International Journal of Mechanical Sciences 86 (2014) 60–68

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Parameterized optimal design of a novel cellular energy absorber

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ARTICLE INFO

Article history:
Received 2 July 2013
Received in revised form
5 September 2013
Accepted 14 September 2013
Available online 8 October 2013

Keywords:
Cellular material
Energy absorption
Optimal design
Parameterization
Functionally graded material

ABSTRACT

As an advanced lightweight porous medium, SKYDEX®material has been applied as the energy absorbing structures for personnel protection. Its hourglass-like microstructures made of thermoplastic can dissipate kinetic energy and reduce pressure transfer during crushing. Based on the SKYDEX® cell, this paper develops a novel twin-spherical microstructure, where the shape and size were represented with two key geometric parameters. 3D finite element models were then constructed to demonstrate the cellular deformation modes with different configurations along with the quantitative responses in terms of the energy absorption and pressure transfer. An optimization was performed to find the best design. Using this optimal configuration thus obtained, models with multilayers were built, and each layer was either uniformed or graded in density. Their responses under low and high speed compressive loadings were compared, and the results showed that the direction and degree of the density gradient as well as impact velocity are important parameters affecting the energy absorbing capability.

1. Introduction

Cellular solid materials with a large number of microstructures have been widely used as energy absorbers in the areas of aerospace, aeronautical, shipbuilding and automotive industry, as well as defense engineering. Integrated with two composite or metallic facesheets, such materials are frequently used as the core of sandwich structures. During the crushing process, the cellular core undergoes large deformation at nearly constant stress, and thus absorbing a large amount of kinetic energy before collapsing into a more stable configuration or fracture [1,2]. Based on the geometries and topologies of the microstructures, cellular materials can be classified into stochastic cells and periodic cells. The first type of materials, including open and closed cell foams, have random microstructures; while in the second type of materials, the microstructures are periodic in either two-dimensional channels(e.g. honeycombs) or three-dimensional truss or textile based assemblies. Compared to the stochastic celled foams, the materials with periodic microstructures have numerous advantages. For example, the topology and distribution of the individual cell can be designed based on specific loading conditions. In other words, it is possible to tailor the structural performance for a given load by adjusting the geometric parameters of the periodic microstructures [3].

Currently, most of such periodic microstructures are made of metals and very few polymer-based cellular energy absorbers have been investigated to date. Recently, a novel light weight energy absorber, namely the SKYDEX® pad (SKYDEX Technologies Inc., Centennial, CO) was developed. A SKYDEX® pad consists of double layers of periodic microstructures made of grey thermoplastic polyurethane [4], as shown in Fig. 1a. The microstructure has a unique shape, created by molding durable plastics into chemically bonded hourglass-like structures. It has been reported that SKYDEX® pad can be used as the vehicular floor matting material (shown in Fig. 1b) to reduce the lower extremity injury due to mine blast [4]. In crushing, the two microstructures compress against each other and deform layer by layer to dissipate energy and reduce the pressure transfer.

Currently, SKYDEX® material is designed using a conventional "trial-and-error" approach to determine the shape and size of the cell based on a specific load. Adjustment of the cell is largely in an arbitrary way, and once the load is changed, the microstructure has to be re-designed. Therefore, the entire design procedure consists of many iterations, which are very time consuming. Besides, no optimal design can be achieved with this method. To eliminate such limitation in design practice, this paper proposes a parameterized optimization approach, where the shape and size of the cell are described by a number of key geometric parameters. The relationship between the structural responses and these key parameters (i.e. the "knowledge" about this structure) is established through numerical modeling. Then the optimized microstructure under any intended design loading conditions can be easily obtained by

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http://dx.doi.org/10.1016/j.ijmecsci.2013.09.021

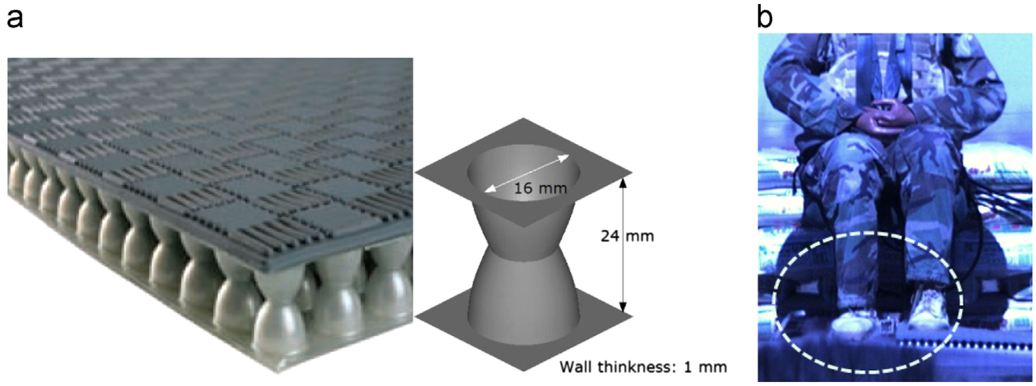

Fig. 1. SKYDEX® material and its application: (a) A SKYDEX® pad with a rubber top surface as well as a single cell (enlarged view); (b) SKYDEX® pad used as the vehicular floor matting to mitigate mine blast effect on the lower extremity [4].

adjusting these parameters. Similar knowledge based computer-aided design (K-CAD) system has been developed for several types of thin—walled energy absorbers [5].

