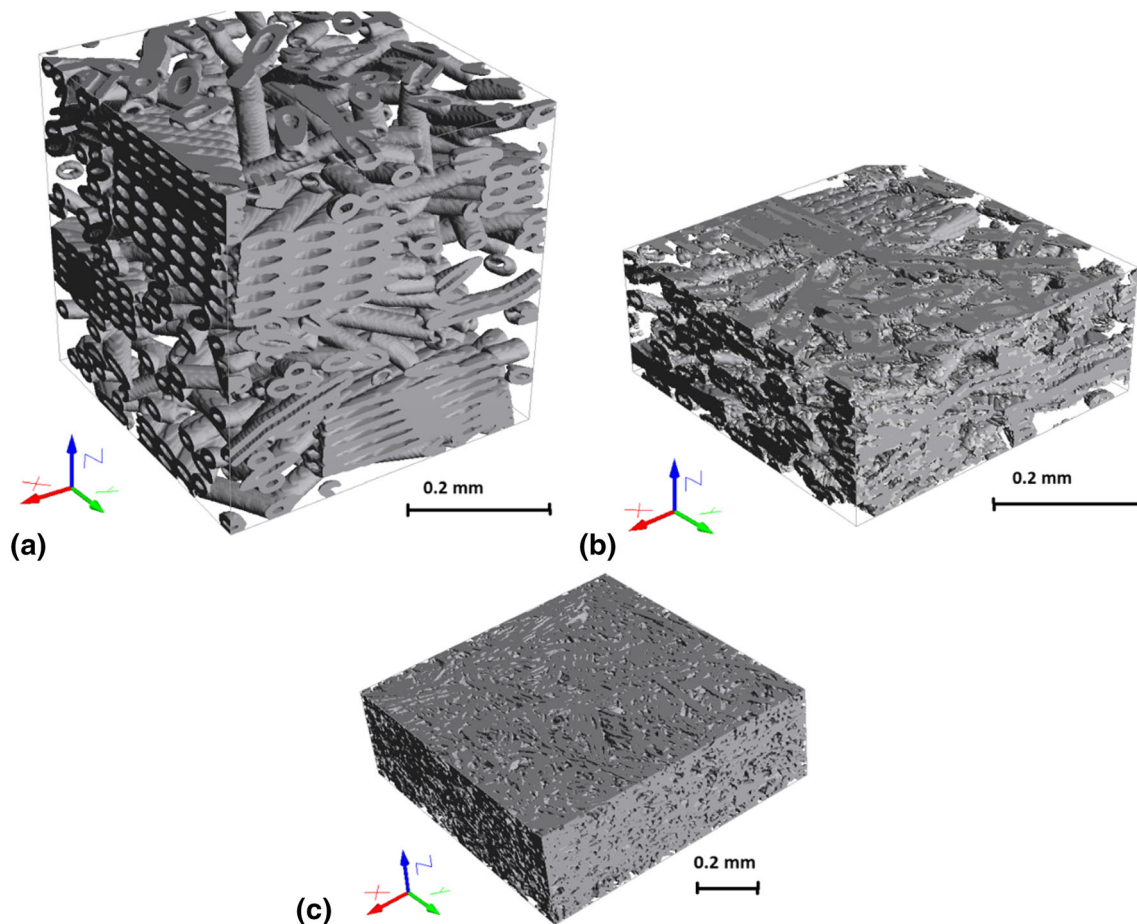
Three-point bending tests and simulations of the MDF were carried out. Force–displacement curves were obtained. The stress–strain curves in outer MDF layers were obtained using analytic formulas (based on Euler–Bernoulli beam theory). On the other hand, simulation of tensile test for microstructures, which are present in outer layers of MDF, was done. Numerical and experimental results show good agreement (see Fig. 4). The standard deviation of numerical results is about  $10 \%$ . Elastic properties (modulus of elasticity, shear modulus and Poisson’s ratio) and stress–strain curves were obtained by using Monte-Carlo method by generating five random microstructures for each type of MDF. The experimentally obtained stress–strain curves are in acceptable agreement with numerically obtained curves.

