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Deformation and failure mechanisms of lattice cylindrical shells under axial loading

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ABSTRACT

The lattice cylindrical shells wound from the planar lattice plates, which have significant applications in aerospace engineering, exhibit different deformation modes with their planar counterparts because of the curvature of the cell wall. In this paper, deformation mechanisms are systematically investigated and failure analyses are conducted for the lattice cylindrical shells with various core topologies. Analytical models are proposed to predict the axial stiffness, critical elastic buckling load or effective yield strength of these shells. Finite element simulations are carried out to identify the validity of the models. The models can be employed for the optimal design. As an example, we construct the failure map for the Kagome lattice cylindrical shell made from an elastic ideally-plastic material. Various failure mechanisms, including yielding, global elastic buckling and local elastic buckling are taken into account. Moreover, optimizations are performed to minimize the weight for a given stiffness or load-carrying capacity for three types of lattice cylindrical shells. It is found that the Kagome and triangular lattice cylindrical shells have almost equivalent load-bearing capacity and both significantly outperform the hexagonal one under axial compression.

1. Introduction

The interest of lattice structures with various core topologies has grown rapidly over the last decade for their superior properties of high specific stiffness and strength, effective energy absorption, shock mitigation and heat insulation [1–4]. These studies have shed light on that well-designed lattice structures are able to outperform the solid plate and shell components in many applications. In general, the structural topology, as the primary concern in the design, plays a significant role in dominating the overall mechanical response of the structures. Understanding the deformation mechanisms of various topologies undoubtedly aids to attain the best design.

Most of the previous studies were focused on the two-dimensional planar lattices. Figs. 1(a)–(d) exhibit four types of the planar lattice configurations, namely diagonal square, hexagonal, Kagome and triangular, respectively. Each of them has the periodic patterning formed from a two-dimensional geometric shape with an infinite out-of-plane thickness. The overall effective in-plane stiffness and strength of the diagonal square, hexagonal, Kagome and triangular lattices have been analyzed recently, and they show a rich diversity in deformation [5–8]. For the diagonal square and hexagonal lattice plates, each truss member undergoes bending deformation under most in-plane loading conditions, except for the diagonal square lattice plate uniaxially loaded along the axial directions of its truss member. For the triangular and Kagome lattice plates, the deformations of their truss members are always dominated by their axial stretching or compressing, resulting in higher stiffness and load capacity than the former two. The hexagonal lattice structure can be processed easily using standard sheet metal fabrication method. The elastic modulus, plastic yield as well as buckling behavior of the hexagonal honeycomb have been extensively explored [1,9,10]. A new kind of fabrication method named *powder processing technology* has been developed recently [11], thus activating more varieties of complicated configurations to be fabricated by this approach. Wang and McDowell [8,12] systematically analyzed the stiffness, strength and yield surfaces of several types of planar lattice patterns. Fleck and Qiu [13] estimated the fracture toughness of elastic-brittle planar lattices using finite element method for three topologies: the hexagonal, triangular and Kagome lattices. Zhang et al. [14,15] proposed two novel statically indeterminate planar lattice structures and furthermore formulated their initial yield surfaces and utmost yielding surfaces.

As an ultra-light-weight material, lattice material is an ideal candidate of traditional material in aerospace engineering. For example, utilizing the winding technology, one can manufacture lattice cylindrical shells, which, as depicted in Figs. 1(e)–(h), are the key components of aerospace craft and airplane. The three dominating geometrical parameters of the representative unit cell

