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Development of Rheological Model of Random Fibrous Networks in the Frame of Generalized Continua

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ABSTRACT

In this work, we construct a micropolar (Cosserat) rheological model for biological membranes, considered as random networks of elastic filaments in the plane, based on the finite element method. The calculated effective mechanical properties rely on micromechanical approaches to investigate scale effects related to the microstructure on the macroscopic properties of biomembranes. The filaments of the random network are modeled as Timoshenko beams and are connected at intersection points by welded joints. The evolution of higher-order moduli with network parameters, such as network density, internal bending length of fibers, and the size of the window of analysis, is determined.

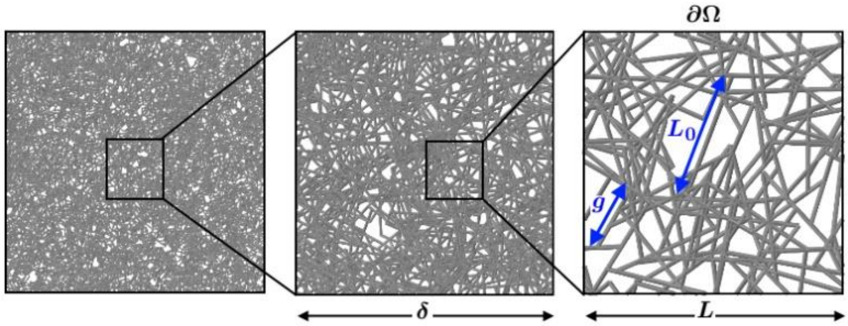
Keywords: Biomembranes, random fiber network, non-affinity, size effects, micropolar medium, homogenization.

1. Introduction

Collagen is the most abundant protein, presenting itself in the form of fibers and representing approximately one-third of the proteins in the human body. Other fibers exhibit elastic properties that allow mobility and deformability of tissues in the reversible domain [1]. In this work, we consider the biological membrane as a semi-flexible network composed of rigid and highly cross-linked filamentous aggregates at the scale of their thermal persistence length. Semi-flexible networks store energy from axial and flexural elastic deformation of the filaments. This property makes the behavior of semi-flexible networks and its relationship with the mechanical properties of its constituents more complex than the behavior of flexible networks where energy is stored only in the axial deformation mode of the filaments [2,3]. Biopolymer network models [4-6] account for interactions between elongation and bending of fibers in the overall nonlinear elastic behavior on a macroscopic scale. In this work, we adopt the framework of generalized continuum theories, which have been widely used to explain size effects for a broad class of materials but not for random fibrous materials to our knowledge. This constitutes the main originality advocated so far in the current work.

2. Generation of random structures

The random fiber network is composed of fibers of finite length, with random orientation and random positions of their centers of gravity. Here, we consider two-dimensional network systems in which the fibers have an identical length L_0 and occupy a square region with dimensions L.



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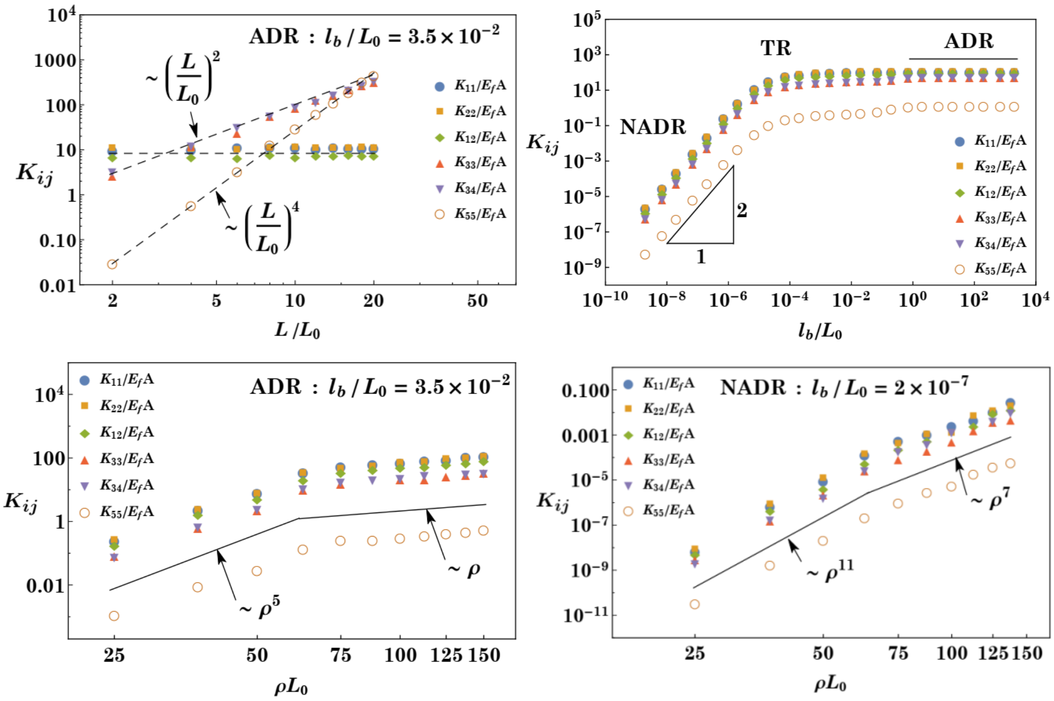
3. Results and Discussion

The micropolar moduli K_{ij} strongly depend on the competition between flexural and axial deformation energies quantified by the parameter l_b. We investigate the variation of micropolar moduli as a function of the normalized internal bending length, the fiber density in the network and the size of the window of analysis.



4. Conclusions

A model of a Cosserat generalized continuum has been identified to analyze the mechanical response of random fibrous networks modeling biomembranes and to study the dependence of micropolar moduli on network parameters. As the network density and the internal bending length of the fibers increase, a transition from the non-affine deformation regime to the affine deformation regime is observed. The results indicate also a strong dependence of these micropolar moduli on the size of the analysis window and highlights both the need to develop more reliable higher-order homogenization schemes to calculate size-independent moduli and homogenization towards a micromorphic medium, which better captures internal deformation gradients due to these additional degrees of freedom. Both of these significant issues will be addressed in future developments.

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