The considered MDF plates showed linear-elastic behavior in three-point bending up to  $0.4 \%$  strain (see Fig. 6). Computational homogenization of MDF in linear elastic region was done.

**Table 3** Mechanical properties of wood fiber

Parameter	Value	Reference
Young’s modulus, $E_1$	50 GPa	Persson (2000)
Young’s modulus, $E_2$	3 GPa	Persson (2000)
Shear modulus, $G_{23}$	3 GPa	Persson (2000)
Poisson’s ratio, $\nu_{12}$	0.3	Persson (2000)
Poisson’s ratio, $\nu_{13}$	0.3	Persson (2000)
Damage hardening modulus, H	100 MPa	–
Fiber axial strength, $X_A$	100 MPa	Joffe et al. (2009)
Fiber transversal strength, $X_T$	8 MPa	–
Fiber cell wall shear strength, $X_S$	8 MPa	–





**Fig. 2** Voxel models (RVEs), **a** virtually generated model before compression, **b** virtually generated model after compression, **c** experimentally obtained  $\mu$ CT image

Damage growth starts in fibers, which are oriented in the direction of load. As can be seen in Fig. 5, all three damage variables tended to locate in the same regions. Due to curved shape and elliptical cross section of the wood fiber and multiple joints for each fiber, it can be seen that there are multiple potential crack initiation places for each fiber (see Fig. 5).

The computed in-plane modulus of elasticity is in good agreement with experimentally measured one (see Fig. 6). Furthermore, the fiber bundle effect on stiffness of MDF was investigated. The simulation results of microstructures including fiber bundles are in better agreement with experiments than those without fiber bundles. Simulations showed that fiber bundles reduced the stiffness of MDF. After analyzing stress fields in wood fiber network, it turned out that fiber bundles have not enough contact points with other fibers to effectively transfer loads.

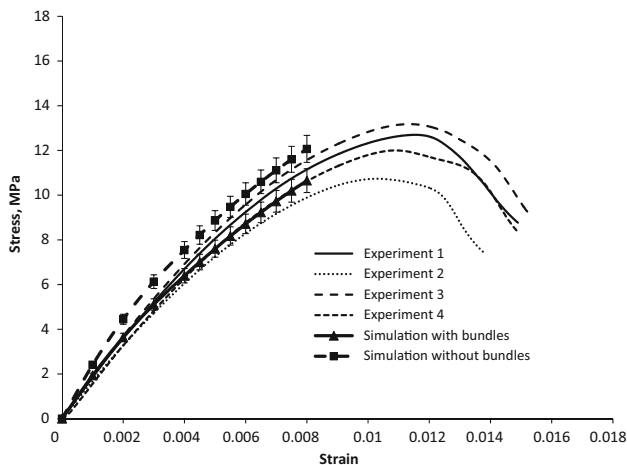
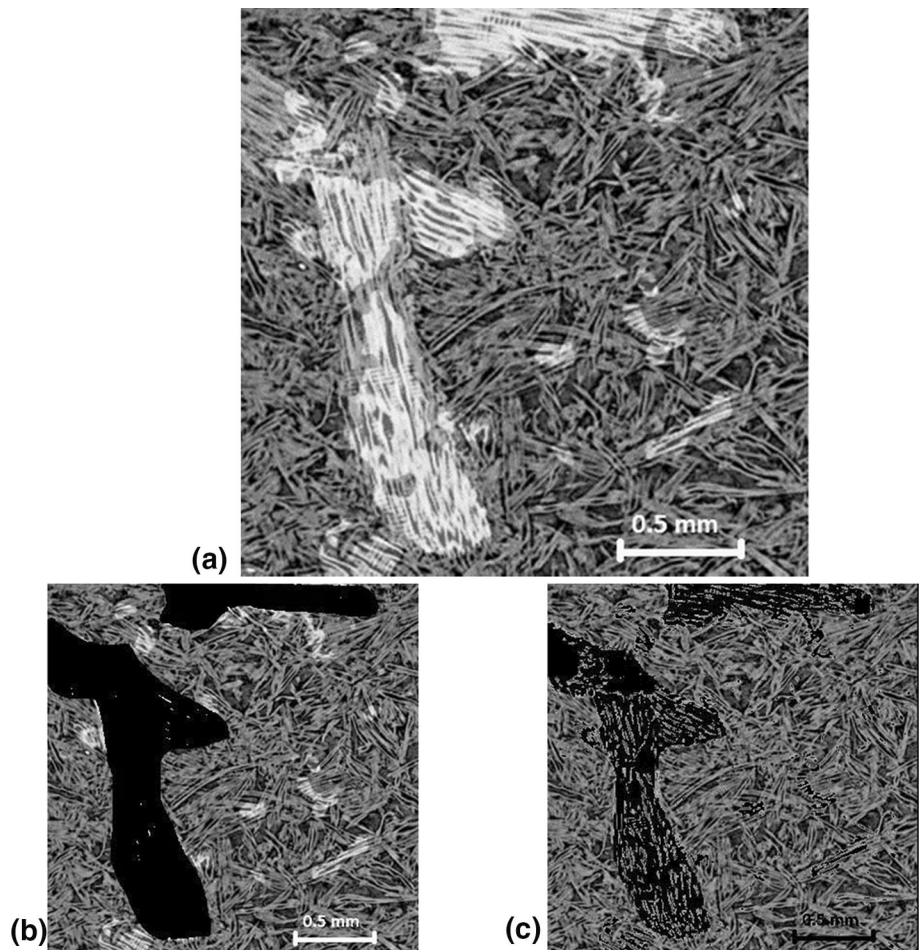
Computational homogenization also allows computing shear modulus and Poisson's ratios of MDF. Experimentally, these elastic constants are difficult to measure. The computation results of transversal modulus of elasticity  $E_3$

