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Propagation of the compaction waves in a cellular block with varying cross-section

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Current work aims to broaden our previous work on the compaction waves in a cellular block with varying cross-section under impact. Complement experiments were carried out to obtain the force signals of the foam specimen with varying cross-section in the dynamic crushing. Two impact scenarios were employed. In the first impact scenario, the foam block together with a back mass impinged onto a rigid target; and in the second scenario, a stationary foam block was impinged by a rigid mass. The foam/mass was fired from a gas gun barrel. The impact velocity was measured before the impact happened. The deformation processes were captured by a high speed camera and an aluminum bar was served as the rigid target. Two groups of semi-conductive strain gauges were attached at the surface of the bar to obtain the strain/stress signals. Typical force signals were analyzed together with their deformation processes.

Then, an improved analytical model is proposed, incorporating the strain hardening property of the aluminum foam. Comparisons are made between the analytical models and experimental results, showing that the proposed model is able to predict the dynamic forces with sufficient accuracy. Based on the modified analytical model, typical propagations of the compaction wave are described. Correspondingly, parametrical studies are implemented based on the proposed analytical model.

1. Introduction

When the cellular material is compressed, it exhibits plastic property at an almost constant nominal load with large strokes (Gibson and Ashby, 1997). Due to this property, it is widely used in engineering for energy absorption of an impact, such as packaging applications and crashing situations. Under dynamic loading, compaction shock waves show up, resulting in the dynamic stress enhancement. To explain such feature, Reid and Peng (1997) investigated the behavior of the wood under high speed impact and proposed a rigid-perfectly plastic-locking (R-PP-L) material model. After their pioneering work, improvements of the model were achieved by a number of researchers (Lopatnikov et al., 2003 , 2004; Tan et al., 2005a, 2005b; Pattofatto et al., 2007; Karagiozova et al., 2012). In the work of Karagiozova et al. (2012, 2015), the densifications strain was derived as velocity dependent, based on the actual stress–strain curves together with their Higoniot strain–velocity representation. Most recently, Barns et al. (2014a) systematically investigated the open-cell aluminum foam under a direct impact and validated the velocity-dependent approach. Similar work has been implemented by Zheng et al. (2014). Their later work (Barns et al. 2014b) and that of Gaitanaros and Kyriakides (2015) employed randomly generated open-cell aluminum foam in conducting a numerical analysis, which confirmed the parabolic characteristic of the Hugoniot strain–velocity dependences. Compared with the R-PP-L material model, the accuracy of the analytical predictions has been improved by using the Hugoniot strain–velocity relationship. The concept of graded cellular solids has been introduced in the field of material science. Such cellular solids possess a gradient in their properties (e.g. density, parent strength and cell size/volume) along one direction so that the mechanical response/performance of the material/structure could be improved in a particular loading condition (e.g. explosive loading). Here, a gradient in the geometry (cross-section) but with uniform material is introduced as an alternative, to adjust the desirable impact response such as energy absorption.

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Most of the related research in literature is based on finite element (FE) simulations. Due to its simply structure, early work employed regular (Ali et al., 2008) or Voronoi honeycomb (Ajdari et al., 2009, 2011; Wang et al., 2011) to investigate the behavior of the structure under impact, introducing a gradient in the density/thickness of the cell wall. For the foam material, most studies (Cui et al., 2009; Kiernan et al., 2009; Li et al., 2014) employed uniform foam with several layers with different material properties in each layer, instead of continuous material. These studies focused on the final energy absorption capacity, neglecting the influence of the impact velocity on the deformation process of the material.

Limited experimental studies on the graded cellular material have been reported in the literature. Shim and Yap (1997) investigated the influence of the geometry arrangement of the foam-plate systems on its response under dynamic loading using a drop hammer. The velocity was up to 8 m/s, which limited the study; and no further investigation was presented into the influence of the gradient on the deformation process or energy absorption capacity of the system. Brother and Dunand (2008) found that the plateau stress of the density graded foam was higher than the uniformed one by conducting the quasi-static compression tests of the Al-6061 foam with density gradient. Wierzbicki and Doyoyo (2003) conducted the quasi-static compression tests on a cellular block with varying cross-section. A compaction wave was found, propagating from the end with smallest cross-section to the stronger end. Zeng et al. (2010) employed four layers polymeric hollow sphere agglomerates with different thickness to investigate the influence of the density on the response of the graded cellular material. Their results showed that the force at the distal end was smaller when the strongest layer was placed at the proximal end in the early stage.

