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## **A fiber network model to understand the effects of fiber length and height on the deformation of fibrous materials**

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### **Abstract**

Fiber networks, in which the natural or artificial fibers are randomly or directionally aligned and bonded together through a chemical, mechanical and/or thermal processes, form the structural foundations for fibrous materials such as nonwoven fabrics, paper and paperboards. Fiber network deformation plays critical role in determining the mechanical properties of such materials. Therefore, there have been extensive efforts to generate fiber network models in two and three dimensional space. As a contribution to the modelling efforts, a fiber network model is introduced in the present study. The main goal is to understand the microstructural parameters including fiber length and cross-section affecting the fiber network deformation and compute the mechanical properties of the aggregate. The present numerical advancement is believed to guide researchers and designers to analyze fiber network characteristics more efficiently and in shorter time spans.

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### **1. Introduction**

Fiber networks, in which the natural or artificial fibers are randomly or directionally aligned and bonded together through a chemical, mechanical and/or thermal processes, form the structural foundations for various engineering materials. Some of these include nonwoven fabrics used in hygiene products, car panels, building and roof coverings, waddings and geotextiles; fiber mats and filters used in electromagnetic shielding and fuel cell gas diffusion layers; sintered metallic fiber networks for prosthetics and metal-matrix composite applications; felted or layered wood fiber networks used in paper and packaging products [1-6]. Their deformation and failure characteristics are dependent on the geometrical and spatial properties of constituents [7-9].

Due to direct correlation and accuracy, there have been extensive microstructural modelling investigations on fiber networks in two and three dimensional space [10-15]. The earliest two dimensional network models were based on random line generation and consolidation in transverse plane. Two dimensional models have been successfully used to determine the in-plane properties where the specimen thickness is of order of one tenth or less of average fiber length and negligible [5]. However, determination of three dimensional properties necessitates an additional dimension, for which the fibers can be deposited and bend on top of each other [16]. Hence, more realistic fiber network structure can be generated with three dimensional models, which also gives a better insight into microstructural properties.

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As a contribution to these efforts, a fiber network model is introduced so as to analyze the effects of microstructural parameters including fiber length and cross-section on the fiber network deformation and compute the mechanical properties of the aggregate. The present numerical advancement is believed to guide researchers and designers to analyze and test fiber network characteristics more efficiently and in shorter time spans.

## 2. Methodology

### 2.1. Geometric model

In the present study, fiber intersections are favored in contrast to the literature studies mainly focusing on short fiber reinforcements and elimination of fiber collision [9]. Foundation of the present study follows daily practices such as long fiber reinforced composite materials, paper and paperboards. Elements of the model consists of geometrical description of fiber, planar projection, fiber trimming and intersection search processes.

In  $XYZ$ -Cartesian coordinate system, each individual fiber was described in terms of its spatial properties, i.e. centroid  $C(X_i, Y_i, Z_i)$  with positive integer index  $i$ , in-plane and polar fiber orientations  $\theta$ ,  $\phi$ , respectively, and geometry, i.e. length  $l$  and cross-sectional properties, width  $w$ , height  $h$  and wall thickness  $t$  which was assumed to be same for all cell walls. In addition to this, specimen was described as a rectangular prism with length  $L$ , width  $W$  and thickness  $T$ , which is composed of layers with thickness  $T_{\text{layer}}$  as seen in Fig. 1.

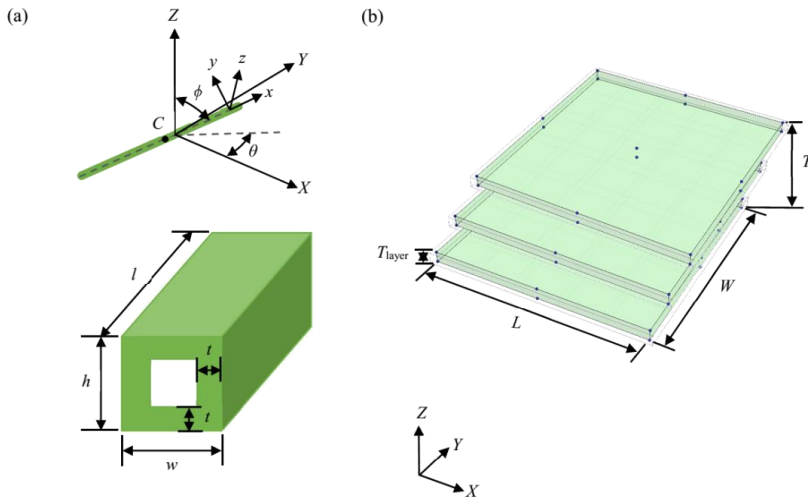


Fig. 1 Fiber profile and distribution: (a) fiber spatial properties in global  $XYZ$ -Cartesian coordinate system and geometrical properties in local  $xyz$ -Cartesian coordinate system, (b) layered structure of specimen in global  $XYZ$ -Cartesian coordinate system.

