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Mechanics of instability-induced pattern transformations in elastomeric porous cylinders

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ABSTRACT

In this paper, we combine experiments and numerical simulations to investigate the large deformation mechanics of periodically patterned cylindrical structures under uniaxial compression. Focusing on cylinders with a square array of circular pores, we show that their buckling behavior is not only controlled by the porosity (as for the case of the corresponding infinitely large planar structures), but also by the length and thickness of the shell and the number of pores along the full circumference. While infinitely long cylindrical shells only support long wavelength (global) modes, by reducing the length and tuning the thickness, short wavelength (local) modes can be observed. Furthermore, frustrated short wavelength modes are triggered when a local instability is critical, but the buckling pattern is not compatible with the number of pores along the circumference.

1. Introduction

Structural materials are often inhomogeneous on small scales and possess specific microstructures. In particular, porous materials with well-defined periodicity are ubiquitous not only in nature, but also in synthetic structures and devices (Gibson and Ashby, 1999). Periodic porous materials are used to design lightweight structures (Queheillalt and Wadley, 2005) with exceptional mechanical characteristics such as high energy absorption (Wierzbicki and Abramowicz, 1983; Papka and Kyriakides, 1994) and excellent acoustic damping (Verdejo et al., 2009). Moreover, these materials are attractive media for controlling and manipulating the propagation of waves with applications ranging from optical fibers and sound filters to photonic integrated circuits and acoustic mirrors (Maldovan and Thomas, 2009).

Periodic porous structures made of elastic materials are capable of undertaking homogeneous and reversible pattern transformations under compression due to the buckling of their beam-like ligaments. For example, upon reaching a critical applied deformation a square array of circular holes in a 2D elastomeric matrix suddenly transforms into a periodic pattern of alternating, mutually orthogonal ellipses (Mullin et al., 2007; Michel et al., 2007; Zhang et al., 2008). Such pattern transformation has been found to be robust and only marginally affected by small imperfections and edge effects (Bertoldi

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et al., 2008). However, its emergence can be compromised in structures characterized either by low levels of porosity or by multiple nucleation sites (Bertoldi et al., 2010; Zhu, 2011; Kang et al., 2013). In fact, it has been found that by progressively reducing the porosity a transition from instabilities with a short wavelength to instabilities characterized by a wavelength much larger than the scale of the microstructure occurs (Bertoldi et al., 2010). Moreover, the presence of multiple nucleation sites has been shown to result in domains of uniform buckling patterns separated by antiphase boundaries (Zhu, 2011; Kang et al., 2013).

Motivated by recent studies on porous shells that derive functionality from mechanical instabilities (Shim et al., 2012; Lazarus and Reis, 2015), here we investigate the non-linear response under uniaxial compression of elastomeric cylindrical structures patterned with a square array of circular pores. Our combined experimental and numerical results show three key features. First, differently from the case of an infinite 2D matrix perforated with a square array of circular pores that supports short wavelength modes for large enough values of porosity (Michel et al., 2007; Bertoldi et al., 2008), only long wavelength modes can be triggered in infinitely long patterned cylinders. Second, by reducing the length of the cylindrical shells and tuning its thickness and porosity, short wavelength modes resulting in a checkerboard pattern similar to that found in their 2D counterparts can be observed. Third, the response of the cylindrical shells is also significantly affected by the number of pores along the full circumference. More specifically, frustrated short wavelength modes characterized by a line of defects can be observed in samples with an odd number of pores along the circumference. In contrast to the 2D periodic structures, the line of defects is not introduced because of multiple nucleation sites, but it is due to the incompatibility between the periodicity of the short wavelength mode and the odd number of pores along the circumference.

This paper is organized as follows. After presenting the family of porous cylindrical structures considered in this study (Section 2), in Section 3 we describe the experiments conducted by subjecting three different elastomeric structures to uniaxial compression. Then, in Section 4 we explain the numerical analyses that are used to investigate the nonlinear response of the structures on both full size and unit cell models. Finally, numerical and experimental results are compared and discussed in Section 5, highlighting the effect of the cylinder length, thickness, porosity and number of pores along the full circumference on the response of the structure.

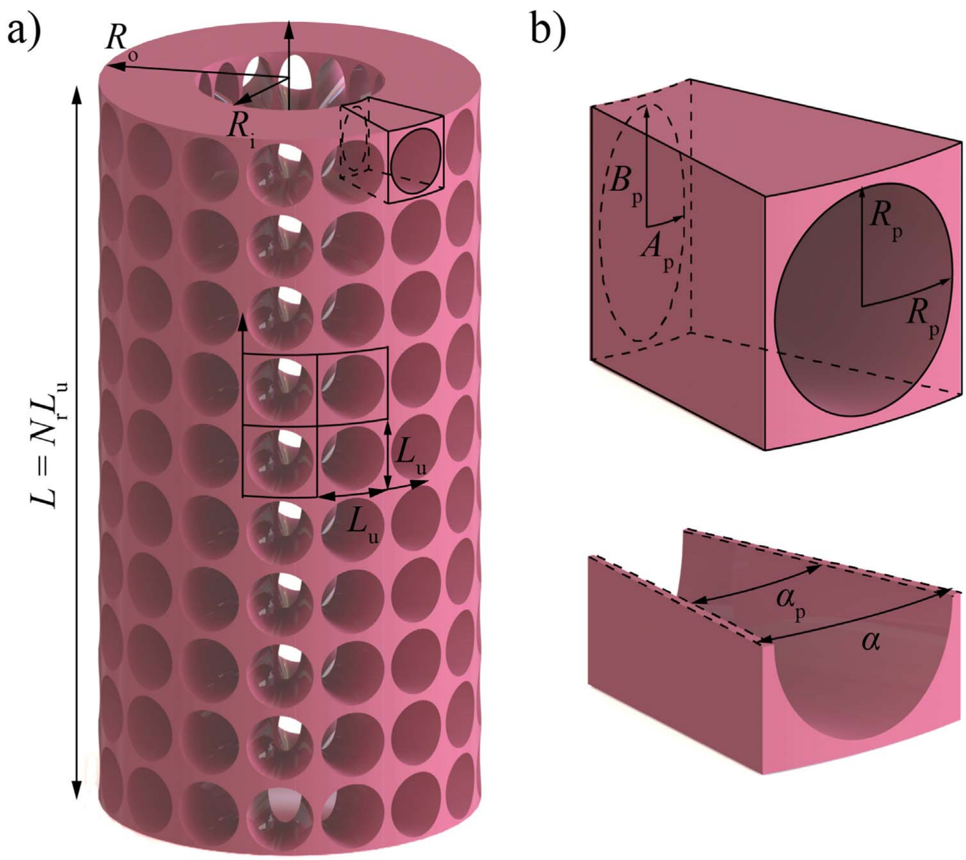

Fig. 1. Periodic porous cylinder with a square of circular pores: (a) schematic of the full size structure and (b) schematic of the unit cell.