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# Structure-property Relationship of Bio-Inspired Fibrous Materials

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**Abstract**

Natural fibrous tissues exhibit excellent mechanical properties and functional behavior. These functional behaviors are desired in many recent designs such as soft robotic devices and tissue engineering application. A sensible strategy to reproduce the functionality of natural materials is to mimic their microstructures, which are in the form of fibrous networks. However, literature on how fibrous networks affect the mechanical behavior in tissues is still lacking. In this study, the deformation of microscopic fibrous networks was investigated using finite element analysis. Fibrous networks were generated in MATLAB by constructing lines from random points with random angles. The fibers were then modeled by beam elements in finite element software ABAQUS. A noodle-like behavior resembling collagen fibers was defined. Finite element analysis showed that fibrous networks deformed in a non-continuum manner and allowed large deformation. Parameters such as fiber properties, fiber diameter, fiber and bonding density were found to significantly affect material stiffness. In conclusion, understanding the structure-property relationship provides useful guidelines for the creation of bio-inspired materials with desired stiffness.


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*Keywords:* fibrous networks; bio-inspired materials; structure-property; finite element analysis

## 1. Introduction

Bio-inspired fibrous materials assemble the microstructures of natural tissues in order to exhibit similar mechanical behavior of natural tissues. These materials have been extensively studied in the last decade due to their potential application in tissue engineering and bio-inspired robotics. For tissue engineering application, materials consisting of nano- to micrometer sized fibers have been used to encourage the proliferation of cells [1, 2]. For robotics, fibrous materials have the potential to be used in the application of soft actuators and soft sensors. Design principles have been learnt from nature to inspire future generation of robotics [3, 4]. For instance, principles underlying human and animal locomotion have been applied in the design of robotic motions [5]. One key characteristic of biological muscle and joints that allow smooth motions is the constant change of stiffness during locomotion. This understanding from nature inspires recent development of new functional materials in the design of robotic joints and soft actuated materials.


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Mimicking the material structures of natural tissue to produce new functional materials which have similar mechanical behaviors is a sensible strategy. However, natural tissues exist in complex fibre-like structures on more than one length scale [6-10]. The mechanics of fibrous networks have been studied in order to facilitate the production of new fibrous materials with enhanced properties [11-14]. Existing studies suggest that the mechanical properties of fibrous materials are governed by many factors including the material microstructure topology (*i.e.* crosslink, fiber diameter) and material constituents (*i.e.* fiber modulus and ductility). However, there is a lack of detailed understanding in demonstrating the universal network behavior by the consideration of interaction among these factors. This paper focuses on enhancing fundamental understanding of the universal network behavior for fibrous materials. Design principles have been derived from such understanding, including knowing the primary features to govern network deformation.

## 2. Finite Element Modeling

The mechanical behaviors of both short and long fibrous networks were studied by finite element (FE) method. The modeling of fibrous networks was similar to previous studies [12-14]. The modeling began with generating random points in an unit cell in MATLAB. Fibrils were then generated by constructing lines from these random points with random angles. Fibril lines which exceed the unit cell edges were cut. In addition, the fibril lines were also meshed in MATLAB. The meshing was generated by assigning nodes and elements on fibrils lines. The bonds among the fibrils were modeled as rigid bonding. After generating the meshed fibrils in MATLAB, the fibrils were modeled by approximately 1 μm beam elements in FE software ABAQUS. These beams were assigned to a stretching stiffness (*i.e.* the force needed to induce an unit of axial strain) and a bending stiffness (*i.e.* the force needed to induce an unit radius of curvature). Loading was applied on the fibrous networks under planar tension condition. When the unit cell was uniaxially stretched, the bottom plate was fixed and the top plate was stretched vertically. The rest of the nodes including those located at the left and right edges were free to move both vertically and horizontally.

Two types of network presented here include short and long fibrous networks. Short fibrous networks represent microstructures of some synthetic fibrous scaffolds such as polypropylene/polyethylene (PP/PE) nonwoven fabrics (Fig. 1). Long fibrous networks exist in both human amniotic membranes and synthetic polycaprolactone (PCL) scaffolds. A number of FE models were modeled to investigate important features that govern the network deformation. The parameters studied in this paper include fiber diameter, fiber density, bonding density and fiber modulus.

