Composites Part B 148 (2018) 114–122

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Instabilities and pattern formations in 3D-printed deformable fiber composites

Jian Li[a], Viacheslav Slesarenko[a], Pavel I. Galich[a], Stephan Rudykh[b,*]

[a] Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel
[b] Department of Mechanical Engineering, University of Wisconsin – Madison, Madison, WI 53706, USA

ARTICLE INFO

Keywords:
Instability
Pattern formation
Fiber composite
Finite deformation

ABSTRACT

We investigate elastic instabilities and pattern formations in 3D-printed deformable fiber composites. We experimentally realize the instability induced patterns in the deformable 3D systems of periodically distributed fibers embedded in soft matrix. We observe that the fiber composites exhibit significant softening upon achieving the critical strain at which the stiff fibers cooperatively buckle into wavy patterns. For periodically distributed fiber composites with square in-plane periodicity, we observe the transition of the instability induced patterns from small wavelength wavy pattern to long wave mode with an increase in fiber volume fraction. Both experimental results and rigorous Bloch-Floquet numerical analysis show that the critical wavenumber and critical strain decrease with an increase in fiber volume fraction. For composites with rectangular in-plane periodicity of fibers, we observe that the cooperative buckling mode develops in the direction, where the fibers are close to each other; and an increase in the periodicity aspect ratio leads to a decrease in critical wavenumber and critical strain. In addition, we present our theoretical, numerical, and experimental results for single fiber in soft matrix system. For the single fiber system, we observe that the critical wavelength has a linear dependence on fiber diameter. An explicit formula is derived to estimate the dependence of critical wavelength on shear modulus contrast, and further verified by experimental data and numerical simulations.

1. Introduction

Elastic stiff fibers embedded in a soft matrix are ubiquitous in natural and synthetic systems, e.g., microtubules in living cell [1,2], fibrous biological tissues [3,4], and fiber-reinforced polymer composites [5–8]. It is well known that an isolated fiber experiences classical Euler buckling, when subjected to axial compressive loads. However, for stiff fibers embedded in a soft matrix, the presence of soft matrix significantly decreases the critical wavelength and increases the critical strain [2,9,10]. This mechanical phenomena has drawn considerable attention, due to its importance in fiber composite designs [11–14], functional material designs [15,16], and biological systems [3,17].

The buckling behavior of a single stiff circular wire embedded in an elastic matrix was firstly theoretically investigated by Herrmann et al. [18], which considered the elastic matrix as a three-dimensional continuous body and proposed two foundation model to investigate the buckling behavior of the stiff wire: (a) exact foundation model that considered the displacement and force continuity requirements between the elastic matrix and the stiff wire, (b) approximate foundation model that only considered the displacement and force in radial direction and neglected the shear deformation between the elastic matrix and the stiff wire. For the approximate mode, Herrmann et al. [18] derived an explicit expression to estimate the stiffness of the matrix. Later, Brangwynne et al. [2] employed Herrmann's approximate foundation model to elucidate their experimental observations on the buckling of microtubules in living cells, and derived an expression to approximate the value of matrix stiffness. Recently, Su et al. [19] studied the buckling behavior of a slender Nitinol rod embedded in a soft elastomeric matrix. Planar wavy patterns and non-planar coiled buckling modes were experimentally observed; these experimental observations were interpreted based on consideration of the two lowest buckling modes. Zhao et al. [10] examined the buckling of finite length elastic fiber in a soft matrix; the authors derived a formula to connect the overall strain and the strain state in stiff fiber. This formula showed that the buckling of stiff fiber could be significantly tuned by the slenderness ratio of the fiber. More recently, Chen et al. [20] examined the buckling of stiff wire in soft matrix, and numerically showed that the stiff wire buckled in 2D sinusoidal configuration first, then gradually transited the configuration from 2D sinusoidal into 3D helical mode. In many studies, Winkler foundation model [21] is used to

* Corresponding author.
E-mail address: rudykh@wisc.edu (S. Rudykh).

https://doi.org/10.1016/j.compositesb.2018.04.049
Received 28 January 2018; Received in revised form 18 April 2018; Accepted 24 April 2018
Available online 28 April 2018
1359-8368/

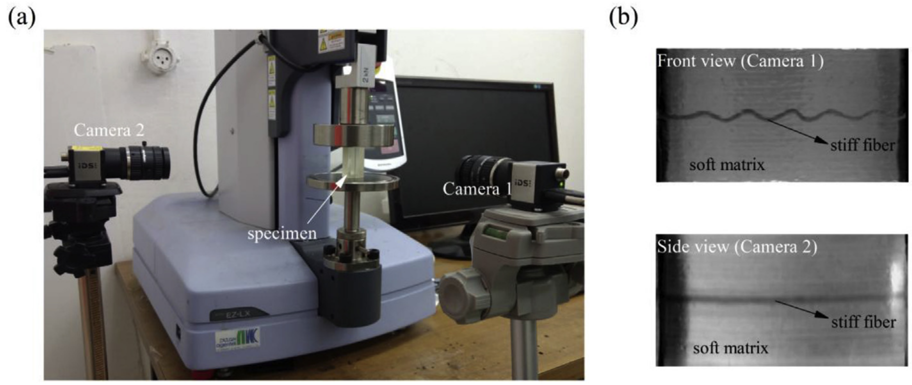

Fig. 1. Experimental setup (a) and typical buckled configurations (b).

provide analytical linear elasticity based estimates for buckling of a single fiber in matrix. However, the accuracy of this model in a wide range shear modulus contrast is not examined. Here, we first experimentally observe the buckling process of a stiff fiber embedded in a soft matrix under an axial compressive load by 3D printer fabricated specimens, and show the dependence of the critical wavelength on the stiff fiber diameter. Then, based on the Wrinker foundation model, we mathematically derive a new estimation for the effective stiffness, and give an explicit formula to calculate the critical wavelength of the stiff fiber in this system. The accuracy of this formula is verified by experimental data and numerical simulations.

