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# Geometrical and spatial effects on fiber network connectivity

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ABSTRACT

For fibrous materials such as nonwoven fabrics, paper and paperboards, inter-fiber bonds play a critical role by holding fibers, thus providing internal cohesion. Being a physical phenomenon, inter-fiber bonds occur at every fiber crossing and can be also geometrically detected. In relation to the idea, a statistical geometrical model was developed to investigate the effects of fiber geometry, (i.e. length and cross-sectional properties), spatial distribution, (i.e. location and orientation), and specimen size on fiber network connectivity, which refers to inter-fiber bonds at fiber crossings. In order to generate the fiber network, a geometrical fiber deposition technique was coded in Mathematica technical computing software, which is based on the planar projections and intersections of fibers and provided as supplementary material to the present article. According to this technique, fiber geometries in discrete rectangular prismatic segments were generated by using uniform distributions of the geometrical and spatial parameters and projected onto the transverse plane. Then, projected geometries were trimmed within the transverse boundaries of the specified specimen shape, rectangular prism in this particular study. After this step, fiber crossings were determined through a search algorithm, which was also used as the basis for the fiber spatial regeneration. Thereafter, fibers were accumulated on top of each other by taking fiber crossings into account and eventually fiber networks based on selected properties were formed. By means of the proposed technique, a series of simulation experiments were conducted on paper fiber networks to investigate the correlation between the fiber network connectivity and fiber length, cross-sectional properties, orientation and specimen length, width and thickness.



## 1. Introduction

Fiber networks, in which the natural or artificial fibers are randomly or directionally aligned and bonded together through chemical, mechanical and/or thermal processes, form the structural foundations of various engineering materials. As seen in Fig. 1, 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 [1–5]. Their deformation and failure characteristics are dependent on the geometrical and spatial properties of constituent fibers and fiber network connectivity referring to inter-fiber bonds at fiber crossings [6–9].

In order to model fiber network characteristics, various studies have been conducted in which the main strategy is based on continuum or microstructural models. In continuum models, material details and microscopic heterogeneities, e.g. geometrical properties of constituents and their variations, are averaged over the representative volume elements RVEs. The accuracy in continuum models is dependent on the selected RVE size and how well the material details are approximated and represented with these RVEs [15,16]. Therefore, continuum models are safely used in the analyses for which the material details do not have the highest priority [17]. In microstructural models, geometrical and other physical properties are modeled for each constituent separately, which increases the computational cost. However, it is possible to determine the stresses and strains in each constituent accurately wherein the properties of the material and its constituents can be directly related to each other in microstructural models [18].

Due to direct correlation and accuracy, there have been extensive microstructural modelling investigations on fiber networks in two- and three-dimensional spaces [19–21]. The earliest two dimensional network models were based on random line genera-

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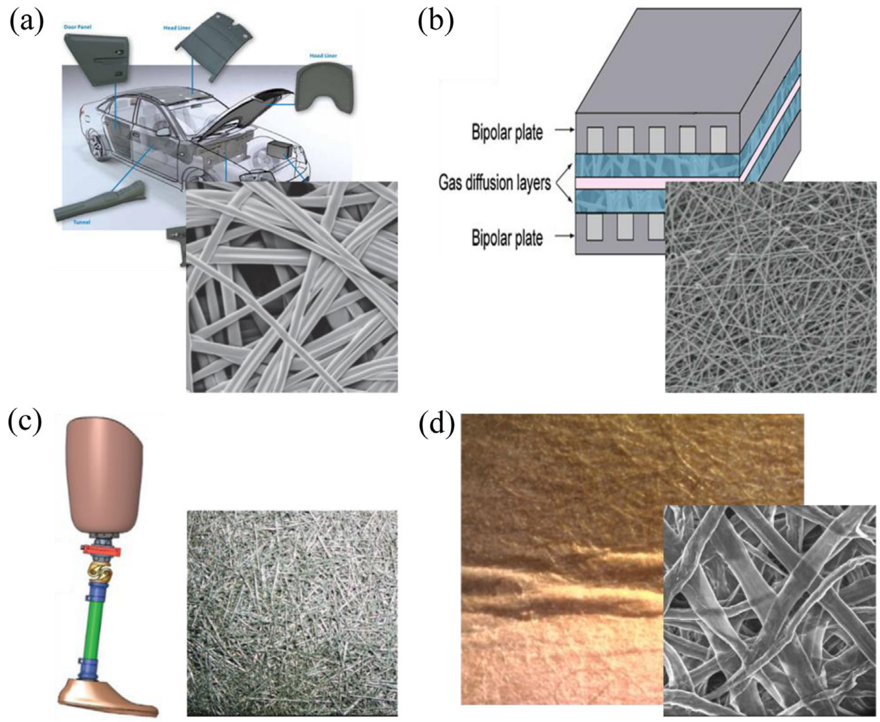


