SIZE-DEPENDENT AND TUNABLE MECHANICAL PROPERTIES OF MICRO-AND NANO-SIZED STOCHASTIC FIBROUS STRUCTRES

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Abstract Filamentous networks can be widely found in biomaterials at the micro- and nano-scales. Some conventional theories may not apply to the materials with dimension at the micro- or nano-scale. The effects of strain gradient at the micro-meter scale and the effects of surface elasticity and initial stresses/strains at the nano-scale are incorporated into the deformation mechanisms in the analysis of stochastic fibrous structures. A random beam network model with cross-linkers has been developed to describe the fibrous networks whose relative density can be controlled to different values by adjusting the concentration of cross-linkers. The size-dependent effects on the relationships between the relative density and the elastic constants of micro- and nano-sized fibrous structures are investigated.

INTRODUCTION

Fibrous materials are another type of porous materials with low density and high stiffness and strength, which promise for a wide range of engineering applications. Fibrous structure can be widely found in biomaterials at the micro- and nano-scales. For instance, a typical extra-cellular matrix (ECM) is composed of structural protein nanofibres such as collagen with a diameter of the order of microns [1]. Increasing evidence has shown that the mechanical stiffness of ECM plays an important role in regulating cellular behaviours, including adhesion, proliferation and differentiation of mesenchymal stem cells (MSCs) [2]. Cytoskeleton (CSK) is a network of filamentous proteins within a cell's cytoplasm, composing of filamentous actin (F-actin), microtubules and intermediate filaments with diameters of the order of nanometers [3]. The mechanical stiffness of intracellular material, to a great extent, is governed by the cytoskeleton. In industrial engineering, micro- and nano-structured fibrous materials can be used in micro-electro-mechanical systems (MEMS) and nano-electro-mechanical systems (NEMS) devices, which are of great interest to scientists and engineers. The understanding of the mechanical properties of macro-sized porous materials has well been established. However, when the dimensions of fibrous structures are reduced to the micro- or nano-scale, the stiffness or rigidity is much different from that of their macro-sized counterparts.

It is crucial to incorporate the strain gradient effects at the micro-meter scale, and the surface elasticity and initial stress effects at the nano-meter scale into the deformation mechanism of fibrous materials. To the best of our knowledge, the size dependent mechanical behaviour of fibrous materials has not been reported. The objective of this paper is to investigate the effects of relative density on the size-dependent mechanical properties of micro- and nano-sized fibrous structures.

SIZE-DEPENDENT EFFECTS AT MICRO-SCALE

At the micro scale, the strain gradient has a dominant effect on the mechanical behaviour of the stochastic fibrous materials. l_m/d is used to describe the gradient strain effects in the micro-scale [4, 5], where the l_m is the intrinsic material length at the micrometer scale (which can be experimentally measured and is usually in the range between submicron and microns, and different for different materials), d is the diameter of the circular cross-section of the fibres. We have conducted the simulations for different values of l_m/d ($l_m/d = 0, 0.2, 0.5, 1.0$) to investigate the size-dependent effects on the elastic properties of the stochastic fibrous materials at the micro scale. It should be noted that when l_m/d is 0, in which the diameter of the fibres is much larger than the intrinsic material length scale l_m, the size-dependent effect vanishes and the elastic constants reduce to those of their conventional counterparts. The three-dimensional random beam model with cross-linkers developed to describe the stochastic fibrous networks is given in Fig1. The simulation results suggest that the smaller is the diameter of the fibres, the larger are the dimensionless Young's moduli of the fibrous materials; and that the larger is the relative density of the fibrous materials, the larger are the dimensionless Young's moduli, as shown in Fig2.