and shear modulus  $G_{23}$ ,  $G_{13}$  and  $G_{12}$  are shown in Fig. 7. It can be seen that in-plane shear modulus  $G_{12}$  is about 2 times greater than out of plane shear modulus. The microstructures with fiber bundles have around 13 % smaller shear modulus than those without fiber bundles. Poisson's ratios  $\nu_{12}$ ,  $\nu_{13}$  and  $\nu_{23}$  were computed. All Poisson's ratios were in the range between 0.2 and 0.25 (see Fig. 8). By taking into account fiber bundles, the average difference of Poisson's ratios is around 5 %.

## 5.2 Influence of fiber orientation on mechanical properties of MDF

Experimentally, MDF plates with oriented fibers and average density of about  $620 \text{ kg/m}^3$  were produced. The fiber orientation was obtained using a technique, which is described in Lippe (2013). A slight difference in fiber orientation can significantly affect mechanical properties of MDF. Due to curved and broken shape of deliberated wood fiber, practically it is only possible to orient fibers partially. To understand how many wood fibers are actually oriented,

**Fig. 3** Segmented fiber bundles in one slice of  $\mu$ CT image (a). b Indicates manually segmented fiber bundles in black colour and c automatically segmented fiber bundles in black colour



**Fig. 4** Experimentally measured and numerically computed stress–strain curves of MDF without oriented fibers

the fiber orientation of oriented medium density fiberboards (OMDF) was analyzed by using image processing tools.  $\mu$ CT images of MDF and OMDF were created. The average orientation in different material layers was computed by a method described in Sect. 4

