Materials Science & Engineering A 680 (2017) 411–420

Contents lists available at ScienceDirect

Materials Science & Engineering A

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

Crashworthiness of graded cellular materials: A design strategy based on a nonlinear plastic shock model

Jie Yang, Shilong Wang, Yuanyuan Ding, Zhijun Zheng*, Jilin Yu

CAS Key Laboratory of Mechanical Behavior and Design of Materials, University of Science and Technology of China, Hefei 230026, PR China

ARTICLE INFO

Keywords:
Graded cellular materials
Crashworthiness
Density design
R-PH idealization
Shock model
Finite element method

ABSTRACT

Dynamic behaviors and crashworthiness design of density graded cellular materials are investigated by using theoretical method and finite element simulation. A nonlinear plastic shock model is employed to guide the gradient design of cellular rod under mass impact and cell-based finite element models are used to verify the design strategy. Effects of impact-force parameter on the design of relative density distribution of graded cellular material and on the residual velocity of the striker for different lengths of graded cellular rods are explored. Three cases of design strategy with different impact-force parameters are analyzed and verified. The results reveal that the design strategy is reliable when the impact-force parameter is not less than zero. If the relative density distribution of graded cellular rod increases monotonically, the actual deformation mode of graded cellular rod is identical with the assumed one in the theoretical derivations. It is noticed that a portion of the graded cellular rods close to the distal end is not fully compacted. A scheme with restricting the shock strain not less than a specific value is proposed to shorten the graded cellular rods. Therefore, the desirable crashworthiness of graded cellular materials can be obtained by designing the density distribution of graded cellular materials.

1. Introduction

Cellular materials may improve the crashworthiness of structures used in automotive, railway and aeronautical industries [1,2]. Under quasi-static loading rates, the nominal stress-strain curves of cellular material present three distinct deformation stages, namely elastic, long plateau and densification stages [3]. Under high loading rates, the dynamic behaviors of cellular material can be featured by stress enhancement and deformation localization [4–6]. The typical feature of strength enhancement can improve the capacity of energy absorption of cellular materials. Introducing a density gradient to cellular materials may further improve their dynamic mechanical properties [7,8].

The dynamic features of cellular materials are resulted from inertia [5], as explored in shock models [9–16]. Several idealizations of cellular materials have been proposed to develop shock models [9–16]. A rate-independent, rigid–perfect plastic–locking (R-PP-L) idealization was first introduced by Reid and Peng [9] to develop a shock model and explain the dynamic behavior of wood. This model was further applied to investigate the dynamic behavior of metal foams by Tan et al. [10]. Recently, Zheng et al. [15,16] introduced a rate-independent, rigid–plastic hardening (R-PH) idealization to describe the uniaxial compression behavior of uniform cellular materials, in which the stress–strain relation is expressed as

$$\sigma(\varepsilon) = \sigma_0 + \frac{C\varepsilon}{(1-\varepsilon)^2}, \tag{1}$$

where σ_0 is the initial crushing stress and C the strain hardening parameter. The R-PH shock model was then developed by Ding et al. [17] to investigate the anti-blast behavior of cellular sacrificial cladding. An asymptotic solution of critical length was proposed to guide the design of cellular sacrificial cladding, which shows a good agreement with the finite element (FE) results.

Graded cellular materials have been widely investigated due to their considerable capacity of impact resistance and energy absorption. Researches have showed that a density gradient has significant influence on the mechanical response of cellular materials under quasi-static compression [18,19]. Dynamic response of graded cellular materials revealed that a density gradient could improve the energy absorption capacity [20,21]. Due to the limitations of material fabrication technology, some density-graded open-/closed-cell foam specimens were manufactured by using adhesive technique [22–25], which integrates graded cellular materials by bonding different densities foam layers. Experimental results may be affected by the complicated stress

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* Corresponding author.
E-mail address: zjzheng@ustc.edu.cn (Z. Zheng).

http://dx.doi.org/10.1016/j.msea.2016.11.010
Received 9 October 2016; Received in revised form 31 October 2016; Accepted 5 November 2016

wave transmission and reflection occurring at the interface between layers [23,25]. As graded cellular specimens with a specific relative density distribution are not yet easily obtained in practical application, many researchers turn to apply FE methods [7,21] and shock models [8,20] to study the mechanical responses of graded cellular materials with different relative density distributions.

Investigations based on the stress wave theory and FE method were performed to reveal the mechanism of deformation and energy absorption of graded cellular metals and to estimate the energy absorption capability and impact resistance. Results indicated that a density gradient can influence stress waves in the graded cellular materials during impact [26,27] and reduce the maximum impact stress for the protected structures [28]. Three deformation modes of graded cellular materials under impact loading were found and analyzed [21], and it was found that graded cellular metals with a specific density gradient could improve the performance of energy absorption and impact resistance for different protected objects [29–32]. However, most researches in the literature [7,21,30,33] were focused on the dynamic responses of graded cellular materials with a specific relative density distribution, but few on the crashworthiness design [31,32]. Wang et al. [31] investigated the optimal density-gradient parameters of graded cellular metals with a linear density gradient of different average relative densities to meet the crashworthiness requirements of high energy absorption, stable impact resistance and low peak stress. Thus, the applicable potential of cellular materials in crashworthiness structures may be enhanced by developing crashworthiness design methods.

