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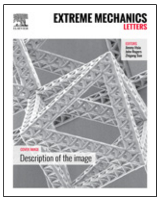

Tension-induced tunable corrugation in two-phase soft composites: Mechanisms and implications

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ABSTRACT

We numerically investigate the elastic deformation response of a two-phase soft composite under externally applied concentric tension. We show that by carefully designing the inclusion pattern, it is possible to induce corrugations normal to the direction of stretch. By stacking 1D composite fibers to form 2D membranes, these corrugations collectively lead to the formation of membrane channels with shapes and sizes tunable by the level of stretch. Furthermore, we show that by using specific inclusion patterns in laminated plates, it is possible to create pop-ups and troughs enabling the development of complex 3D geometries from planar construction. We have found that the corrugation amplitude increases with the stiffness of inclusion and its eccentricity from the tension axis. We discuss the mechanisms leading to the development of corrugations as well as their different implications. We hypothesize that the techniques discussed in this paper provide greater flexibility and controllability in pattern design and have potential applications in a variety of fields including tunable band gap formation and water treatment.

1. Introduction

Composite materials are ubiquitous in nature [1–4] as well as in industrial applications [5–7]. The combination of the soft and stiff phases usually leads to simultaneous optimization of several mechanical properties including stiffness, toughness and strength [8]. New multifunctional materials are also composite structures. These materials optimize objectives that go beyond mechanical functions to functions such as electrical and thermal conductivities [9], optical properties [2,6] and energy efficiency [10,6]. More recently, the area of programmable metamaterials [5,11] is emerging as a cutting edge research frontier with promising applications in several fields. Many metamaterials may be regarded as a composite material in which the softer phase is voids with different shapes [12,11]. In this paper we focus primarily on polymer reinforced composites in which a soft matrix is reinforced with stiffer inclusions. We investigate the influence of the stiffer phase distribution on the global deformation patterns and its different implications.

Reinforced composites are frequently found as building blocks in tough biological structures [3,13,4,14]. An example usually cited is human bone. Bone is a hierarchical composite of collagen and hydroxyl-apatite with remarkable combination of stiffness and toughness [1,4,7]. The basic building block of bone at the micro scale is mineralized collagen fibrils (MCF) [15] in which the soft collagen matrix is reinforced by platelet inclusions of stiff hydrated calcium phosphates. The mineral plates are elongated in one direction with an in-plane aspect ratio of 8–12 [16]. The common viewpoint is that the apatite plates are not distributed randomly but are rather arranged periodically with a specific staggering pattern [16]. This points to the possible role of pattern design in achieving optimal properties [3]. In this paper, we show that the inclusion pattern controls both in-plane and out-of-plane deformations in the composite and may be used to create complex geometries and designs.

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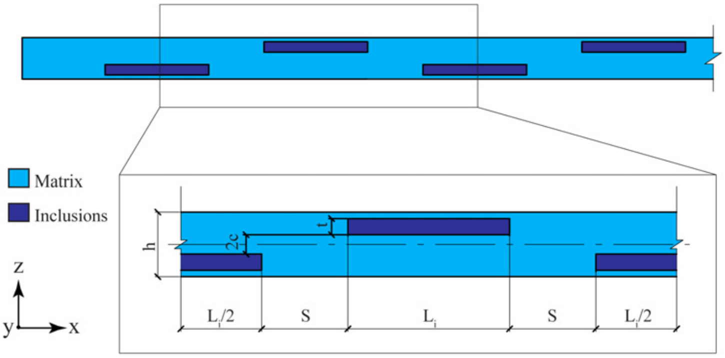

Fig. 1. Geometrical dimensions of unit cell of single composite fibril.