After formation of fibers based on the geometrical description, fiber intersection search process was executed and fiber network was formed, an example of which can be seen in Fig. 2.

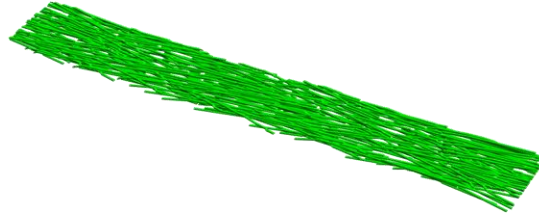


Fig. 2 Specimen generated with the present model.

## 2.2. Mechanical model

In the present study, wood fibers forming a paper stripe was considered. The fibers were modelled as eight noded linear brick elements denoted as C3D8 in commercial finite element solver Abaqus CAE [17] where the fiber wall material was assumed to be linear elastic and isotropic with  $E_{fib}=10$  GPa and  $\nu_{fib}=0.3$  [18]. Fiber intersections were modeled as interfiber bonding sites for which hard contact approximation was used to overcome fiber penetration and stick-slide formulation with maximum shear stress of 7.6 MPa provided in [18] was used to define the in-plane shear at the bonding sites. Explicit dynamic integration, i.e. forward Euler method, was used to solve the contact problem.

Uniform displacement boundary conditions were applied with multipoint constraints where the formulation follows

$$\begin{aligned}\vec{u} &= \vec{r} \cdot \mathbf{e}^M ; \\ u_j^i &= u_j^{i+1}, \theta_j^i = \theta_j^{i+1} \text{ at } \Omega_j^1 ; \\ u_j^i &= u_j^{i+1}, \theta_j^i = \theta_j^{i+1} \text{ at } \Omega_j^2 ; \\ i &= \{1, 2, \dots, n\}; j = \{X, Y, Z\} .\end{aligned}\tag{1}$$

Here,  $\vec{u}$  is the displacement vector,  $\vec{r}$  is the relative position vector,  $\mathbf{e}^M$  is the macroscopic constant strain,  $\Omega$  stands for the boundaries. In Fig. 3, multipoint constraints are represented for the opposing boundaries along  $X$ -direction.

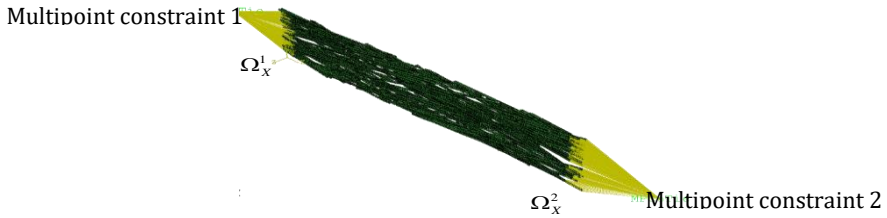


Fig. 3 Representation of constraints and boundaries.

Then, macroscopic (effective) compliance  $\mathbf{C}^M$  was obtained from the relationship between the given macroscopic infinitesimal strain  $\mathbf{e}^M$  and computed macroscopic stress  $\mathbf{s}^M$  so that [19, 20]

$$\mathbf{e}^M = \mathbf{C}^M : \mathbf{s}^M .\tag{2}$$

### 3. Results

The main goal of the simulation experiments was to understand the microstructural parameters including fiber length and cross-section affecting the fiber network deformation and compute the mechanical properties of the aggregate. Therefore,  $L=5$  mm,  $W=1$  mm and  $T=0.060$  mm with  $T_{\text{layer}}=0.020$  mm were designated as the specimen dimensions. For each specimen, in-plane fiber orientation  $\theta$  was taken to be uniformly distributed within  $\pm 15^\circ$  range while polar orientation  $\phi$  was taken to be null. For each fiber, fiber wall thickness  $t$  was kept constant with the value of 0.0025 mm whereas fiber width  $w$  was taken to be 0.025 mm. As a case study, effects of fiber length and height on normalized elastic modulus  $E_X/E_{\text{fib}}$  were studied, design of experiments of which is shown in Table 1. In these experiments, each set was tested for three times.

