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Dynamic response of a cellular block with varying cross-section

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ABSTRACT

In this paper, the plastic crushing response is studied for an aluminum foam block of varying cross-section under impact. The influence of the gradient on the cross-section is investigated. Based on the one-dimensional shock theory, an analytical model is proposed to investigate an impact scenario, in which a foam block with a gradient in its cross-section together with a rigid mass impinges onto a rigid target. Because of the change in the cross-sectional area along the length, two possible deformation modes may appear, namely the double shock mode and the single shock mode. When the largest cross-section is impinged, two compaction zones in the foam block are found, while only one compaction zone appears from the impinged end when the smallest cross-section is impinged. Of particular interests are the absorbed energy and the force transmitted to the target. The analysis reveals that the energy absorption capacity is weakened with a negative gradient while positive gradient has no influence on the energy absorption capacity of the graded foam.

An experiment was then designed to investigate the behavior of the graded foam block under impact. The rigid mass together with the foam block was fired from a gas gun barrel, and its speed was measured before it collided onto the rigid target. The deformation history of the specimen was recorded by a high-speed video camera. Image analysis was employed to obtain the velocity of the impinging mass during the process. Observation of the deformation profile demonstrates the two basic deformation modes described in the analytical modeling.

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1. Introduction

Due to their excellent properties, such as low weight, high stiffness and strength and heat insulation, cellular materials are widely used in engineering applications, especially in the aerospace and defense industries, as energy absorption devices. To improve the performance of the cellular material, optimization of the material property has attracted considerable research interest [1–7]. For cellular solids, a gradual variation in the cell size/volume distribution or material strength/density may significantly influence many properties, such as mechanical shock resistance and thermal insulation. Such graded cellular material can be easily found in nature. For example, human bone processes a density gradient, maximizing the biological mechanical performance [8]. As previous studies [9–15] mainly focused on the inhomogeneity and imperfection of the cellular materials, it is worthwhile to further explore mechanical properties of graded cellular structures under dynamic loading.

Up to now, most related studies reported in the literature have been based on Finite Element (FE) simulation. By using the FE modeling, Ali et al. [1] investigated the response of the hexagonal honeycomb block with different wall thickness under low velocity impact (up to 20 m/s). In their work, the regular honeycomb block was divided into 6 layers and each layer was assigned with a different wall thickness. They observed the deformation process and investigated the energy absorption capacity of the graded honeycomb. However, the impact velocity in their study was low such that no obvious influence on the deformation process was found. The study of Ajdari et al. [3] focused on the quasi-static compressive behavior of functionally graded Voronoi structures by using FE simulations. It was found that the effective modulus and yielding strength of the structure increased after introducing the density gradient. In their later study [4], a gradient in the cell wall thickness was introduced into the regular hexagonal honeycomb. Results showed that the decrease of the relative density along the direction of crushing enhanced the energy absorption of

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honeycombs at early stages of crushing. Similar work on the graded Voronoi honeycomb was conducted by Wang et al. [5]. However, those studies mentioned above focused on the final energy absorption of the structure under limited low impact velocity, neglecting the deformation process under high impact velocities. Cui et al. [6] proposed a graded foam model by using FE simulation. Based on the model proposed by Schraad and Harlow [7], they determined the stress-strain curves for all layers of the foam due to different initial density. The density gradient employed is expressed as,

$$\rho(y) = \rho_1 + (\rho_2 - \rho_1)\left(\frac{y}{d}\right)^n, \quad 0 \le y \le d \tag{1}$$

where ρ_1 and ρ_2 are the initial densities at the proximal and distal layers, respectively; d is the thickness and y is the position through the thickness; and n is the power. Their study focused on the type of the density gradient (i.e. the value of n), neglecting the influence of the gradient on the deformation mode.

Only a little experimental work in the literature are related to the graded cellular material. Shim et al. [16] studied the impact response of the foam-plate systems comprising ten layers of crushable foam separated by mild steel plates. Four geometry arrangements, namely uniform and tapered, hourglass and double tapered profiles were investigated. Their results indicated that the response was significantly influenced by the system geometry. The limit of the study is that the impact velocity in their study only ranged from 3 to 8 m/s; and no further investigation into the influence of the gradient on the deformation and energy absorption was carried out. A graded syntactic foam material was studied in the work of Gupta [17]. No significant loss in the strength or failure took place when the graded foam was under 60–75% compression. Brother and Dunand [18] measured the compressive mechanical properties of the Al-6061 foam with density gradient under quasi-static loading. Their results showed that the plateau stress of the density-graded foam was higher than the uniform one. Zeng et al. [19] investigated the influence of the density gradient on the mechanical response of graded polymeric hollow sphere agglomerates under impact loading. In the early stage, the force at the distal end was found much higher when the strongest layers were placed near the proximal end. Their study showed that placing the strongest layer as the first impacted layer and weakest layer as the last had some benefit to minimize the force level transmitting to the protected structure.