Developing complex and 3D controllable geometries, especially at nano and micro scales, is a topic of immense interests in a variety of fields [17–20]. Significant progress has been made in that field in the last 10 years with the advancement of 3D printing techniques [21] as well as the exploitation of certain mechanical effects such as compressive buckling [20]. Here we show, numerically, that the application of a tensile loading to a reinforced elastomeric fiber with designed inclusion patterns induces local bending deformation modes in the form of corrugations normal to the load application directions. By controlling the distribution of the stiff inclusions within the soft matrix, in a way that is inspired by the staggered patterns of elongated mineral particles in MCF, we are able to control the location, amplitude, and wavelength of these corrugations. This opens new opportunities for hierarchical material design in 2D and 3D.

The remainder of the paper is organized as follows. We describe the model setup and material properties in Section 2. We summarize our results related to tension-induced corrugations in 1D, 2D, and 3D in Section 3. There we examine the different factors affecting the corrugation amplitude such as the elastic moduli ratio of the composite constituents, the aspect ratio of the mineral plates and their location relative to the fibril axis. In Section 4 we discuss our findings, their significance, and potential applications.

2. Material and methods

Geometry: Our starting point is a long and slender polymer fibril (Fig. 1) of total length L and depth h ($L \gg h$). The fibril is reinforced with two rows of staggered platelets with length L_i, width t, offset $c + t/2$ from the fibril axis and inter-platelet spacing $L_i + 2s$. If $s < 0$, the platelets in the two rows are overlapping. A typical unit cell representing the fibril composition is shown in Fig. 1. We choose $L = 1000\ \mu\text{m}$, $h = 30\ \mu\text{m}$ and $t = 7.5\ \mu\text{m}$ for manufacturing convenience but specific values are irrelevant since elasticity equations are scale free. We vary the remaining parameters in a controlled way to explore the design space. We choose micrometer (μm) as a unit of length, and Giga Pascal (GPa) as a unit of stress.

We construct 2D membranes and 3D plates using the composite fibril as a template. Two examples are shown in Fig. 2. The 2D membrane is constructed by gluing the fibrils along their longer edges using a weak polymeric adhesive. The 3D composite plate is constructed by extruding the fibril in the y-direction (normal to the plane of 2D model in Fig. 2(a)). The inclusions are represented by square plates of thickness t.

Material properties: The polymer matrix is modeled as a hyperelastic material using Neo-Hookean constitutive description. We consider two systems: (1) A mixture of two polymers with different elastic moduli, and (2) mineralized polymer matrix. In the first case, the initial Young's modulus of the background polymer matrix is $E_m = 0.005$ GPa corresponding to a commercial rubber [12]. In the second case, the initial Young's modulus for the polymer matrix is $E_m = 1$ GPa which is similar to the value observed for collagen fibers in bone [22]. In both cases the initial Poisson's ratio for the background matrix is $\nu_m = 0.495$ to approximate incompressibility and density of bulk materials is assumed to be 1500 kg/m^3. The inclusions are modeled as hyperelastic material in case (1) and linear elastic minerals in case (2). Several values of (initial) Young's modulus E_i are assumed for the inclusion material to investigate the influence of modulus contrast $r = E_i/E_m$ on the deformation pattern. Here, we vary r between 1 and 50. This range corresponds to the range found in natural materials. For example $r \sim 20$ in mineralized collagen fibrils. Poisson's ratio is assumed to be 0.3 for mineral inclusions and 0.495 for initial value of polymeric inclusions. The weak adhesive used to glue the fibrils in the 2D membrane case is modeled using a bi-linear cohesive law with maximum elongation $\delta_f = 6\ \mu\text{m}$, peak strength $T_{ult} = 3$ kPa at $\delta_f/2$ and resulting fracture energy $G_c = 9\ \text{mJ/m}^2$. Interfacial glue materials of this strength and ductility have been observed in some biological materials [23]. We discuss the practical implications of the cohesive interface modeling assumption in Section 4.

Numerical model: We use the finite element software Abaqus [24] to model the composite fibril and discuss the effect of mesh size on corrugation amplitude results in Appendix A. In 2D models (such as in the fibril and the membrane cases), we use 8-node biquadratic elements to model the behavior of composite fibrils and assume that both ends of the fibrils are clamped. One end is stretched at a constant rate along the longitudinal direction to represent displacement controlled loading while the other end