Composite Structures 131 (2015) 966–974

Contents lists available at ScienceDirect

Composite Structures

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

Superelasticity and reversible energy absorption of polyurethane cellular structures with sand filler

Jialv Zhou [a], Xiaobin Deng [a], Yuan Yan [a], Xi Chen [b,*], Yilun Liu [a,*]

[a] International Center for Applied Mechanics, SV Lab, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China
[b] Columbia Nanomechanics Research Center, Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, USA

A R T I C L E I N F O

Article history:
Available online 4 July 2015

Keywords:
Superelasticity
Reversible energy absorption
Polyurethane cellular structures
Sand filler

A B S T R A C T

As a promising candidate for energy absorption and resilient system, a polymer encased sand structure is studied experimentally. The polyurethane (PU) cellular structures are consisted of periodically arranged hollow truncated hemi-ellipsoids with sand particles filled inside. The resilience of PU and dissipation of sand are combined to construct a high performance energy absorption material and structure (EAMS) which exhibit superelasticity with reversible compression strain up to 0.9 and have recoverable energy absorption capability of about 3.4 MJ/m^3 per loading cycle. The compressive stress of the sand filled PU cellular structures is also significantly enhanced (thanks for the sand filler) for compressive strain larger than 0.4. The sand filled PU cellular structures are soft and flexible to stretch, bend and twist, thus compatible for personnel protection. The results presented in this work provide guidelines for designing and engineering high performance EAMS that are resilient, flexible, and of high energy absorption density.

1. Introduction

Energy absorption materials and structures (EAMS) are widely used to protect persons and systems from external impulsive loads such as crashing, blasting and ballistic impact in automotive, sporting and defense applications. Developing high performance EAMS has attracted extensive research interest for both scientists and engineers in recent years [1–3]. Cellular structures are perhaps the most widely employed platform of EAMS, due to their ability to absorb the impulsive energy and their compressibility to lower the intensity of an impulse by extending its duration [4–7]. The development, design, manufacturing and optimization of cellular structures have long been studied and reviewed [8,9]. Quite many previous works have focused on optimizing the cell geometry, size, topology and materials to improve energy absorption of the cellular structures [10–14].

In order to improve the mechanical properties and energy absorption, the cellular structures can be further filled with elastic medium, such as aluminum foam, polymer foam, liquid and polymer [15–19]. The elastic filler may significantly enhance the stiffness, yield strength and energy absorption, in addition to suppression of local buckling of the cellular structures [20]. However, the elastic filler usefully weakens the compressibility of the cellular structures which is a disadvantage of EAMS [19]. Besides, for the solid filler the bonding strength between the solid filler and the cellular structures should be strong enough to avoid the filler-network mismatch during compression [16,19]. Although the liquid filler can accommodate the compression of the cellular structures very well, sealing of the liquid filler presents a significant challenge [17,20].

Recently, elastomeric cellular structures have attracted considerable interest because of the large and resilient deformation [21,22]. For example, upon reaching a critical compressive deformation, a square array of circular pores in an elastomeric matrix is found to suddenly transform into a periodic pattern of alternating, mutually orthogonal ellipses [23]. Because of the controllable pattern transformations, the elastomeric cellular structures exhibit unusual properties, such as negative Poisson's ratio, phononic and photonic switches, programmable mechanical properties and reconfigurable devices [23–26]. Besides, the elastomeric cellular structures are soft and flexible to stretch, bend and twist, all with reversible deformation, which is compatible to reusable personnel protective structures. However, the compressive deformation of the elastomeric cellular structures is usually elastic, which lacks efficient energy dissipation mechanism.

* Corresponding authors.
E-mail addresses: xichen@columbia.edu (X. Chen), yilunliu@mail.xjtu.edu.cn (Y. Liu).

http://dx.doi.org/10.1016/j.compstruct.2015.06.059
0263-8223/

Granular materials have long been used as energy dissipation materials to absorb the external impacting energy and mitigate the impulsive shock wave. The mechanical behaviors of granular materials are very complicated. They are heterogeneous and can behave either like liquids or solids [27–29]. However, the fluidity of granular materials makes them suitable for the filler of cellular structures. The granular filler can accommodate the compression of the cellular structures very well, while the intergranular friction and shock wave disintegration at the interface of particles provide the energy absorption and impulse dissipation [30,31]. In this work, the benefits of both elastomeric cellular structures and granular materials are utilized to develop flexible and reversible EAMS. In Section 2, we describe the fabrication of elastomeric cellular structures (PU truncated hemi-ellipsoid) and the measurement of the mechanical properties of the PU material and the granular filler (sand) used in this work. Next in Section 3, the quasi-static compressive behaviors of PU cellular structures with sand filler are studied in experiments. Based on the experiments a mechanical model is proposed to describe the compressive behaviors of the sand filled elastomeric cellular structures. Then, the discussions of the failure, optimization and dynamic response of the sand filled elastomeric cellular structures are presented in Section 4, followed by conclusions in Section 5.