Table 1 Design of experiments

	Set	Untrimmed fiber length $l$ (mm)	Fiber height $h$ (mm)
Fiber length	1	1.0	0.010
	2	1.5	0.010
	3	2.0	0.010
Fiber height	4	2.0	0.005
	5	2.0	0.010
	6	2.0	0.020

As seen in Fig. 4, there is a direct relationship between fiber length and normalized elastic modulus  $E_X/E_{\text{fib}}$ . This relationship can be explained in terms of the number of crossings (bondings) per fiber. As shown in the right hand side of Fig. 4, this quantity increases with fiber length, which results in stiffer fiber network.

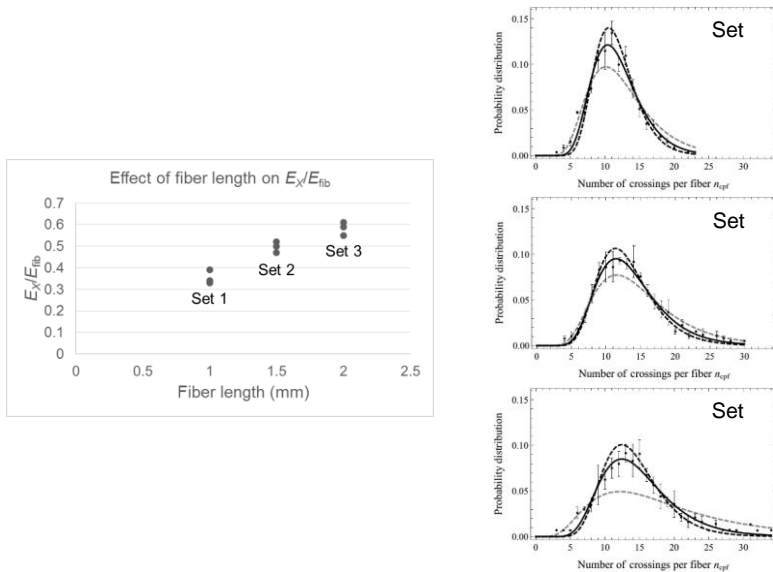


Fig. 4 Effect of fiber length on normalized elastic modulus  $E_X/E_{\text{fib}}$ .

In case of fiber height analysis shown in Fig. 5, it is seen that there is an inverse effect on normalized elastic modulus  $E_X/E_{\text{fib}}$ . This is again due to decrease in number of crossings

per fiber as a result of decreasing number of fibers in predefined specimen volume  $L \times W \times T$ .

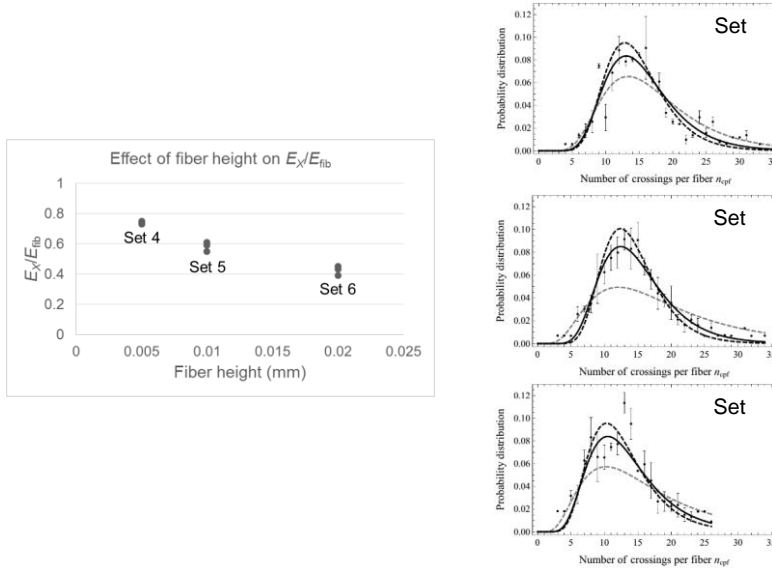


Fig. 5 Effect of fiber height on normalized elastic modulus  $E_X/E_{fib}$ .

#### 4. Discussions and conclusions

In the present investigations, a fiber network model was introduced so as to analyze the effects of microstructural parameters including fiber length and cross-section on the fiber network deformation. Geometrical description of the model was used to mimic long fibers used in paper and packaging products. Eight noded linear brick elements were used to generate the finite element mesh whereas a contact model was described at interfibre bonding sites. Uniform displacement boundary conditions were used with multipoint constraints under homogenization framework. The problem was solved by means of explicit dynamic integration in Abaqus CAE. By using the introduced methodology, a case study was carried out to understand the effects of fiber length and height on the normalized elastic modulus  $E_X/E_{fib}$ . It was deduced that fiber length has positive impact on  $E_X/E_{fib}$  whereas latter has negative effect. The present numerical advancement is hence believed to guide researchers and designers to investigate fiber network characteristics more efficiently and in shorter time spans.

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