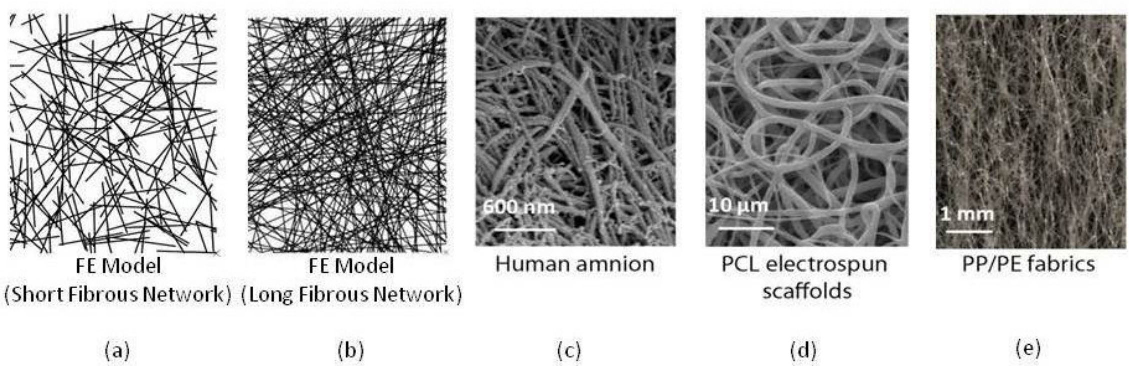


Fig. 1. Finite element models for (a) short and (b) long fibrous networks. SEM images of fibrous networks in (c) human amnion [12], (d) PCL electospun scaffolds and optical microscope image of (e) PP/PE fabrics [11].

## 3. Results

### 3.1 Deformation of Fibrous Networks

The deformation of fibrous networks under planar tension condition was investigated using finite element analysis (Fig. 2). When the strain was increased, the fibers were percolated parallel to the applied loading and then axially stretched. The fibers reorientated upon small strain and stretched parallel to the applied loading upon large strain. A state of pure shear exists in the network at a 45 ° to the loading direction. Fibers orientated at 45 ° were compressed and some buckled near the edges.