2. Preparation of specimens and materials testing

In this work the PU cellular structures are consisted of hollow truncated hemi-ellipsoids periodically arranged in a plane which are similar to the twin hemi-ellipsoidal microstructures of SKYDEX pad [32]. These microstructures have shown good stability and dynamic response [33,34]. In this section, we first fabricate the PU cellular structures via vacuum casting. In order to improve the load capacity and energy absorption of the PU cellular structures, the hemi-ellipsoids are further filled with sand and sealed by a plastic sheet. The mechanical properties of the PU material and the sand filler used in this work are also measured in experiments.

2.1. Preparation of specimens

The PU cellular structures are shown in Fig. 1(a). We first print the geometrical model of the PU cellular structures via 3D printing, which then is transferred to PU cellular structures via a vacuum casting procedure. First, a silicone rubber mold is fabricated based on the 3D printed model, and then PU liquid (UPX 8400) is poured into the mold, and is dropped into a vacuum oven to cure the PU liquid at 70 °C for one hour [35]. After that, the mold is removed and the desired PU cellular structures are obtained. The PU cellular structures are consisted of hollow truncated hemi-ellipsoid with the height of 20 mm, the diameter of 10 mm at the flat top and the diameter of 20 mm at the bottom, as shown in Fig. 1(b). The hemi-ellipsoids are squarely arranged on a plane at the bottom with neighboring distance of 4 mm. The neighboring distance can be precisely controlled for specific relative density of the PU cellular structures. In this work, two different thicknesses of the hollow hemi-ellipsoid (2 and 4 mm) are studied, respectively. It is worth noting that the PU cellular structures with different patterns and different shapes of microstructures can also be prepared in the same procedure, which provides more design freedom for specific requirements in practical applications and will be studied in our future works.

As the PU material is a kind of rubbery material, the PU cellular structures are soft and lack an efficient energy dissipation mechanism. In order to improve load capacity and energy absorption, the hemi-ellipsoid is further filled with sand. Here, the sand filler is selected as the sea sand for beach volleyball. As the mechanical properties of granular materials are significantly influenced by their size and shape, and the sea sand for beach volleyball has relatively uniform particle size and smooth surface, which is beneficial to guarantee the reproducibility of the experimental results. Indeed, the pre-stress and wetness have very significant influence to the mechanical behaviors of sand filler. In this work the sand is dried in atmospheric environment with average relative humidity about 35%, and then poured into the hollow hemi-ellipsoid. Therefore, the sand filler is just densified by its gravity and as the PU cellular structures are very small, we can ignore the pre-stress in sand filler. After fully filled with sand, the PU cellular structures are sealed by a plastic (polyvinylchloride) sheet with thickness of 0.2 mm, as shown in Fig. 1(b). The function of the polyvinylchloride (PVC) sheet is the sealing of the sand filler and it should be compatible with the PU cellular structures. Other polymer materials of good elasticity and adhesion are also suitable. In this way we combine the benefits of elastomeric cellular structures and granular materials to construct EAMS with superelasticity and reversible energy absorption, without losing flexibility (Fig. 1(c)) and thus suitable for personal protection such as helmet, kneelet, insole, etc.

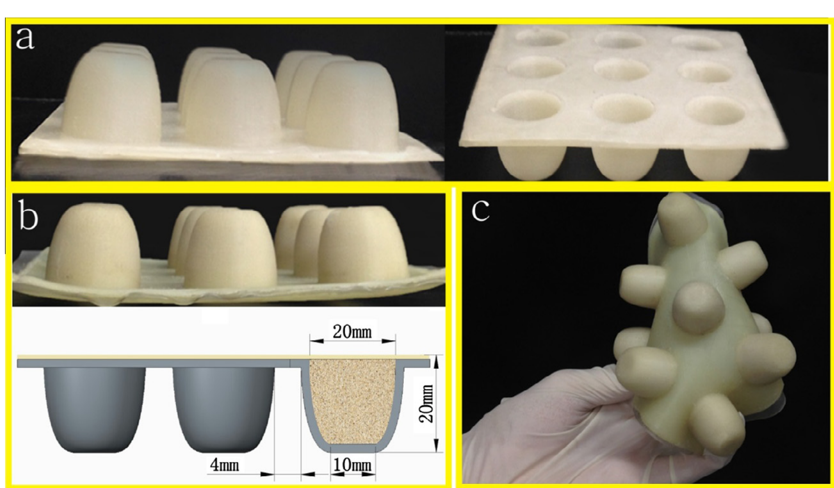

Fig. 1. (a) The PU cellular structures. (b) The sand filled PU cellular structures and the dimensions of the hemi-ellipsoid. (c) The illustration of the flexibility of the PU cellular structures with sand filler.