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A hybrid elastomeric foam-core/solid-shell spherical structure for enhanced energy absorption performance

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ABSTRACT

Energy absorption structures have been pursued to protect personnel and infrastructures over the last few decades. In this study, a novel hybrid foam-core/solid-shell spherical (FSS) structure is presented and investigated. The internal foam core inherits merits of large deformation from conventional foam structures and the introduction of the external thin solid shell is to reach high strength and delay deformation further, thereby achieving high energy absorption efficiency in FSS structures. Theoretical models are developed to characterize elastic modulus and buckling behavior of FSS structures under a compressive loading, and are verified through extensive finite element analysis (FEA). Typical deformation mechanisms are revealed by addressing competition of buckling deformation of the foam core and solid shell, and are identified through the proposed theoretical models. Further, the energy absorption efficiency is proposed to optimize the specific energy absorption density and critical triggering force of activating energy absorption, and is correlated with deformation mechanism and geometric parameters of FSS structures. Both numerical and theoretical analyses show that the employment of a thin solid shell surrounding the foam structures will enhance the energy absorption efficiency with high capability and safe comfort. The present study is expected to provide a useful guideline for a hybrid design of future energy absorption structures with unprecedented performance.

1. Introduction

Natural cellular materials such as beehive, sponge, cancellous bone, wood and plant parenchyma cell possess both lightweight and extraordinary mechanical performance of super-high toughness and specific stiffness, robust energy absorption density (Kepler, 2011; Meyers et al., 2008; Wegst et al., 2014). These intriguing properties are attributed to their hierarchical and hybrid architectures. Inspired by the biological structures, a large number of artificial foams and cellular materials have been designed and utilized to protect people and important structures and devices from impacting, collision and damage in the past few decades (Ajdari et al., 2011; Avalle et al., 2001; Gaitanaros and Kyriakides, 2015; Gaitanaros et al., 2012; Liu and Antoniou, 2013; Yu et al., 2009). With a proper design on porous foam or cellular structures, high energy absorption density per mass or volume can be achieved through extensive buckling, bending, collapsing, slipping and plastic deformation of cell faces or struts (Ashby et al., 2000; Gibson and Ashby, 1997; Lu and Yu, 2003). For example, three dimensional lattices with periodic structures of unit cells such as tetrakaidecahedral cell (Gong et al., 2005; Jang et al., 2010), Kagome lattice (Kang, 2009; Lee and Kang, 2010; Li et al., 2011), and octet truss (Dong et al., 2015; Kooistra et al., 2004) have been explored to improve the energy absorption capability recently. In comparison with utilizations of solid filaments in cellular materials, thin-walled shell structures, and hollow tubes with different cross sections (Eyvazian et al., 2014; Ghamarian and Abadi, 2011; Yan and Chouw, 2013) and multi-cell columns (Hong et al., 2014; Nia and Parsapour, 2014; Tang et al., 2013; Zhang and Zhang, 2013) are also employed as crucial energy absorbing components to absorb a large amount of mechanical energy through additional buckling and collapsing of the hollow walls and shells.

With the development of advanced manufacturing and synthesis of materials and structures, micro/nano-lattice (Meza et al., 2014; Schaedler et al., 2011; Zheng et al., 2014), nanoporous systems (Cao, 2012; Surani et al., 2005), bi-continuous composites (Lee et al., 2012; Wang et al., 2011), multi-stable structures (Shan et al., 2015) and hierarchical porous materials (Yang et al., 2016; Zheng et al., 2012) have become very attractive because of enhanced strength and energy absorption capacity. For example,

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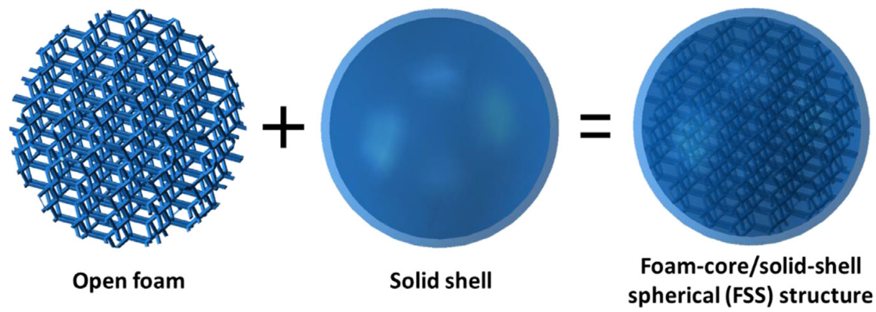

Fig. 1. Conceptual design of the proposed foam-core/solid-shell spherical (FSS) structure, where the FSS structure seamlessly combines the conventional open foam (left) and thin solid shell (middle) together for achieving high energy absorption performance in FSS structures (right) beyond either of them.