This paper is organized as follows: The experimental and computational study of the compressive behavior of the SKYDEX® microstructure has been conducted and the procedure and results are reviewed in Section 2. Then in Section 3, the microstructure is approximated as a twin-hemispherical cell and parameterized for further analysis and optimization. Section 4 reports the simulation results of the parameterized cell with different dimensions, including the deformation modes observed and quantitative responses, i.e. peak stress and energy absorption. Using energy absorption as the objective, an optimal design is conducted in Section 5, by considering the pressure transfer and deformation modes as the constraints. In Section 6, the compressive responses of multilayers with uniformed and non-uniformed twin-hemispheres are studied and dynamic effect is discussed.

2. Compressive behavior of the SKYDEX® cell

The compressive behavior of the SKYDEX® cell and pad has been studied experimentally and numerically as reported in [6,7]. For the sake of integrity, the results are briefly reviewed in this section.

2.1. Experiments

Uniaxial compression tests were conducted on the square SKYDEX® pads using a high-speed Instron machine at six strain rate levels, i.e. 0.01 s^{-1}, 0.1 s^{-1}, 1 s^{-1}, 10 s^{-1}, 100 s^{-1} and 300 s^{-1}. The experimental setup is shown in Fig. 2a. The size effect of the microstructures were checked by testing the samples with 2×2, 3×3, 4×4 and 5×5 cells, and it has been found that 4×4 cells could sufficiently ensure the convergence of the results. Therefore, all of the specimens studied had 4×4 cells. Since this type of cellular material is usually applied as the core of sandwich plates and works together with two stiff face-sheets, the SKYDEX® specimen used in this study was sandwiched between two 3.5 mm-thick high-strength acrylonitrile butadiene styrene (ABS) plastic sheets using a strong epoxy adhesive (Loctite 411, R.S. Hughes Co., Sunnyvale, CA). The experimental results were highly reproducible and the averaged curves at each strain rate are shown in Fig. 2b. The curves at different strain rates demonstrate an identical pattern: a nearly linear elastic deformation stage, then a softening-hardening transition stage and finally a densification stage. More details of the testing procedure can be found in [6,7].

2.2. Numerical modeling

Finite element (FE) model has been built to simulate the compressive response of each individual microstructure. The material properties of the base material, i.e. grey thermoplastic polyurethane, were characterized using uniaxial tensile tests [6]. The results indicate that this type of material behaves as an elasto-plastic medium, but exhibits much more ductile than metals. A bi-linear elastic-viscous plastic constitutive model was used to describe its behavior, where the flow stress is calculated using the following equation:

$$\sigma_Y^d(\varepsilon_{eff}^p, \dot{\varepsilon}_{eff}^p) = \sigma_Y(1+E_{\tan}\,\varepsilon_{eff}^p)+\sigma_Y\left(\frac{\dot{\varepsilon}_{eff}^p}{C}\right)^{1/P} \tag{1}$$

with σ_Y and σ_Y^d being quasi-static yield strength and dynamic flow stress, respectively. ε_{eff}^p and $\dot{\varepsilon}_{eff}^p$ are effective plastic strain and effective plastic strain rate, respectively. $E_{\tan}$ is tangent modulus describing strain hardening effect. P and C are two strain rate related parameters. By fitting the experimental data using Eq. (1), a Young's modulus E of 60 MPa, tangent modulus $E_{\tan}$ of 50 MPa, yield stress σ_Y of 8.6 MPa, C of 15 s^{-1}, and P of 3 were obtained.

Each cell was modeled using Belyshoko-Tasi shell elements with the average mesh size of 0.45 mm. Mesh sensitivity study has been conducted to ensure the convergence of the result. The FE model well captured the deformation mode and stress–strain responses obtained in the compressive tests. Details of the FE model validation have been reported in [6], and are not repeated here.

3. Parameterization of the microstructure

As mentioned earlier, the cell of SKYDEX® material needs to be parameterized for further analysis and optimal design. To simplify the problem, the shape of the cell is idealized to be twin-hemispherical. The sketch of a twin-hemispherical cell is shown in Fig. 3, together with the top and bottom face-sheets. The shape of cell is governed by four geometric parameters, R, h, t, and θ. The structural response can be controlled by adjusting these parameters.

It is known that the response of a structure with periodic microstructures is a function of the relative density ($\overline{\rho}$) [1], which is defined as the density of the cellular material (ρ^*) divided by that of the solid material from which the microstructures are made (ρ_s). In the present case, considering an individual cell,

$$\overline{\rho}=\frac{\pi t(2Rh+R^2-h^2)}{4R^2h}=\frac{\pi}{4}\times\frac{t}{R}\left(2+\frac{1}{\sin\theta}-\sin\theta\right) \tag{2}$$

From Eq. (2), one can see that the relative density is determined by t/R and θ, which are two design variables to be determined. In