Bruck [20] proposed a one-dimensional model to describe the stress wave propagation in the functionally graded material. Li et al. [21] investigated the behavior of the graded structure under impulsive loading. However, these studies are only applicable for the graded continuum material, instead of the graded cellular material. The propagation of the stress wave in the graded cellular material was investigated by Kiernan et al. [22]. They adopted the same approaches as those in the work of Cui et al. [6] to introduce the density gradient. Employing the energy balance method, Zhu et al. [23] studied the effect of the length and density on the maximum deflection of a foam sandwich plate. Nevertheless, the deformation mode was not considered. Wierzbicki and Doyoyo [24] investigated the behavior of a cellular block with varying cross-section under quasi-static loading. They found that a compaction wave propagates from the end with the smallest cross-section to the stronger end of the specimen. Due to the effect of the shear, the compaction surface was not perpendicular to its loading direction. Based on the one-dimensional shock theory, the authors [25] presented an analytical study of a cellular rod with yield stress gradient impinged by a rigid mass. Basic deformation modes and the influence of the stress gradient on the energy absorption capacity were investigated. It was found that two compaction zones appear from both the impinged and distal ends during the impact when the strongest end of the block is placed at the impinging end.

The present study is aimed at the understanding of the behavior of a foam block with varying cross-section under impact. An analytical model is proposed, assuming that the material property is rigid-perfectly plastic-locking (R-PP-L) [26–29]. Similar to the previous study with yield stress gradient [25], it is found that two compaction zones appear when the largest cross-section is placed at the impinged end while only one initiates from the impinged end when the impinged cross-section is the smallest. Attention is paid to the influence of the gradient on the energy absorption capacity and the force transmitted. Experiments were conducted and the results validate the analytical model, in terms of the velocity history of the impinging mass. In the experiments, two types of specimens with varying cross-sectional areas were used, aluminum foam blocks and aluminum honeycomb blocks. Both types of specimens had a gradient in their cross-section along the loading direction. The specimen together with a rigid mass was fired out from the barrel of a gas gun onto a rigid target. The impact process was recorded by using a high-speed camera.

2. Analytical analysis using one-dimensional shock theory

To understand the underlying mechanism of the deformation in a foam block with graded cross-section, analytical analysis is presented in this section. We propose an impact scenario (see Fig. 1), in which a stationary cellular block together with a rigid mass G impinges onto a rigid target with an initial impact velocity V_0. The graded foam block has an initial length l_0, initial density ρ_0 and the cross-section gradient Θ_A. It is defined that $\Theta_A > 0$ when the proximal end has the smallest cross-section; i.e. the cross-section increases from the proximal end along the rod; and $\Theta_A < 0$ when the end with the largest cross-section is at the proximal end. The cross-section gradient is defined as,

$$\Theta_A = \frac{A_d - A_p}{(A_d + A_p)/2} \tag{2}$$

where A_d and A_p are the cross-sectional areas at the distal end and the proximal end, respectively.

By considering of the equilibrium at the two ends of the foam block, shock fronts at both the proximal end and the distal end may co-exist from the very beginning when the gradient is negative, while only a single shock appears in the block with the

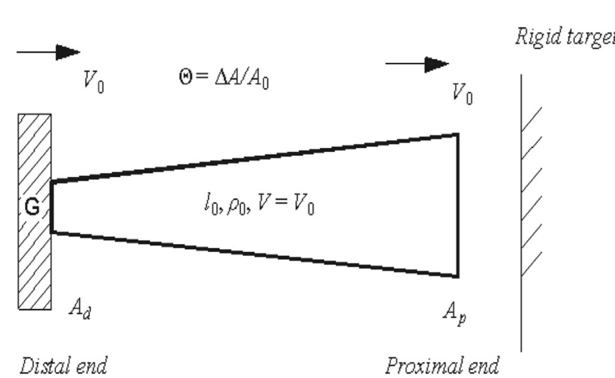

Fig. 1. Impact scenario: a foam block with graded cross-section together with a rigid mass G impinges onto a rigid target with impact velocity V_0. Note: $\Delta A = A_d - A_p$ is the difference of the cross-sectional area between the two ends and $A_0 = (A_d + A_p)/2$ is the average cross-sectional area of the block.

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