Numerical simulation of tensile testing using stochastically produced fibre networks of paper

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1 GEOMETRY OF STRUCTURE

The development of continuum mechanical models to simulate the behaviour of natural fibre materials under mechanical loads requires in-depth knowledge regarding the characteristics of the individual fibres, in particular their morphology, situation in the network, strength, stiffness and their qualities at the fibre contact areas. A consideration at the micro mechanical level is therefore necessary. The material structure of special paper grades can be realistically recreated on a numerical basis by the parameter-controlled generation of fibre networks with stochastic distributions of geometrical properties, e.g. taking the anisotropy of the machine direction into consideration by using a sieve-jet difference in velocity and the statistics of the resulting orthogonal strengths linked with it, see fig. 2a). Above all, this generic micro structure contains the fibre walls, metric and curvature information on their surfaces, hollow cavities within fibres, information about neighbouring fibres for contact, and where appropriate additional particles and pigments. This will make modelling possible in different physical areas, e.g., optics, continuum mechanics and fluid dynamics with one model. Depending on the respective objectives pursued by the simulation, idealisations must be made which lead to more or less abstracted models.

2 MECHANICAL MODEL

2.1 Discretisation with finite elements

Special studies of the mechanical behaviour at small network extracts can be made with discretisation of the fibre walls with shell elements. Investigations were carried out with surface-related multi-director finite shell elements which are applicative in particular for contact, see [1, 3]. Fig. 2b) shows a derived mechanical model of the same fibre network like in 2a), in which the fibre centre line (brown) and fibre bonds (blue), which form between the fibre walls of touching fibres in real geometry, are represented by different beam models. Their material models take viscoplasticity and failure in particular into consideration in each case. The image of additives and particles is taken into account indirectly by qualities in the fibre contact zones and fibre bond discretisation, respectively.

2.2 Fibre Bonding

Bonding between fibres plays an important role in the network deformation process, particularly affecting the ultimate loads the network can sustain. Factors which are important for the bonding mechanical properties are particularly geometry of the bonds, the shape of the bonded area, material and surface properties in the bonded region. Modelling on this scale is used to systematically study the contribution of each factor into the deformation process. In order to capture all the details of the bonding, it is necessary to create a detailed, parameterised model of the bond between two fibres considering mechanical contact and adhesion, see fig. 1. The development of the bond should be understood with the reference to the manufacturing processes, including forming, pressing and drying.

The information extracted on the fibre bond level are used in the mechanical fibre network model for changing the investigation level in order to can maximize the desired properties of paper.

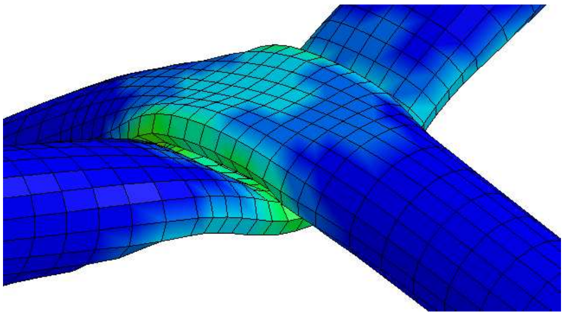

Figure 1. Two-fibre contact model, outer fibre surface discretised with shell elements. Lighter and green colouring shows high plastic strains.

3 TENSILE TESTING

In this case, the model shows a paper fibre network consisting of 500 fibres (0.5mm to 0.75mm in length) on a surface area of $1mm^2$ with a height of 0.09mm and a sheet density of $0.6g/cm^3$. Nine material identity curves could be obtained with aid of several stochastic realisations of this model, e.g. by an accurate numerical evaluation of the stress-strain relationships in the case of normal and shear loads of this representative volume element (RVE) in all spatial directions for a completely three-dimensional orthotropic material