In analytically studying the impact response of a cellular rod with strength gradient, the authors (Shen et al., 2013) firstly proposed a double shock model for the negative gradient case. Subsequently, in order to explore the existence of this phenomenon of double shock deformation, an experiment was conducted by the authors (Shen et al. 2014) in which a foam block with varying cross-section together with a back mass impinged onto a rigid target. Two deformation modes were identified in relation to the influence of the gradient. Two compaction zones (shock fronts) were found when the strongest end of the block was placed at the proximal end while only one compaction wave was observed when the impinged end was the weakest. Based on the one-dimensional shock theory (Reid and Peng, 1997), a simple analytical model was proposed to investigate the behavior of the foam block with varying cross-section. However, the analytical model proposed in that study (Shen et al., 2014) employed a rigid-perfectly plastic-locking (R-PP-L) material model, which only involves two parameters (plateau stress and locking strain) and is not accurate enough for good predictions. Also, the experiment only presented the deformation process and the force signals were not captured.

The present study is aimed to broaden the previous research work (Shen et al., 2014) on the investigation into the compaction waves in the cellular block with varying cross-section under impact. Two impact scenarios were conducted. The first impact scenario was the same as the previous study, in which the foam together with a back mass impinged onto a rigid target. In the second impact scenario, the foam was directly impinged by a rigid mass. A 4 m long aluminum bar was employed to serve as the rigid target and two semi-conductive strain gauges were attached to capture the force signals. Afterward, an analytical model, incorporating the strain hardening property and the strain-velocity dependence, was proposed. Comparisons are made between the analytical and experimental results.

2. Experiment set-up and specimen description

2.1. ALPORAS foam

The ALPORAS foam, a type of closed cell aluminum foam was used in the experiment. The chemical composition of the cell wall material is Al–0.45 wt.%Mg–0.52 wt.%Ca–0.21 wt.%Ni. The weight of each specimen was weighted to calculate the relative density, which is defined as the density of the foam divided by the density of the parent material (i.e. ρ_0/ρ_s). The density of the foam used in this study is in the range of 8–11.5%. To obtain the stress–strain relationship of the foam, quasi-static uniaxial compression tests were carried out on a servo-hydraulic MTS machine, using uniform and cubic foam specimens with the dimension $50 \times 50 \times 50\,\text{mm}^3$. The nominal stress–strain relationship is shown in Fig. 1. The uniaxial quais-static compression results are consistent with those in the work of Shen et al. (2010). Due to the inhomogeneity of the foam specimen, the densities of the tested specimen in the dynamic tests may be different from the one in the quasi-static compression test (10%). Hence, the following scaling method was implemented to obtain the stress–strain relationship for the foam specimen with different densities. The locking strain for the foam (10%) is determined as 0.48 by using the energy efficiency method (Tan et al., 2005b). From a quasi-static analysis in Gibson and Ashby (1997), the stress and the locking strain are expressed in terms of the relative density as follows,

$$\frac{\sigma_0}{\sigma_{ys}} = C_1\left(\frac{\rho_0}{\rho_s}\right)^n \qquad \varepsilon_d = 1 - C_2\frac{\rho_0}{\rho_s} \tag{1}$$

where σ_0 is the plateau stress of the foam, σ_{ys} is the yielding stress of the cell wall material, ε_d is the locking strain, and C_1, C_2, n are constants determined by experiments. In the current study, n is taken as 1.5.

Consequently, the scaled stress is expressed as

$$\sigma_2(\varepsilon_2) = \left(\frac{\rho_{02}}{\rho_{01}}\right)^n \sigma_1(\varepsilon_1) \tag{2}$$

where the subscript "$_1$" pertains the property of the given foam and the subscript "$_2$" pertains the scaled property.

The corresponding strain is expressed as,

$$\varepsilon_2 = \frac{\varepsilon_{d2}}{\varepsilon_{d1}}\varepsilon_1 \tag{3}$$

where the locking strain is determined from,

$$\frac{1-\varepsilon_{d2}}{1-\varepsilon_{d1}} = \frac{\rho_{02}}{\rho_{01}} \tag{4}$$

The scaled stress–strain relationships for the foam with other densities are also shown in Fig. 1. Similar method was adopted in the research work by Cui et al. (2009). However, it should be noted that the scaling method could result in an inaccurate prediction since every foam specimen would naturally vary because of the randomness of the microstructure. Consequently, comparison has been made between the empirical equation and the experimental stress–strain curves. Fig. 1b shows the comparison for the ALPORAS foam used with a relative density of 9.5% and 10.5%, respectively. The agreement is broadly reasonable. The power-law material model proposed by Pattofatto et al. (2007) was used to fit the stress–strain relationship of ALPORAS foam.

$$\sigma = \sigma_0 + k\varepsilon^m \tag{5}$$

where k and m are constants determined to fitting the stress–strain curves, which are listed in Table 1 as 6.85. When $m = 1$, k is the