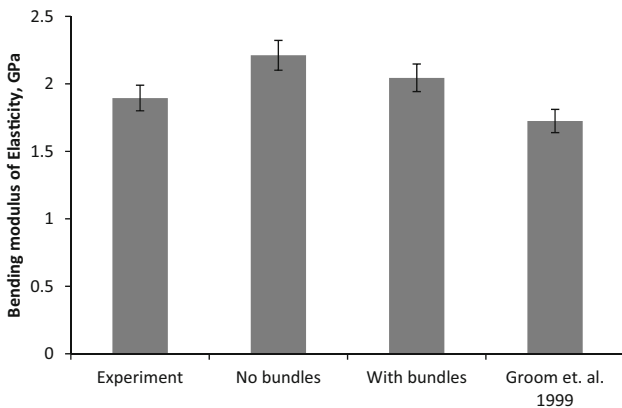
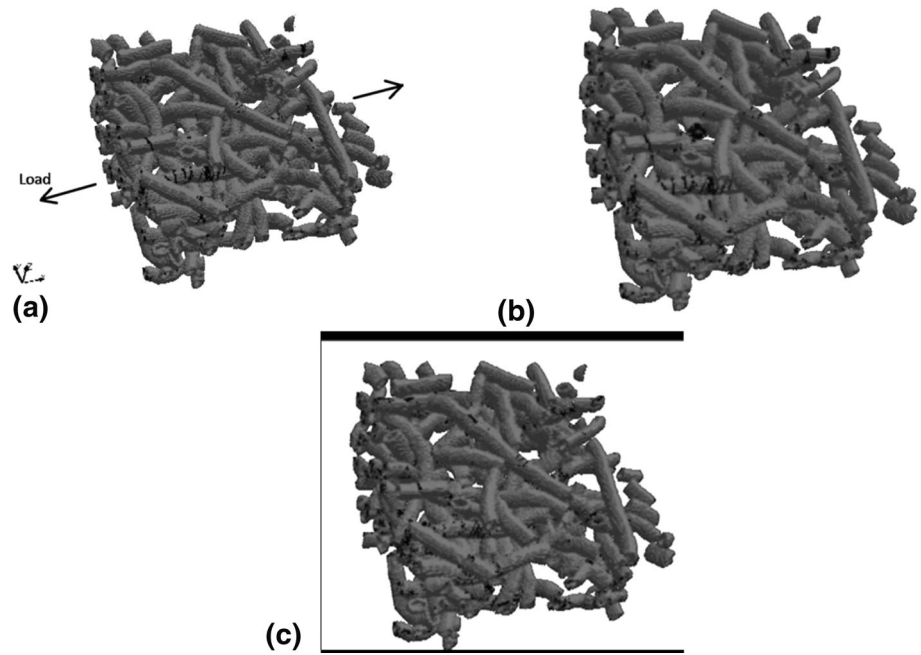
The shape of stress–strain plot for tensile loads on OMDF is similar to standard MDF (see Figs. 9, 10). Up to 0.4 % strain is linear elastic region according to experimental measurements. As can be seen in Figs. 9 and 10, numerical results show greater stiffness in linear elastic region. However, the average experimental results are always inside the standard deviation of numerical results. The ultimate tensile stress in fiber direction is about 16 MPa, and in orthogonal in-plane direction about 12 MPa. Simulations were carried out till 90 % of ultimate stress.

This constitutive model was calibrated using standard MDF plates with non-oriented fiber structure. As can be seen in Figs. 9 and 10, the calibrated material model shows good agreement with experimental results for OMDF. Therefore, it is possible to use this simulation tool for optimization and virtual design of MDF with oriented fibers.

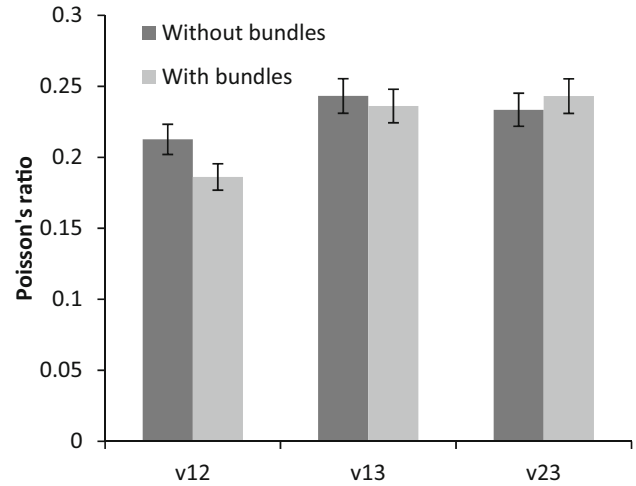
### 5.3 MDF with multilayer structure

The bending behavior of MDF is mainly governed by surface layers. Therefore, it makes sense to orient fibers