The pioneering work on the stability analysis of layered and fiber composites was laid by Rosen [22], who derived an explicit expression to predict the buckling strain of layered composite with linear elastic material. Triantafyllidis and Maker [23] investigated microscopic and macroscopic instabilities in periodic layered composites with hyperelastic phases. Geymonant et al. [24] established rigorous theoretical foundation for microscopic instability analysis in periodic composites, connecting the specific case of long wave limit and the macroscopic loss of ellipticity analysis. The loss of ellipticity analysis has been used to study macroscopic instability in fiber-reinforced hyperelastic solids based on phenomenological models [25–28]. An alternative approach of micromechanics based homogenization was utilized to estimate the macroscopic instabilities in transversely isotropic hyperelastic fiber composite [29,30]. Recently, Greco et al. [31] investigated the influence of matrix or fiber/matrix interface microcracks on the failure behaviors of periodic fiber-reinforced composites under biaxial loading conditions. By making use of the Bloch-Floquet analysis superimposed on large deformations, Slesarenko and Rudykh [13] analyzed the interplay between macroscopic and microscopic instabilities in periodic hyperelastic 3D fiber composites subjected to an axial compressive load. Moreover, the buckling modes with wavy patterns in periodic layered composites under compressive loads were observed in experiments [32,33]. However, to the best of our knowledge, instabilities of deformable periodic 3D fiber composite has not been experimentally investigated. In this paper, we study the buckling behavior of periodic 3D fiber composites with square and rectangular arrangements of periodic fibers; to this end we utilize a multimaterial 3D printer, and fabricate and mechanically test the periodic composite specimens. The experimentally obtained critical wavelengths and critical strains are compared with numerical results by Bloch-Floquet analysis.

The paper is structured as follows: Section 2 presents the introduction for the fabrication of specimens, experimental device and setup. The experimental investigation and theoretical analysis of buckling of a single fiber embedded in a soft matrix are given in Section 3. Section 4 is devoted to instability induced pattern formations in periodic fiber. Section 4.1 presents the results for fiber composites with periodic square arrangement, and Section 4.2 focuses on fiber composites with periodic rectangle arrangement. Section 5 concludes the study with a summary and discussion.

2. Experiment method

2.1. Specimen fabrication

To experimentally observe the buckling process of fiber composite subjected to uniaxial compression along the fibers, we fabricated the specimens composed of stiff fibers embedded in an elastomeric soft matrix by using the multi-material 3D printer Object Connex 260-3. The soft matrix was printed in TangoPlus (TP) with the initial shear modulus $G \approx 0.23$ MPa, the stiffer fiber was printed in a digital material (DM) with the initial shear modulus $G \approx 240$ MPa; the digital material is a mixture of the two base material (TangoPlus and VeroWhite). Here, we considered two cases: single stiff fiber embedded in a soft matrix (Case A); periodic fiber composites with square and rectangle arrangements (Case B). All the specimens were printed in the shape of rectangular blocks to provide a clearer visualization of the buckled fiber shapes and pattern formations through the nearly transparent soft matrix material. Guided by the theoretical and numerical predictions of the buckling wavelength of the stiff fiber and considering the resolution of the multi-material 3D printer, the samples composed of a centrally located single DM fiber embedded in TP matrix (case A) were printed in dimensions $20 \times 20 \times 40$ mm (length × width × height) and in stiff fiber diameters ranging from $d = 0.5$–1.0 mm; the samples composed of 36 periodically distributed fibers embedded TP matrix (case B) were printed in dimensions $30 \times 30 \times 40$ mm (length × width × height) and in stiff fiber volume fractions ranging from $c_f = 0.01$ to 0.025, except for the sample with $c_f = 0.025$, whose height was printed in 50 mm. For the composites with periodically distributed fibers, to reduce the influence of boundary effects on the buckling behavior of stiff fibers, the samples were printed with a boundary TP material layer of the thickness $t = 5$ mm.

2.2. Experimental setup

The uniaxial compression tests were carried out using Shimadzu EZ-LX testing machine (maximum load 2 kN). Fig. 1 shows the experiment setup of the uniaxial compression of 3D-printed samples (a), and an illustration of the buckled configurations of the sample (b). To reduce the influence of material viscoelasticity on the observed behavior of the composite, the tests were performed at a low strain rate of 4×10^{-4} s^{-1}. Upon achieving the critical compression level, the stiffer fibers start developing the buckling shape; the process was captured by two digital cameras (located in front and on the side of the tested samples, as shown in Fig. 1(a)). An example of the single fiber buckling induced configuration obtained from these orthogonal views is shown in Fig. 1(b).