Full sample fiber network models of nonwoven textiles

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Abstract

Network models are frequently used for the computational analysis of various fibrous materials. The resolution of single fibers is often viewed as a descend to the microscopic level opposed to the macroscopic level of deformations of the apparently continuous material. This two-level approach gives the ground to the constitutive modeling of the fibrous material via a representative volume element (RVE) that resolves the discrete fiber network microstructure. Uniform strains are imposed on the RVE through some boundary conditions and the averaged stresses are returned as the superposition of the equilibrium forces in the fibers (2). However, the assumed scale separation does not hold for many fibrous materials. Nonwoven textiles are made of long fibers that match the dimensions of the macroscopic sample. Thus a single microscopic cell can not properly represent the inhomogeneous deformations within the materials and the response of the fiber network beyond the simulation window no matter how large is the size.

As an alternative, one can model the entire random fiber network within the macroscopic sample. This requires an effective numerical method for the equilibrium of the system. We have recently developed a new fiber network model describing irreversible deformations of needlepunched nonwoven materials (3). Fibers are considered to be inextensible cables that can only be loaded in tension. They respond to the applied loads by relative sliding in the entanglements introduced by the needle-punching process. The frictional forces in the knots need to be overcome in order to initiate this mechanism of deformation. The rate-independent loading of such network structure is constituted within the theory of standard dissipative systems. A minimum principle for incremental potential is formulated with respect to the displacement-based variables: nodal coordinates, segment end-to-end vectors, segment lengths and incremental fiber slidings. It takes the form of second-order cone programming (SOCP) similarly to the case of elastic cable networks (4). A pure complementary energy principle is derived as the dual formulation in terms of stress-like variables: nodal reactions, fiber force vectors, axial forces and friction forces. Both SOCP problems can be solved numerically by interior-point methods.

This makes feasible the simulation of the entire domain of the macroscopic sample with hundreds of thousands of segments and sliding systems. We show that the model captures qualitatively the response of the needle-punched materials (5). The analysis relates the internal structure of the fiber network: the orientation of fibers, their curl as well as the pattern of the bonding sites introduced through the needlepunching to the strength and toughness of this type of materials.

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