



The dynamic response of sandwich beams with open-cell metal foam cores

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ABSTRACT

The deformation and failure modes of dynamically loaded sandwich beams made of aluminum skins with open-cell aluminum foam cores were investigated experimentally. The dynamic compressive stress–strain curves of core materials, open-cell aluminum foam, were obtained using Split Hopkinson Pressure Bar. And then the dynamic impact tests were conducted for sandwich beams with open-cell aluminum foam cores. The photographs showing the deflected profiles of the dynamically loaded sandwich beams are exhibited. Several impact deformation modes of sandwich beams can be observed according to contrastive photographs, i.e. large inelastic deformation, face wrinkle and core shear with interfacial failure. A comparison of the measurements is made with analytical predictions, which indicates that the experimentally measured deflections agree well with predictions employing both the inscribing and circumscribing yield loci. For comparison, the quasi-static punching deformation and failure modes of sandwich beams is presented.

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1. Introduction

Metal foams can dissipate a large amount of energy due to its relative long stress plateau, which makes it widely applicable in the design of structural crashworthiness. Sandwich structure with metal foam core is of current academic and industrial interest due to its superior properties like high specific strength, high specific stiffness and high energy absorption ability, etc. In recent years, considerable studies have been conducted focusing on constitutive relationship of foam materials [1–3] and failure mechanism of sandwich structures [4–6]. While Fleck and Deshpande [7] developed an analytical model for the shock resistance of clamped sandwich beams, Xue and Hutchinson [8] conducted Finite Element simulations to investigate the response of sandwich beams subjected to impulse loadings. Similarly, Cantwell et al. investigated the high-velocity impact response of composite and FML-reinforced sandwich structures [9]. Several main collapse modes including delamination and longitudinal splitting of the composite skins have been observed. To perfectly classify the impulsive response of sandwich beams, several studies have been further conducted to investigate experimentally [10] and theoretically [11] the response of sandwich beams subject to shock loading. Foo et al. [12] have already examined the failure response of

aluminum sandwich panels subjected to low-velocity impact. Strain-hardening behavior of the aluminum alloys and the honeycomb core density were shown to affect the impact response. On the basis of the studies so far available, Yu et al. [13] have investigated the response and failure of the sandwich beams with open-cell aluminum foam core subjected to low-velocity impact loading by using the drop weight machine. However, few experimental investigations on the structural response of open-cell aluminum foam core sandwich beams under high-velocity impact have been reported to date. Therefore, a deep insight into dynamic response of sandwich beams with open-cell aluminum foam by using metal foam projectile loading, which was proved to be a convenient experimental tool to simulate shock loading on a structure in Ref. [14], is required to design these structures with significantly enhanced energy-absorbing and shock-resistant performance.

In this study, a large number of experiments were conducted to investigate the deformation and failure modes of dynamically loaded sandwich beams made of aluminum skins with open-cell aluminum foam cores. First, the dynamic compressive stress–strain curves of core material, open-cell aluminum foam, were obtained by an SHPB technique. And then the dynamic tests of sandwich beams were achieved, the deformation and failure modes of specimens are reported. The resistance to shock loading is evaluated by the permanent deflection at the mid-span of the beams for a fixed magnitude of applied impulse and mass of beam. Moreover, the comparative study between the measurements and analytical predictions is conducted. Finally, several characteristic deformation modes of sandwich beams subjected to quasi-static are discussed comparing with dynamic failure modes.

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2. Dynamic compressive behaviors of aluminum foam

2.1. Material and specimen

Open-cell aluminum foam was provided by Hong Bo Metallic Material Company (China) for testing. Aluminum foams with approximate relative density of 0.40 were investigated. The morphology of the foam was characterized with a conventional scanning electron microscope (SEM), as shown in Fig. 1. The foam has an open-celled structure without the typical wavy distortion of cell column or wall of a close-celled structure, and most of column surface appears to be rough [15]. The average cell sizes (i.e. column

spacing) of these foams are approximately 0.75 mm, 1.5 mm, 2.5 mm, respectively. The composition of the cell wall material is Al–Mg1.31 (wt.%). This material was made by infiltration casting process. The SEM photographs of undeformed aluminum foam material with different cell sizes are given in Fig. 1. To obtain the stress–strain relations with a large strain (exhibits three universal deformation characteristics) [1,16,17], cylindrical samples in dynamic compressive tests, 35 mm in diameter and 10 mm in height, were cut into the final geometry using an electrical discharge machine from blocks of the foam material.

2.2. Experimental results

Dynamic compression tests at strain rates of up to 1200 s^{-1} were conducted on the cylindrical samples described above at room temperature using a split Hopkinson pressure bar apparatus. A brief description of the experiment set-up is given below, with complete details given by Sathiamoorthy [18]. The striker, incident and transmitter bars consisted of 37 mm diameter aluminum bars and their lengths were 800, 2000 and 2000 mm, respectively. The end surfaces were lubricated to reduce the frictional restraint. The compressive pulse is generated by axial impact on the incident pressure bar by the striker bar. When the compressive pulse reaches the specimen, a portion of the pulse is reflected from the interface, while the remainder is transmitted through to the transmitter bar. The incident pulse and reflected waves in the incident bar are recorded by the resistance strain gauge attached at the incident bar. The transmitted wave is also recorded by the semiconductor strain attached at the transmitter bar. Dynamic compressive stress–strain curves could be obtained from the measured results. Compressive tests were also performed at a quasi-static strain rate of 10^{-3} s^{-1} using a servo-hydraulic test machine and specimens of 35 mm in diameter and 30 mm in height.