This study aims to propose a method for guiding the crashworthiness design of graded cellular material and to obtain the desirable crashworthiness property. Based on the R-PH shock model, a design strategy to determining the relative density distribution of graded cellular material for specific crashworthiness requirements is presented in Section 2. An FE method using 3D Voronoi models with specific relative density distributions of graded cellular material is introduced also in Section 2. Influences of an impact-force parameter on the crashworthiness and relative density distributions of graded cellular rods are analyzed in Section 3. Three cases of mass impact with specific impact forces are investigated by using the shock model and verified by the FE method also in Section 3. Conclusions are given in Section 4.

2. Theoretical and numerical models

2.1. Problem description

We consider an object with mass M and initial velocity V_0 impinging a graded cellular rod at time t=0. The object is to be protected, which requires that the impact force acting on the object should be less than that the object can bear. Thus, the graded cellular rod needs a suitable design to satisfy the requirement for protecting the object. In many practical applications, a stable impact force is desirable, i.e. the impact force keeps constant. In some applications, multiple energy absorber elements may be used in a crashworthy system, which is triggered under different values of impact forces, and the design without a step of impact force [34] may be desirable, i.e. the impact force increases gradually. In some other applications, the design may take the tolerable intensity of human body into consideration. For example, as illustrated in Wayne Tolerance Curve [35], the tolerable intensity of human body decreases as the time of exposure to pressure increases, and thus a decreasing history of impact force may be desirable. Therefore, the desirable impact force acting on the object may be very different in applications. For simplicity, we consider the case that the impact force varying with time in a linear manner, written as

$$F(t) = [1 + \alpha(t/T - 1/2)]F_0, \tag{2}$$

where α is an impact-force parameter, T the impact duration, F_0 the impact force at time $T/2$. In the design, the object can be taken as a rigid mass. Then, the relative density distribution of the graded cellular rod, denoted as $\rho(X)$ along the X-axis direction, may be determined with the help of analyzing a shock model.

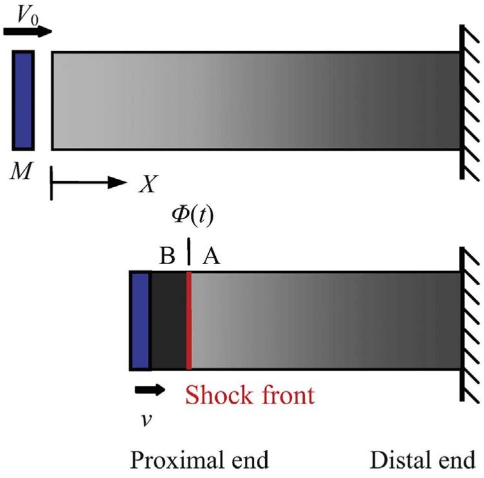

Fig. 1. Mass impact of graded cellular rod and a shock model.

Assuming there is one shock front propagating from the proximal end to the distal end of the graded cellular rod, as presented schematically in Fig. 1. Indeed, this implies that the relative density distribution $\rho(X)$ is a non-decreasing monotonic function [31]. During crushing, the portion behind the shock front moves together with the mass, while the portion ahead of the shock front is stationary. The physical quantities, including strain, stress and particle velocity, behind the shock front are denoted as $\{\varepsilon_B(t), \sigma_B(t), v(t)\}$; while those ahead of the shock front are $\{0, \sigma_A(t), 0\}$. Hereafter, the strain (stress) behind the shock front is named as the shock strain (stress). Thus, according to Newton's motion law, the acceleration of the portion behind the shock front at time t can be given by

$$a(t) \equiv \frac{dv(t)}{dt} = -\frac{A_0\sigma_B(t)}{M + A_0\rho_s\int_0^{\Phi(t)}\rho(X)dX}, \tag{3}$$

where $\Phi(t)$ is the Lagrangian location of the shock front, A_0 the cross-sectional area of the graded cellular rod, and ρ_s the density of matrix material of the graded cellular rod. On the other hand, if the impact force $F(t)$ is specified, e.g. Eq. (2), the acceleration of the mass can be calculated by

$$a(t) = -F(t)/M. \tag{4}$$

From Eqs. (3) and (4), it can be concluded that the impact force is highly dependent on the relative density distribution of graded cellular rod. Thus, the impact resistance performance of graded cellular rod can be improved with a reasonable design of its density distribution. Combining Eqs. (3) and (4), we have the shock stress

$$\sigma_B(t) = \left(1 + \frac{\rho_s A_0}{M}\int_0^{\Phi(t)}\rho(X)dX\right)\cdot\frac{F(t)}{A_0}. \tag{5}$$

Then, with using a material model of the graded cellular rod, we can determine the relative density distribution, as illustrated in the next section. In this study, we take M =50 g, V_0 =100 m/s and F_0 =7.5 kN with different values of parameter α as study cases to demonstrate our design strategy. The impact duration T can be obtained from the impulse-momentum theorem, i.e. $\int_0^T F(t)dt = MV_0$ gives T=0.67 ms.

2.2. Nonlinear plastic shock model

A design strategy based on a nonlinear plastic shock model is proposed to determine the relative density distribution of graded cellular rod. Instead of the R-PP-L idealization [9,31], a more accurate