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Study on buckling response in electrospun fiber with periodic structure

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ABSTRACT

In order to understand the formation of one-dimension periodic structures by electrospinning, an approximate mechanical approach for the critical load and the number of half waves in the buckled shape have been conducted based on the energy method. Diameter of circular cross-section electrospun fiber is assumed to be equal to the length of the rectangular cross-section spitted fiber. Fiber with rectangular cross section buckles more easily than that with circular cross section because of the different flexural rigidity. For rectangular-section fiber, increase of length to width ratio can result in the increase of the number of half waves. Detailed simulation results for buckling responses of circular-section fiber and rectangular-section fiber have been conducted by commercial finite element analysis software (ABAQUS).

1. Introduction

It is well known that structural stability of fiber is vital for optimal performance of functional fiber-reinforced composite materials. Loss of elastic stability of fiber is one of important failure modes for fiber-reinforced composite materials under the compressive loading. The buckling can be formulated as follows: an elastic bar changes from a structural elastic stability to a structural elastic instability induced by compressive stresses along the bar. Mechanical behavior and theoretical calculation of fiber in the composite materials have been conducted and investigated [1–10]. Influence of fiber volume fraction, fiber shape, fiber size, properties of fibers and matrix, fiber-end configuration, specimen geometry on fiber buckling was investigated theoretically and experimentally [3]. Interpolation formulae of fiber buckling in the fiber-reinforced composites were obtained for any value of the fiber volume fraction [5]. At present, most investigations about fiber buckling are based on the fiber in fiber-reinforced composite. However, studies of the assemblies (micro- and nanoscale buckling structures, helical nanospring structures, et al.) of single fiber seem less comprehensive [11–13]. A micro/nanoscale hybrid composite has attracted increasing academic and industrial research [14–21]. The micro- and nanoscale buckling structure is one of the most representatives among the family of one-dimensional structures and attracts attention due to a wide range of potential applications. For example, microscale buckling structure can be used as inductive or smart structural components in microelectro-mechanical systems, delicate optical components and biomaterial [11,22,23]. One-dimensional silica buckling structure has been produced by roller electrospinning technique [24,25]. Researches based on the mechanical mechanism to illustrate the formation of electrospun micro- and nanoscale periodic structures in single fiber are less comprehensive. In order to explore single fiber buckling structure formation in the process of electrospinning and manipulate such assembly, it is necessary to investigate and understand the mechanical mechanism.

Theoretical studies of buckling have been carried out. The investigation by Euler [26] was in view of two main simplifying assumptions: cross section subjection to central pressure and perfectly elastic body. The critical loads for different number of half

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waves in the buckled shapes were figured out by an approximate differential equation of deflection curve. Timoshenko and Gere described the energy method to obtain the critical load [27]. In the energy method, buckling deflection shapes are assumed for all sorts of buckling modes. An important point of the energy method is that calculated buckling load is the upper limit to actual buckling load. With the development of commercial software, the finite element method (FEM) was utilized to study the buckling behavior of bars [28–32].

2. Experimental details

Detailed experiment procedures can be found in Refs. [24,25]. Roller experimental apparatus of NS Lab 500s (Nanospider, Elmarco Company) was used to control the structure of silica fibers. The electrode-to-collector distance was kept at 15 cm, and the electrode rotation rate was controlled at 3 rpm. The applied voltage between collector and electrode was 30 kV. In our previous studies, we have confirmed that the formation of the one-dimensional periodic silica structure was dependent on the electrical conductivity of the collector substrate [24,25]. Once the charged fibers touch the conductive substrate, the charges transfer and the fibers become unstable. Finally the fibers spontaneously contract into the periodic structures by undergoing a structural rearrangement. In this paper, we derive the relationships between the number of half waves in the buckled shape and critical load on the basis of previous research [27] and simulate the formation of electrospun buckling with circular and rectangular section. The critical loads for circular-section fiber and rectangular-section fiber are obtained by applying the finite element method. Critical loads and the number of half waves for circular-section fiber and rectangular-section fiber were conducted and compared.