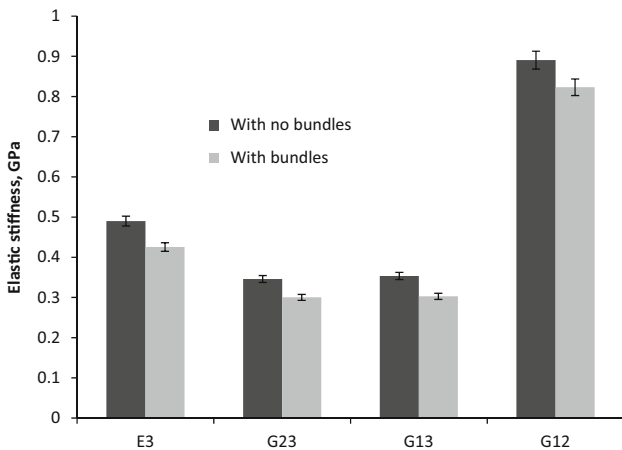
**Fig. 5** Damage variables at 0.8 % strain for non-oriented MDF microstructure. **a** fiber axial damage variable  $d_1$ , **b** fiber transversal damage variable  $d_2$ , **c** shear damage variable  $d_3$ . Black color indicates damage variable value 1



**Fig. 6** Computed and experimentally measured in-plane moduli of elasticity of MDF



**Fig. 8** Computed Poisson's ratios of MDF

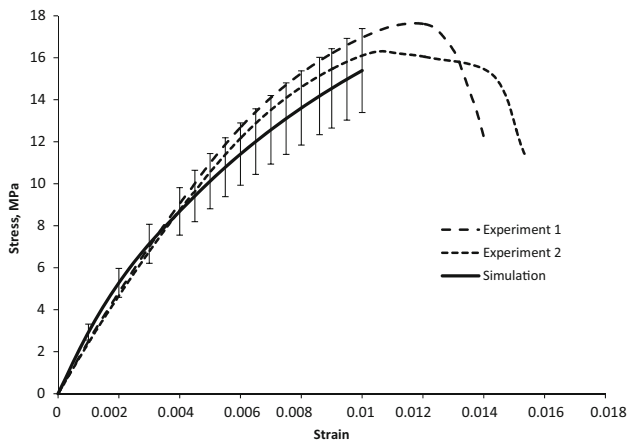


**Fig. 7** Computed transversal modulus of elasticity and shear moduli of MDF

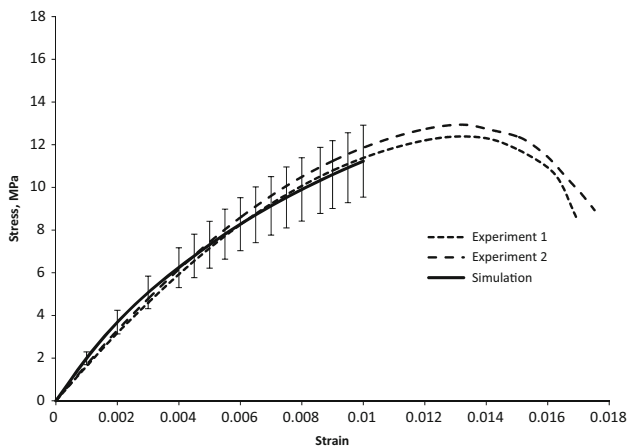
only in surface layers. Multi-layer (in this case 3-layer) oriented medium density fiberboards (MOMDF) were manufactured. Layers were glued together with UF glue. Total thickness of surface layers was approximately 20 % of total thickness. Two types of core layers were tested; first, with 90° orientation with respect to surface layer and also non-oriented core layer.

