Mechanics of Materials 72 (2014) 46–60

Contents lists available at ScienceDirect

Mechanics of Materials

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

Post microbuckling mechanics of fibre-reinforced shape-memory polymers undergoing flexure deformation

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ARTICLE INFO

Article history:
Received 1 December 2012
Received in revised form 28 April 2013
Available online 14 June 2013

Keywords:
Shape-memory polymer
Post microbuckling
Fibre

ABSTRACT

The buckling mechanics of fibre-reinforced shape-memory polymer composites (SMPCs) under finite flexure deformation is investigated. The analytical expressions of the key parameters during the buckling deformation of the materials were determined, and the local post-buckling mechanics of the unidirectional fibre-reinforced SMPC were further discussed. The cross section of SMPC under flexural deformation can be divided into three areas: the non-buckling stretching area, non-buckling compression area and buckling compression area. These areas were described by three variables: the critical buckling position, the neutral plane position and the fibre buckling half-wavelength. A strain energy expression of the SMPC thermodynamic system is developed. According to the principle of minimum energy, the analytical expressions of key parameters in the flexural deformation process is determined, including the critical buckling curvature, critical buckling position, position of the neutral plane, wavelength of the buckling fibre, amplitude of the buckling fibre and macroscopic structural strain of the composite material. The results showed that fibre buckling occurred in the material when the curvature increasing from infinitesimal to the critical value. If the curvature is greater than the critical curvature, the neutral plane of the material will move towards the outboard tensile area, and the critical buckling position will move towards the neutral plane. Consequently, the half-wavelength of the buckling fibre was relatively stabilised, with the amplitude increasing dramatically. Along with the increasing of the shear modulus, the critical curvature and buckling amplitude increase, while the critical half-wavelength of the fibre buckling decrease and the critical strain of the composite material increase. Finally, we conducted experiments to verify the correction of the key parameters describing SMPC materials under flexural deformation. The values determined by the experiments proved that the theoretical prediction is correct. Additionally, the buckling deformation of the carbon fibre generated a large macroscopic structural strain of the composite material and obtained a resulting large flexural curvature of the structure with minimal material strain of the carbon fibre.

1. Introductions

It is widely accepted that a film bonded to a compliant substrate often forms a pattern of wrinkles when subjected to a compressive membrane force (Huang et al., 2004, 2005). However, nanowires or nanotubes on the surface of a compliant substrate can also undergo in-surface buckling under mechanical loading conditions (Ryu et al., 2009; Xiao et al., 2010). In the case of nanofibres buried in the interior of compliant substrates, this paper provides

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http://dx.doi.org/10.1016/j.mechmat.2013.05.012
0167-6636/

experimental and theoretical evidence to the buckling of the carbon fibres in response to external loads.

Common compliant substrate materials include electroactive polymers (EAPs) and shape-memory polymers (SMPs). Electroactive polymers can change their shapes or volumes when exposed to external electrical fields, and they can recover their original shapes or volumes once the electrical fields remove. Because of this characteristic, they can be used as smart transducers in application such as novel actuators, sensors and electric generators (Liu et al., 2008, 2009, 2010, 2011; Li et al., 2011; Suo et al., 2008; Suo, 2010; Leng et al., 2009d). Typical electroactive polymers include silicone and polydimethylsiloxane (PDMS).

In contrast to most other studies, the compliant substrates investigated in this paper are shape-memory polymers (Lv et al., 2010; Lu et al., 2010; Lan et al., 2009; Leng et al., 2008, 2009a,b,c, 2011; Leng and Du, 2010; Yu et al., 2011). SMPs can undergo significant macroscopic deformation upon the application of various external stimulus (e.g., heat, electricity, light, magnetism, moisture and even changes in pH) (Leng et al., 2011).

The shape-memory cycle of a fibre-reinforced SMPC can be described as follows: first, raise the temperature of the laminate to the glass transition temperature of the material. Then, bend the laminate along a cylindrical surface and constrain it to remain bent. While the shape of the laminate is held, lower the temperature until it falls below the glass transition temperature of the polymer. After the laminate is hardened, remove the constraint. As a result, the laminate will keep the deformed shape, and it will not revert spontaneously. Finally, heat the laminate again to realise the deployable characteristic of the structure, which will return to the original shape (Lan et al., 2009; Lv et al., 2010; Yu et al., 2011; Leng et al., 2011; Leng and Du, 2010). For the strong restraint of the cylinder during the deformation process, the fibres in the surface act as a deformation feature, with shearing-buckling as the main deformation mode. The buckled or wavy configurations can be stretched and compressed in a nondestructive way, similar to the physics of the motion of an accordion bellows.