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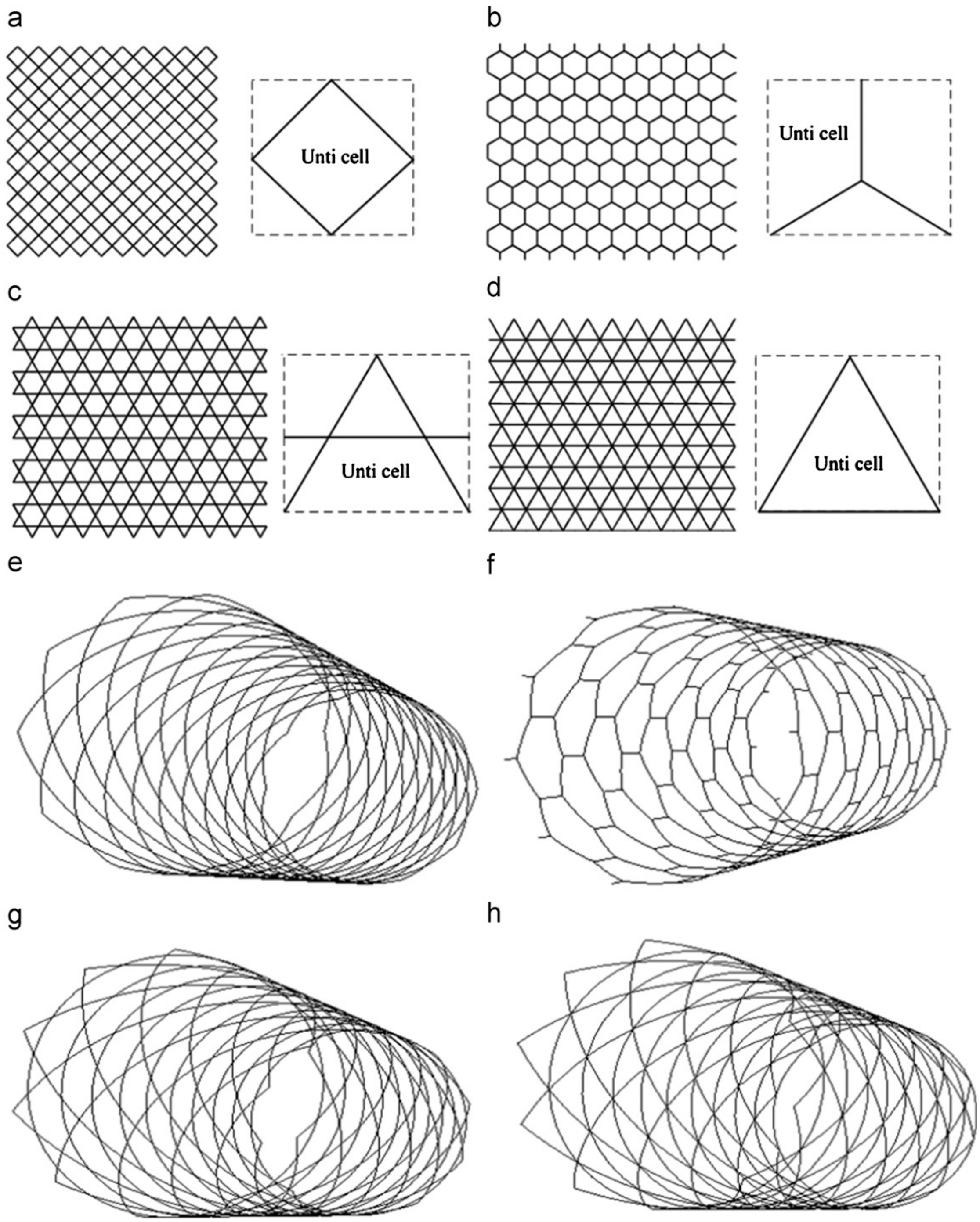

Fig. 1. Configurations of four 2D lattice plates and the corresponding cylindrical shells: (a) diagonal square lattice plate; (b) hexagonal lattice plate; (c) Kagome lattice plate; (d) triangular lattice plate; (e) diagonal square lattice cylindrical shell; (f) hexagonal lattice cylindrical shell; (g) Kagome lattice cylindrical shell; (h) triangular lattice cylindrical shell.

are demonstrated in Fig. 2 by exemplifying the triangular lattice cylindrical shell, where l is the arc length of each beam, b and t denote the thickness of the beam in the radial direction of the cylinder and the thickness of the beam in the shell face, respectively. The hexagonal lattice sandwich cylindrical shell has been popularly utilized in practical applications as fuselage section of aircrafts and load-barring tubes of satellites for several decades [16–19]. Under axial compression, this lattice sandwich cylindrical shell possesses better mechanical performance than the traditional axial stiffened cylindrical shells. Although much attention has been paid on the mechanical behavior of hexagonal lattice, the previous investigations were mainly focused on the simple planar hexagonal lattice structures such as beams and plates, and the delicate investigation on the mechanical behavior of hexagonal lattice cylindrical shell has been scarce. Therefore, the lattice cylindrical shell of hexagonal topology is one focus in this paper. The lattice cylindrical shells made from stretching-dominated topologies, such as the triangular and Kagome lattices, due to their better in-plane mechanical property than that of the hexagonal one [1,8], are likely to be better candidates to the axial stiffened cylindrical shell than the hexagonal lattice cylindrical shell. Under operating, the cylindrical shell must be able to bear