Experimental results show less than 10 % difference of modulus of rupture depending on fiber orientation in core layer of MOMDF (see Figs. 11, 12). This was also observed in the present simulations. The ultimate stress in experiments is about 17 MPa. Up to 0.6 % strain, the experimental results were in good agreement with the

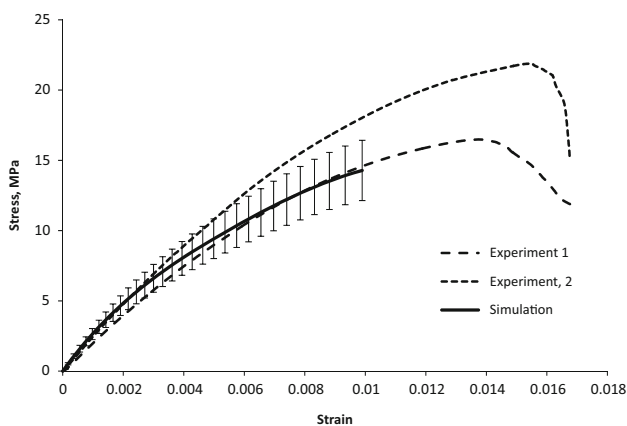




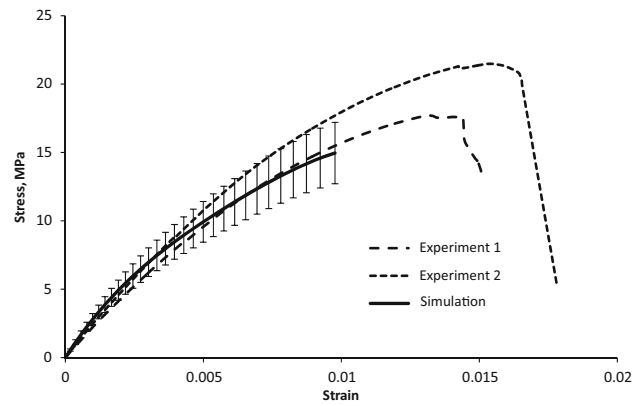
**Fig. 9** Stress–strain curve of single layer MDF in direction of main fiber orientation



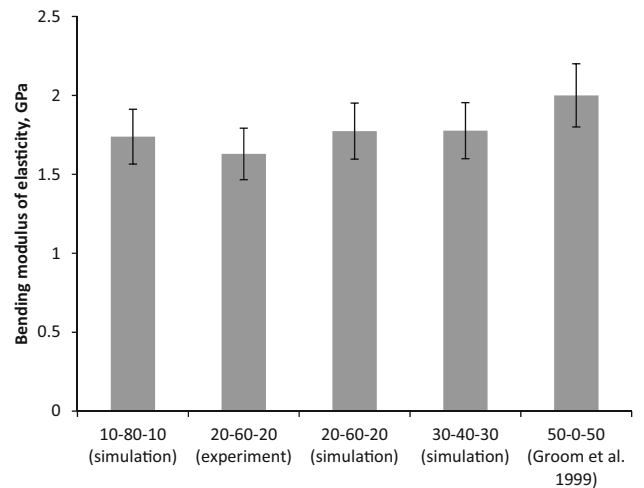
**Fig. 10** Stress–strain curve of single layer MDF in orthogonal direction with respect to main fiber orientation



**Fig. 11** Stress–strain plot of surface layers in 3-point bending test for MOMDF with average density  $620 \text{ kg/m}^3$  and 0/90/0 fiber orientation simulation results. Moreover, the difference between experiments and simulations was in the range of the standard deviation.