SIZE-DEPENDENT EFFECTS AT NANO-SCALE

It has been found that at the nanometer scale, the surface elasticity and the initial strain (stress) can significantly affect the mechanical behaviours [4-6]. l_n/d is used to describe the surface elasticity effects at the nanoscale, where the l_n is the material intrinsic length at the nanometer scale, which can be expressed by $l_n = S/E_s$ (where S is the surface elasticity modulus) and may vary over a range from 0.01nm to 0.1nm[6] for different materials. ε_0^L is the initial strain in the length direction of the fibres, whose amplitude can be controlled to vary by an applied electric potential [7]. We have conducted the simulations using finite element software for different values of l_n/d ($l_n/d = 0, 0.2, 0.5, 1.0$) and ε_0^L ($\varepsilon_0^L = -0.06, -0.03, 0, 0.03, 0.06$) to separately investigate the surface elasticity effects and the initial strain effects on the elastic properties of the stochastic fibrous materials at the nanometer scale. Note that when $l_n/d = 0$ and $\varepsilon_0^L = 0$, the size-

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dependent effects at the nanoscale vanish and the elastic constants reduce to those of their conventional counterparts. The simulation results suggest that for nano-sized fibrous structures, the smaller the size, the larger the Young's modulus as shown in Fig3. Moreover, the non-dimensional Young's modulus can be controlled to vary by adjusting the amplitude of an applied initial strain as shown in Fig4.

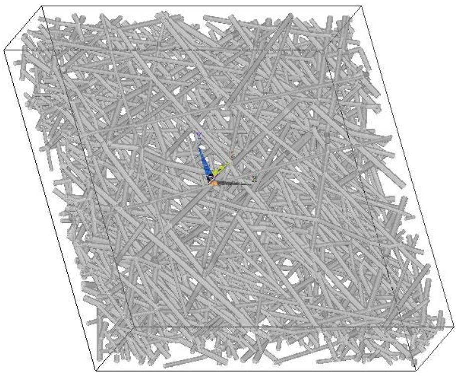

Fig1. Three-dimensional random beam model with cross-linking.

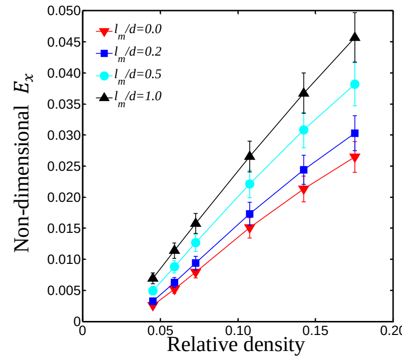

Fig2. Size-dependent effect on the relationship between the non-dimensional Young's modulus in the x direction and the relative density of stochastic fibrous materials at micro-meter scale.

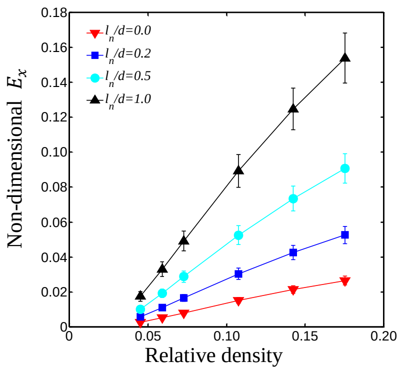

Fig3. Size-dependent effect on the relationship between the non-dimensional Young's modulus in the x direction and the relative density of stochastic fibrous materials at nano-meter scale.

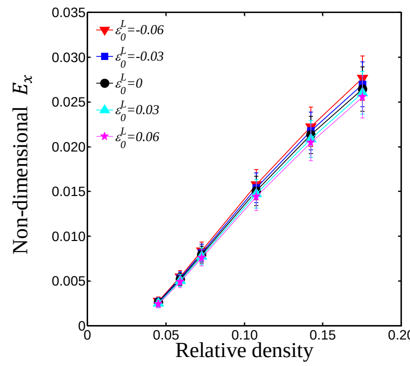

Fig4. Non-dimensional Young's modulus E_x *v.s.* the relative density of nano-sized stochastic fibrous networks with the presence of the effects of initial strains/stresses.

CONCLUSIONS

The elastic properties of filamentous networks are size-dependent at the micro- and nano- scales. By incorporating the strain gradient effects at the micro-scale and the effects of surface elasticity and initial strains at the nano-meter scale into the deformation mechanisms, the size-dependent mechanical properties are investigated for the micro- and nano-sized fibrous structures, which could give a good reference for the scientists in tissue engineering and serve as a guide in the design of MEMS and NEMS.

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