Experimental results indicate that the compressive stress–strain curve of aluminum alloy foam, under either quasi-static or dynamic compression, exhibits three universal deformation characteristics: an initial linear-elastic region; an extended plateau region where the stress increases slowly as the cells deform plastically; and a final densification as collapsed cells are compacted together. A comparison of the nominal stress–strain curves of the aluminum foam specimens under different strain rates is shown in Fig. 2. It is shown that the yield strength and flow stress of aluminum foam material increase with strain rate. The plateau stress is considered as the most important parameter of aluminum foam as all the other characteristics of structural response (e.g. energy absorption and the permanent deflection at the mid-span of the beams) depend on it. So, in this paper, an energy-based approach is proposed to calculate the effective plateau stress, through the stress–strain curves obtained from the standard uniaxial compression tests. Define energy absorption efficiency $\eta(\epsilon_a)$ as the energy absorbed up to a given nominal strain ϵ_a normalized by the corresponding stress value $\sigma(\epsilon)$ [19].

$$\eta(\epsilon_a) = \frac{\int_{\epsilon_{cr}}^{\epsilon_a} \sigma(\epsilon) d\epsilon}{\sigma(\epsilon)_{\epsilon=\epsilon_a}}. \quad (1)$$

Densification strain ϵ_D is the strain value corresponding to the stationary point in the energy absorption efficiency $\eta(\epsilon_a)$ –strain ϵ curve (obtained from Eq. (1)) where the efficiency is a global maximum, i.e.

$$\left. \frac{d\eta(\epsilon)}{d\epsilon} \right|_{\epsilon=\epsilon_D} = 0. \quad (2)$$

The plateau stress is determined by

$$\sigma_{pl} = \frac{\int_{\epsilon_{cr}}^{\epsilon_a} \sigma_c(\epsilon) d\epsilon}{\epsilon_a - \epsilon_{cr}}. \quad (3)$$

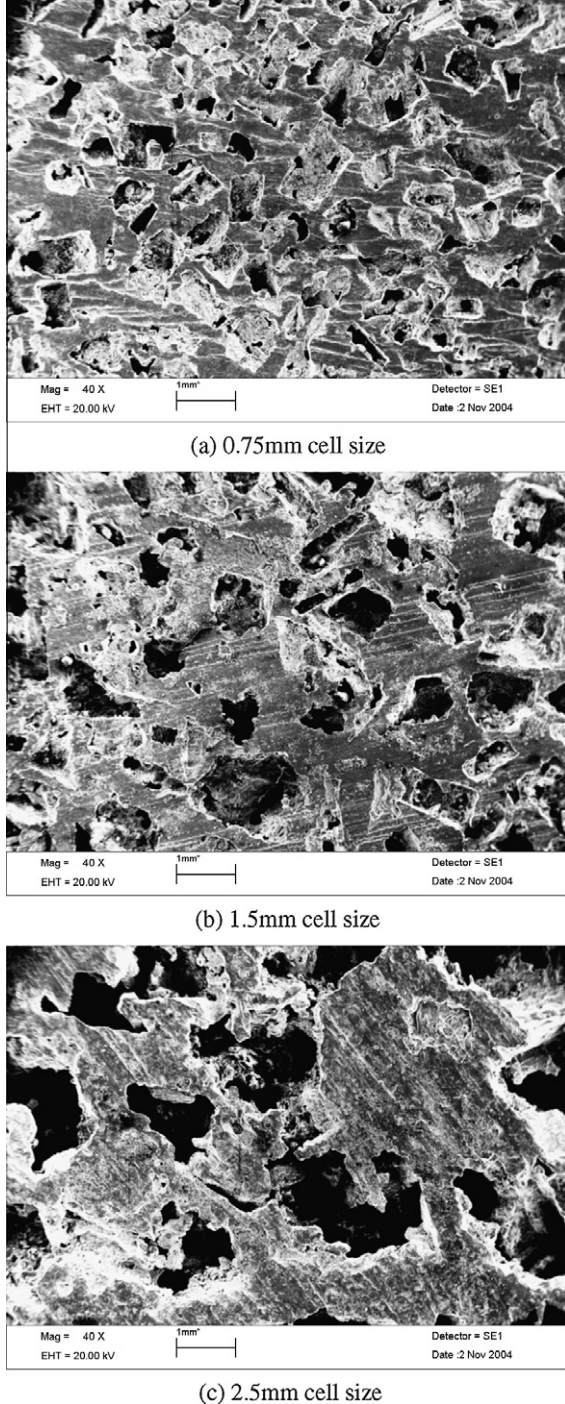


Fig. 1. SEM photograph of the undeformed aluminum foam materials.

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