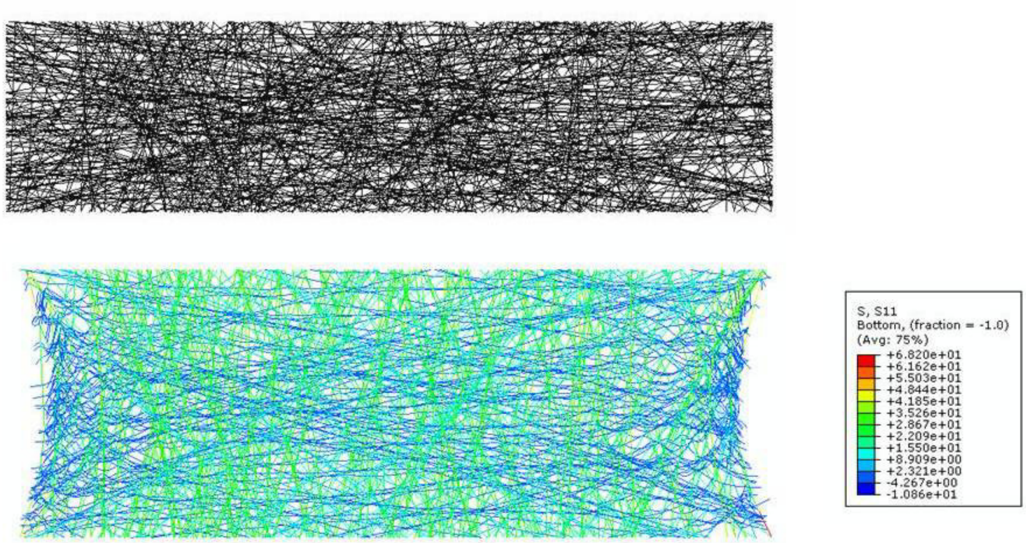


Fig. 2. Undeformed (upper) and deformed (below) fibrous networks

### 3.2 Master Curves

Influence of fiber properties, diameter and density to the stress-strain behaviour of fibrous materials were studied. The master curves were obtained by plotting the dimensionless shear and strain for both long (Fig. 3) and short (Fig. 4) fibrous networks in planar configurations. The shear stress was calculated from the total vertical reaction force at the top edge of the unit cell, divided by the cell size and the beam width. The dimensionless stress was then calculated as a function of fiber diameter $\phi$, fiber density $\rho_f$ and fiber modulus $E_0$ (Eq. 1). The shear strain was calculated from the vertical displacement of the top edge, divided by unit model width.

$$\bar{\tau} = \frac{\tau}{\phi \rho_f E_0} \qquad \text{Eq. (1)}$$

The master curve of long fibrous networks showed two obvious trends: elastic fibers showed linear curves while ductile fibers showed nonlinear curves (Fig. 3). The slopes remained constant for fibers with modulus of 100 MPa and 470 MPa. The slopes were reduced, indicating hardening effect for ductile fibers. The nonlinearity of the dimensionless stress-strain behavior depends significantly on fiber ductility. Unlike fiber property, the influence of other parameters including fiber diameter, fiber density and crosslink density are insignificant to the nonlinearity. The universal characteristics of the stress strain behavior of long fibrous networks can be described by the master curve (Eq. 2).

$$\bar{\tau} = 0.2\phi\rho_f(E_0\gamma_e + \frac{E_p}{E_0}\gamma_p) \qquad \text{Eq. (2)}$$

The trend showed by short fibrous networks was different from that of long fibrous networks (Fig. 4). The decrease of fiber diameter and fiber modulus reduced the slope of dimensionless stress strain curves. No universal stress-strain relationship was found. Moreover, the stress-strain behaviour of the networks also depends remarkably on the plastic behaviour of fibers. The network shows hardening behaviour when the elastic-plastic fibers were assigned.

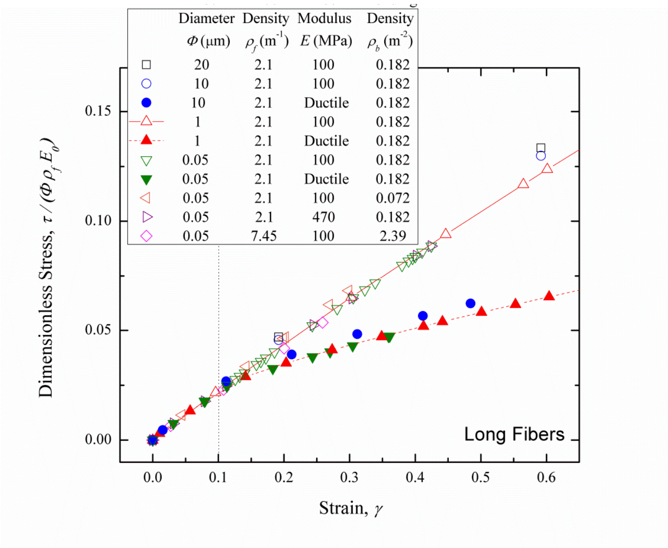


Fig. 3. Deformation responses for long fibrous networks indicating the effect of fiber diameter, density, modulus and density.