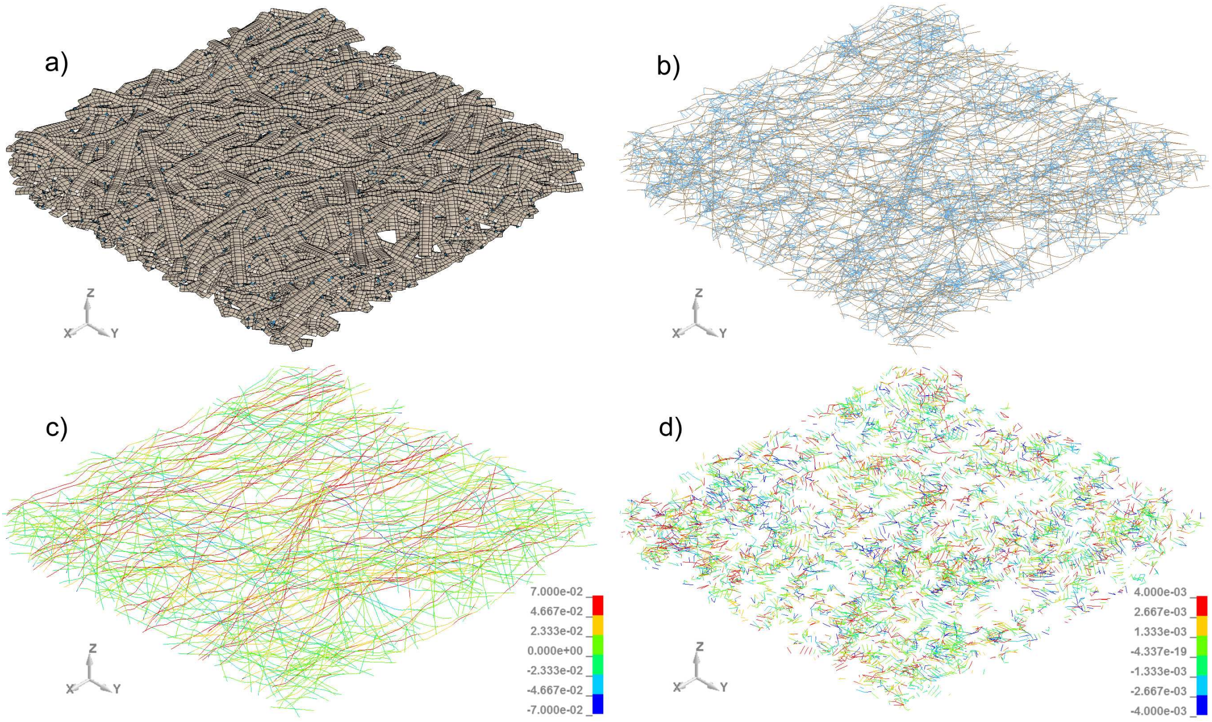

Figure 2. a) Numerically created paper fibre network on a surface area of 1mm² with a height of 0.09 and a sheet density of 0.6g/cm³; **b)** A mechanical model of the same fibre network; brown: centre fibre line, blue: idealised fibre bonds; **c)** longitudinal fibre forces in N when the network is stretched by 2% in the x-direction (tensile test); red: tension; blue: pressure; **d)** bonding forces of the idealised fibre bonds in N when the network is stretched by 2% in the x-direction corresponding to c.

law. This can be used directly to simulate the mechanical behaviour of larger structures, e.g. on the mesoscopic scale, see [2], or in product simulations, to the overall description of the material paper as a so-called homogenised material law. Failure only should be considered in simultaneous multi level simulations to make sense.

The results are presented here for only one of the huge number of necessary simulations, i.e. the normal load expressed as tension in the x-direction (machine direction) at a strain rate of 0.01/s and an achieved strain of 2.0% for one stochastic realisation, i.e. immediately before system failure. A parameter fitting of the model was carried out with varying strain rates even in this tension test and in the cross direction. The transferability to a direction perpendicular to the sheet is of fundamental importance, e.g. when simulating calandering, and is the object of future studies.

Fig. 2c) shows the distribution of forces in the longitudinal direction of the fibres with high longitudinal tension forces (orange to red) in fibres which form a small angle with the x-axis and high pressure forces (light blue to blue) in fibres with corresponding large angles. The resultant force at the front ends of the RVE where x=0.0 and x=1.0 amounts to 4.7 N which corresponds to 52 N/mm² accordingly to tensile tests. Fig. 2d) shows the distribution of the tension and pressure forces occurring in the fibre bonds. An elasticity module for an isotropic fibre wall of 42000 N/mm² and initial plasticity of the bonds at 130 N/mm² and their failure strain of 0.2% were used as the basis. It should be noted that the forces calculated for the fibre bonds cannot be interpreted directly as contact forces. A conclusion about the bonding forces can only be drawn by an in-depth two-fibre contact model.

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