**Fig. 1.** Various engineering applications and microscope images of their constituents: (a) car panels and nonwoven fabrics [10,11], (b) fuel cell gas diffusion layers and carbon fiber mats [4,12], (c) lower-limb prosthesis and sintered metallic fibers in pylon [5,13], (d) paperboard ply and wood fibers [9,14].

tion 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 [4,22]. However, determination of three dimensional properties necessitates an additional dimension, for which the fibers can be deposited and bend on top of each other [23,24]. Hence, more realistic fiber network structure can be generated with three dimensional models, which also gives a better insight into microstructural properties. However, due to limited computing power in previous decades, it has been a big challenge to create fiber networks mimicking the in-situ conditions in three dimensional space [25,26].

As a contribution to the previous modelling efforts, a three dimensional statistical microstructural model is introduced so as to analyze the effects of fiber geometry, i.e. length and cross-sectional properties and spatial properties, i.e. location and orientation and specimen size affecting the fiber network connectivity in a statistical manner. By means of the introduced model, a case study on fiber networks forming paper stripe specimens was conducted. The present numerical advancement is believed to guide researchers and designers to investigate fiber network characteristics more efficiently and in shorter time spans.

## 2. Methodology

### 2.1. Geometrical and spatial properties

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 [20,26–28]. Foundation of the present study follows daily practices such as long fiber reinforced composite materials, paper and paperboards. For this purpose, statistical geometrical model was developed to analyze the effects of geometrical properties of fibers, (i.e. fiber length and cross-sectional properties), and their spatial distribution, (i.e. location and orientation), and specimen dimensions on the fiber network connectivity. Elements of the model consists of geometrical description of fiber, planar projection, fiber trimming and crossing search processes.

As seen in Fig. 2, each individual fiber was described in terms of its spatial properties, i.e. centroid $C\,(X_i, Y_i, Z_i)$ and $i \in \mathbb{Z}^+$, azimuthal orientation $\theta$ and polar orientation $\phi$, 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 $T_{\text{layer}}$. In this study, hollow rectangular profile was selected to mimic the wood fiber cross-section composed of cell walls and lumen [29].

In order to define the spatial distribution of fibers, fiber centroids were first generated with a uniform probability distribution on a rectangular plane with length $L$ and width $W$ in $XYZ$-Cartesian coordinate system where the $Z$ coordinate of centroids, were kept constant [30]. As seen in Fig. 3, a Monte Carlo type simulation was then used for random selection and picking of each $C\,(X_i, Y_i, Z_i)$ in an iterative manner. By this way, selection of same fiber centroids was avoided.

### 2.2. Fiber network formation process

Fibers were generated as hollow rectangular prism parallel aligned in the $XY$-plane and deposited into layers of Fig. 2(b) one after another by picking the distributed fiber centroids illustrated in Fig. 3. In order to conduct the deposition process, fiber volume fraction, which is the proportion between the total fiber volume in the confined space $\sum_{f=1}^{n} V_f$ and specimen volume $V = LW\,T$, was used as the controlling parameter of the iterative deposition algorithm shown in Fig. 4.

Despite the fiber curvature of in-situ, distance between each fiber crossing were assumed to be close enough so that fiber