A fibre-reinforced fabric SMPC was developed for industrial application (Lan et al., 2009; Leng et al., 2009a, 2011; Leng and Du, 2010). The bending recovery force of this SMP-based laminate was larger than those of pure SMP sheets for any given recovery time (Lu et al., 2010; Leng et al., 2009a,b,c). Fibres in SMPs can offer significant improvement in strength, stiffness and resistance against relaxation and creep, thereby providing better mechanical properties. As both functional and structural materials, these SMPs had shown superb potential in many advanced applications (Leng et al., 2009a, 2011; Leng and Du, 2010). For instance, when used as actuator materials, they require no moving parts. Consequently, the use of fibre-reinforced SMPC to produce deployable structures, including antennas, trusses and solar arrays, has attracted considerable interests (Lan et al., 2009; Leng and Du, 2010; Leng et al., 2011).

The local and global buckling analysis of film/compliant substrate systems, as well as nanotube or nanowire/compliant substrate systems, have been the topics of broad research interests recently (Cerda and Mahadevan, 2003; Chen and Hutchinson, 2004; Huang et al., 2004, 2005; Huang, 2005; Audoly and Boudaoud, 2008a,b,c; Ryu et al., 2009; Xiao et al., 2010; Cai et al., 2011).

Several recent nonlinear analyses have determined the wavelengths and amplitudes of sinusoidal wrinkles (Chen and Hutchinson, 2004; Huang et al., 2005). Using the finite element method, Chen and Hutchinson have found that the herringbone pattern has the minimum energy of several competing patterns (Chen and Hutchinson, 2004).

These researchers first obtained the amplitude and wavelength of the sinusoidal wrinkles as functions of the modulus and thickness of the substrate. Their results showed that the wavelength of the wrinkles remains constant as the amplitude of the wrinkles increases. They also developed a spectral method to evolve two-dimensional patterns of wrinkles and represent the exact three-dimensional elastic field of the substrate in Fourier space (Huang et al., 2005).

The emergent nonlinear properties of the buckling behaviours of some of the periodic modes were also elucidated (Audoly and Boudaoud, 2008a,b,c).

Researchers established a continuum mechanics theory for the in-surface buckling of one-dimensional nanomaterials on compliant substrates, and simple analytical expressions were obtained for the buckling wavelength, amplitude and critical buckling strain in terms of the bending and tension stiffness of the nanomaterial and the matrix elastic properties (Xiao et al., 2010).

Further aspects of the nonlinear post-buckling behaviour of a film/substrate system were explored by employing an analytical upper-bound calculation and numerical finite element analysis to determine the relationship between the observed periodic patterns and the level of overstress noted in the next section (Cai et al., 2011).

Based on the analytical method in the Refs. Huang et al. (2005), Chen and Hutchinson (2004), Jiang et al. (2008), Barrett et al. (2006), Francis et al. (2007) and Ryu et al. (2009), this paper developed an improved analysis method of the mechanics of the in-surface buckling for fibre-reinforced SMPC. Similar to the study of the normal buckling of stiff thin films and single wall nanotubes on compliant substrates, the mechanical analysis of in-surface buckling in Section 3 provides an analytical form of the total energy of the system, which consists of the fibre buckling deformation energy, the matrix shear deformation energy in the buckling area and the fibre/matrix tensile deformation energy in the unbuckling area. Furthermore, the analytical expressions for key parameters describing the buckling deformation and local post-buckling mechanics of unidirectional fibre-reinforced SMPC are introduced. These parameters include the critical buckling curvature, the critical buckling position, position of the neutral plane, wavelength of the buckling fibre, amplitude of the buckling fibre and macroscopic strain of the composite material. Additionally, corresponding experiments are conducted to verify the accuracy of the key parameters. The analysis is demonstrated to provide theoretical predictions which are in good agreement with the experimental data.

The fibre-reinforced SMPC with microbuckling can be used for deployable structures in space such as antennas, trusses and solar arrays (Lan et al., 2009; Leng and Du, 2010;