**Fig. 12** Stress–strain plot of surface layers in 3-point bending test for MOMDF with average density  $650 \text{ kg/m}^3$  and 0/non-oriented/0 fiber orientation



**Fig. 13** Modulus of elasticity for MDF with different surface layer thickness

The proposed simulation tool was used to virtually generate MOMDF microstructures with different lay-up and simulate mechanical behavior. In the three point bending test, the bending modulus of elasticity increases less than 5 % when the surface layer is thicker than 10 % of total thickness (see Fig. 13). The bending modulus of elasticity was calculated as average value when applied load was 10–40 % from ultimate load described in the standard EN 310.

## 6 Conclusion

An efficient virtual design method based on micro–macro simulations was proposed to optimize MDF. The simulation method shows good agreement with measured stress–strain curves in three-point bending test. The continuum damage model for wood fibers was calibrated using

mechanical tests of standard MDF. It was possible to simulate MDF with oriented fibers and 3-layer MDF by using the calibrated model. Therefore, this method can effectively be used to optimize MDF fiber network.

Fiber bundles play a significant role for the strength and stiffness of MDF. Better agreement with experiments is shown by a model which includes fiber bundles. According to the present simulations, fiber bundles decrease mechanical properties of MDF. The virtual design of MDF showed that it is sufficient to orient only 20 % of wood fibers in outer layers of MDF.

An accurate contact model to simulate fiber network more precisely should be developed in the next investigations. However,  $\mu$ CT images with resolution below 1  $\mu$ m would be necessary to characterize and investigate fiber shapes and contact zones between fibers.

Further development of the fiber orientation technique is necessary in order to produce MDF with oriented fibers.