The simplified model of an elastic column (electrospun fiber), which is assumed to be subjected to an axially compressive force P, will be considered and shown in Fig. 1(a). The column always keeps stable equilibrium position as long as P is less than a critical value P_{cr}, called the buckling load. If $P > P_{cr}$, the column will become unstable from its stable equilibrium position. Thus, the column will buckle as indicated in Fig. 1(b). The buckling load is the smallest critical load of the column.

3. Results and discussion

An approximate solution for the critical load has been conducted based on the energy method [27]. When a column changes from the straight state into the buckled state, the change in strain energy of the column ΔU is equal to the work done ΔW by the compressive force P that is,

$$\Delta U = \Delta W \tag{1}$$

We use the Fourier sine series to represent the buckling displacement v

$$v = \sum_{n=1}^{\infty} a_n \sin\frac{n\pi x}{L} \tag{2}$$

Then the change in strain energy of the column is

$$\Delta U = \frac{EI}{2}\int_0^L \left(v''\right)^2 dx \tag{3}$$

We substitute equation (2) for the buckling displacement in equation (3) and get

$$\Delta U = \frac{\pi^4 EI}{4L^3}\sum_{n=1}^{\infty} n^4 a_n^2 \tag{4}$$

The work done [33] by the compressive force P is

$$\Delta W = \frac{P\pi^2}{4L}\sum_{n=1}^{\infty} n^2 a_n^2 \tag{5}$$

Now substitution of Equation (4) and Equation (5) into Equation (1), the critical load is

$$P = \frac{\pi^2 EI}{L^2}\frac{\sum_{n=1}^{\infty} n^4 a_n^2}{\sum_{n=1}^{\infty} n^2 a_n^2} \tag{6}$$

We suppose that P reaches a minimum for a particular sine wave and m indicates its number of half waves in the buckled shape.

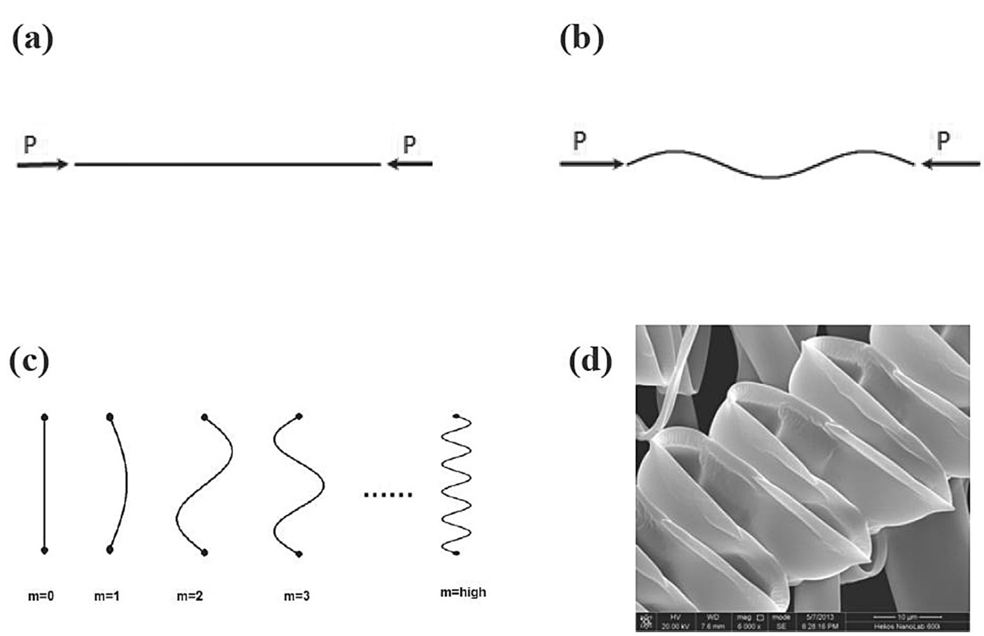

Fig. 1. (a): Sketch of a fiber subjecting to a compressive force; (b): Sketch of a buckled fiber subjecting to a compressive force; (c): The buckling shapes with different number of half waves; (d): An electrospun silica regular periodic structure.