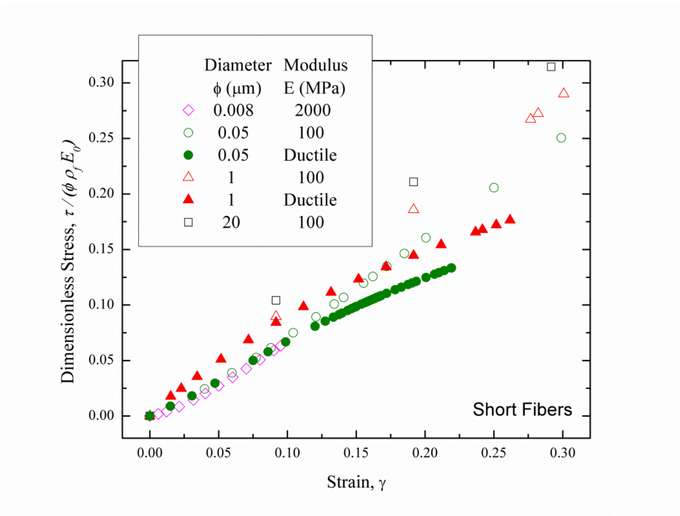


Fig. 4. Deformation responses for short fibrous networks indicating the effect of fiber diameter and modulus.

## 4. Discussions

The nonlinearity of the networks response was demonstrated by plotting the change of dimensionless modulus normalized by the initial stiffness $\Delta G/G_0$ (Fig. 5). Three types of behaviors were shown in the simulation. First, the networks showed linear behavior when there was insignificant change of modulus $\Delta G/G_0 = 0$; (ii) hardening behavior when there was negative change of modulus $\Delta G/G_0 < 0$; and (iii) stiffening behavior when there was positive change of modulus $\Delta G/G_0 > 0$.

The parameters affecting network response were grouped into two categories, *i.e.* network topology and fiber properties. The network topology studied here includes fiber diameter, fiber density and crosslink density. The fiber properties studied here include fiber modulus and fiber ductility. By calculating the dimensionless stress strain curve, the curves presented here normalized the effect of fiber diameter, fiber density, and fiber modulus by $1/(\phi \rho_f E_f)$. The nonlienearity of long fibrous networks depend more on the ductility of fibers. Besides the fiber ductility, the linearity of short fibrous networks also depends on fiber topology. The effect of network topology has more influence especially when the diameter and modulus are small $E\phi = 0.1$ (Fig. 5)

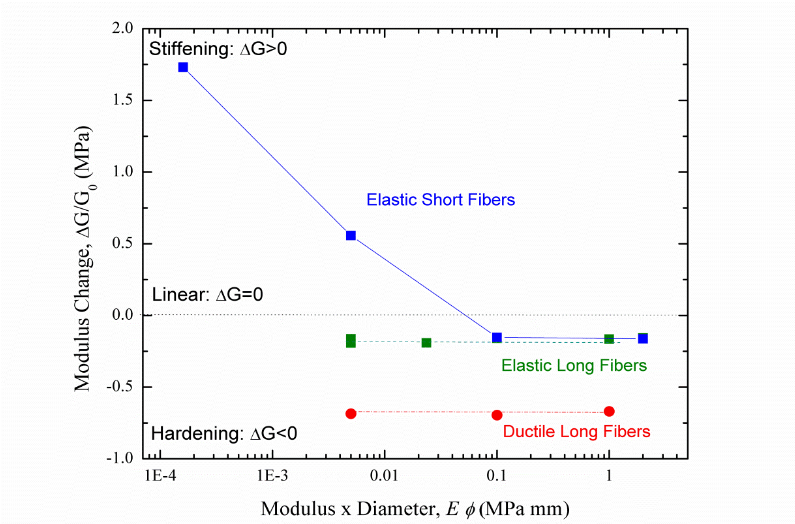


Fig. 5. Effect of fiber modulus and diameter on the material linearity of fibrous networks.

## 5. Conclusion

Bio-inspired materials have emerged as materials that improve functionality, efficiency and flexibility in many new designs. Deformation of fibrous networks has been studied to demonstrate the structure-property relationship. Finite element analysis showed that the network deformation was governed by both network topology and fiber property. The master curve of long fibrous networks which shows the universal characteristic of network deformation was obtained. The nonlinearity of long fibrous networks depends on fiber ductility while the nonlinearity of short fibrous networks depends on both fiber ductility and network topology. This understanding on the structure-property relationship can facilitate the robust production of bio-inspired fibrous scaffolds.

## 6. Acknowledgments

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