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## References

- Andre N, Cho H, Baek S, Jeong M, Young T (2008) Prediction of internal bond strength in a medium density fiberboard process using multivariate statistical methods and variable selection. *Wood Sci Technol* 42(7):521–534
- Deng Q, Li S, Chen Y (2012) Mechanical properties and failure mechanism of wood cell wall layers. *Comput Mater Sci* 62:221–226
- Eichhorn S, Young R (2003) Deformation micromechanics of natural cellulose fibre networks and composites. *Compos Sci Technol* 63:1225–1230
- Feyel F, Chaboche JL (2000) Fe2 multiscale approach for modelling the elastoviscoplastic behaviour of long fibre SiC/Ti composite materials. *Comput Methods Appl Mech Eng* 183(3–4):309–330
- Groom L, Mott L, Shaler S (1999) Relationship between fiber furnish properties and the structural performance of MDF. 33rd International Particleboard/Composite Materials Symposium Proceedings, 89–100
- Heyden S (2000) Network modelling for the evaluation of mechanical properties of cellulose fiber fluff. PhD thesis, Division of Structural Mechanics, LTH, Lund University
- Isaksson P, Dumont P, du Roscoat SR (2012) Crack growth in planar elastic fiber materials. *Int J Solids Struct* 49(13):1900–1907
- Joffe R, Andersons J, Sparrins E (2009) Applicability of Weibull strength distribution for cellulose fibers with highly non-linear behaviour. In: ICCM 17, Edinburgh: 17th International Conference on Composite Materials, 27 Jul 2009–31 Jul 2009, Edinburgh International Convention Centre, Edinburgh, UK
- Kulachenko A, Uesaka T (2012) Direct simulations of fiber network deformation and failure. *Mech Mater* 51:1–14
- Li H, Wang W, Matsubara T (2014) Multiscale analysis of damage progression in newly designed UACS laminates. *Compos Part A Appl Sci Manuf* 57:108–117
- Lippe D (2013) Process development for the experimental proof of property changes of mdf with oriented fibers (in German). Master’s thesis, Fraunhofer-Institut für Holzforschung, Wilhelm-Klauditz-Institut und University of Applied Sciences in Eberswalde (HNEE), Germany
- Liu J, Chen Z, Wang H, Li K (2011) Elasto-plastic analysis of influences of bond deformability on the mechanical behavior of fiber networks. *Theor Appl Fract Mech* 55:131–139
- Matsumoto N, Nairn J (2009) The fracture toughness of medium density fiberboard (MDF) including the effects of fiber bridging and crack-plane interference. *Eng Fract Mech* 76:2748–2757
- Merkert D (2013) Voxel-based fast solution of the Lippmann–Schwinger equation with smooth material interfaces. Master’s thesis, TU Kaiserslautern, Germany
- Moulinec H, Suquet P (1998) A numerical method for computing the overall response of nonlinear composites with complex microstructure. *Comput Methods Appl Mech Eng* 157(12):69–94
- Osemeahon S, Barminas J (2007) Study of some physical properties of urea formaldehyde and urea proparaldehyde copolymer composite for emulsion paint formulation. *Int J Phys Sci* 2(7):169–177
- Persson K (2000) Micromechanical modeling of wood and fiber properties. PhD thesis, Department of Mechanics and Materials, Lund University
- Qing H, Mishnaevsky L (2010) 3D constitutive model of anisotropic damage for unidirectional ply based on physical failure mechanisms. *Comput Mater Sci* 50:479–486
- Rafsanjani A, Lanvermann C, Niemz P, Carmeliet J, Derome D (2013) Multiscale analysis of free swelling of norway spruce. *Compos Part A Appl Sci Manuf* 54:70–78
- Redenbach C, Rack A, Schladitz K, Wirjadi O, Godehardt M (2012) Beyond imaging: on the quantitative analysis of tomographic volume data. *Int J Mater Res* 103(2):217–227
- Schirp A, Mannheim M, Plinke B (2014) Influence of refiner fibre quality and fibre modification treatments on properties of injection-moulded beech wood–plastic composites. *Compos Part A Appl Sci Manuf* 61:245–257
- Schmid HG, Schmid GP (2006) Characterisation of high aspect ratio objects using the powdershape quantitative image analysis system. In: European Congress and Exhibition on Powder Metallurgy (EURO PM), Diamond tooling, vol. 3, Ghent, Belgium, 23–25.10.2006
- Sliseris J (2013) Numerical prediction for the modulus of elasticity of lmdf plates. In: Young researcher symposium (YRS) 2013, November 8, Fraunhofer-Zentrum Kaiserslautern, pp 42–47
- Sliseris J, Rocens K (2010) Curvature analysis for composite with orthogonal, asymmetrical multilayer structure. *J Civ Eng Manage* 16(2):242–248
- Sliseris J, Rocens K (2013a) Optimal design of composite plates with discrete variable stiffness. *Compos Struct* 98:15–23
- Sliseris J, Rocens K (2013b) Optimization of multispan ribbed plywood plate macrostructure for multiple load cases. *J Civ Eng Manage* 19(5):696–704
- Sliseris J, Andrä H, Kabel M, Dix B, Plinke B, Wirjadi O, Frolovs G (2014) Numerical prediction of the stiffness and strength of medium density fiberboards. *Mech Mater* 79:73–84

- Somer D, Perić D, de Souza Neto E, Dettmer W (2014) On the characterisation of elastic properties of long fibre composites using computational homogenisation. *Comput Mater Sci* 83:149–157
- Souza F, Castro L, Camara S, Allen D (2011) Finite-element modeling of damage evolution in heterogeneous viscoelastic composites with evolving cracks by using a two-way coupled multiscale model. *Mech Compos Mater* 47(1):133–150
- Wilbrink D, Beex L, Peerlings R (2013) A discrete network model for bond failure and frictional sliding in fibrous materials. *Int J Solids Struct* 50:1354–1363
- Wirjadi O, Godehardt M, Schladitz K, Wagner B, Rack A, Gurka M, Nisse S, Noll A (2014) Characterization of multilayer structures in fiber reinforced polymer employing synchrotron and laboratory X-ray CT. *Int J Mater Res* 105(7):645–654
- Woodson GE (1977) Density profile and fiber alignment in fiberboard from three southern hardwoods. *For Products J* 27(8):29–34
- Wriggers P, Zavarise G (1997) On contact between three-dimensional beams undergoing large deflections. *Commun Numer Methods Eng* 13:429–438