Meza et al. (2014) created a hollow-tube ceramic nanolattice and the compressive experiments indicated that it can recover after ~50% deformation upon unloading, demonstrating potential uses of mitigating repeated impacts. Periodic bi-continuous composite is another good structure to improve specific energy absorption by interpenetrating two different materials into an interlocked topology (Lee et al., 2012). Recently, liquid-nanoporous composite materials have also been developed to mitigate mechanical energy by converting it to either solid-liquid interfacial energy or potential energy of intercalated liquid into nanopores, and further improves the energy absorption performance (Chen et al., 2014; Xu et al., 2014a; Xu et al., 2014b).

In parallel with optimization of the porous foam structures, the external curviplanar contours and overall spherical geometries in natural materials like beaks, nacre and scallop have proved to be the best configuration for enhancing strength and deformation (Huang et al., 2011; Li et al., 2015; Meyers et al., 2006). For instance, the long and thick toucan beak wrapped by a curviplanar keratin shell exhibits a high resistance to buckling deformation and an excellent ability to mitigate impact energy (Seki et al., 2005). As a representative of man-made shell structures, a hollow CdS nanocrystal sphere has been synthesized and proves to approach the ideal shear strength and sustaining considerable deformation (Shan et al., 2008). Enhanced deformation has also been found in hollow amorphous carbon shell structures (Yang et al., 2016). Another important feature of the spherical shell is the isotropic response to external loadings due to the symmetric nature of geometry in comparison with that of tapered tubes (Qi et al., 2012), conical tubes (Ahmad et al., 2010) and foam-filled columns (Reyes et al., 2004). In addition, unit spherical shell structures are extensively employed for an ordered large scale structure via assembly techniques such as layered arrays for coatings and composite structures for enhanced mechanical properties through buckling and post-buckling behaviors (Liu et al., 2012; Luo et al., 2015). For example, Sanders and Gibson have shown that Young's modulus and strength can be improved using the spherical shell structure (Sanders and Gibson, 2003). The experiment performed by Mueggenburg et al. demonstrated that the two-dimensional arrays of close-packed spherical structures possess remarkable strength and high flexibility of bending deformation (Mueggenburg et al., 2007). Given the merits of cellular foams and spherical shell structures, their seamless combination is expected to yield attractive mechanical properties with enhanced energy absorption performance, yet is less explored.

In this study, we design a new class of hybrid structures by introducing a thin solid shell around conventional foam spherical structures, referred to here as a foam-core/solid-shell spherical (FSS) structure. Fig. 1 shows the schematic illustration of the conceptual design. In the FSS structures, the foam core is expected to inherit the merits of conventional foam structures capable of sustaining large deformation, and the external solid shell will improve the deformation stress and elongate deformation through buckling deformation of the shell, thus achieving enhanced energy absorption performance beyond either conventional foam or shell structures. Besides, the intimate interaction between the foam core and the solid shell will promote energy absorption performance through interlocked deformation of each other. Both theoretical and numerical analyses are performed to quantitatively correlate the key geometric parameters of FSS structures with the elastic modulus and the critical buckling force. The interaction mechanism between the foam core and the solid shell is elucidated through numerical simulations and is confirmed through the proposed theoretical models. Finally, an index of energy absorption efficiency which embodies both deformation stress and specific energy absorption density is proposed and used to characterize the energy absorption performance of FSS structures.

2. Model and computational method

2.1. Geometric features and parameters of hybrid FSS structures

Fig. 2 schematically illustrates the geometry of a hybrid FSS structure with the details of inner cells. The most widely used open tetrakaidecahedral cells (Jang et al., 2008; Okumura et al., 2008) with a body-centered packed pattern are chosen to model the foam-core structure, and the struts in the connections have a uniform cross section with the length of l and the radius of r. With this representative geometric shape, the relative density of the foam core, ρ_f, to the solid counterpart, ρ_s, can be easily deduced and is:

$$\frac{\rho_f}{\rho_s} = \frac{3\pi}{2\sqrt{2}}\left(\frac{r}{l}\right)^2 - \frac{\pi}{\sqrt{2}}\left(\frac{r}{l}\right)^3 \quad (1)$$

where the overlap volume of the struts at each vertex is approximately represented by a sphere and has been verified in comparison with the real geometry of the open foam. As for the spherical shell with the thickness of t and the radius of R, its relative density, ρ_{ts}, to the solid counterpart, ρ_s, can be expressed as a function of t/R, and is:

$$\frac{\rho_{ts}}{\rho_s} = 3\frac{t}{R} - 3\left(\frac{t}{R}\right)^2 + \left(\frac{t}{R}\right)^3 \quad (2)$$

For a thin spherical shell ($t/R < 0.05$), ρ_{ts}/ρ_s can be approximately simplified to be proportional to the first order of t/R, and Eq. (2) becomes:

$$\frac{\rho_{ts}}{\rho_s} = 3\frac{t}{R} \quad (3)$$

Given the relative density of foam-core and solid-shell structures, the overall density, ρ, of FSS structure relative to the solid counterpart, ρ_s, is:

$$\frac{\rho}{\rho_s} = 1 - \left(1 - \frac{\rho_f}{\rho_s}\right)\left(1 - \frac{t}{R}\right)^3 \approx \frac{3t}{R} + \frac{\rho_f}{\rho_s}\left(1 - \frac{3t}{R}\right) \quad (4)$$