Compressive behavior and energy absorption capacity of unconstrained and constrained open-cell aluminum foams

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Abstract
In practical engineering applications, while the open-cell aluminum foam as crash absorber is filled to the hollow structures, its deformation occurs under constrained stress boundaries. The experimental work was conducted to examine the effect of radial constraints on the mechanical behavior of the open-cell aluminum foam under quasi-static and dynamic compression. Results show that the radial constraints induce significant strain hardening of the open-cell aluminum foam. The open-cell aluminum foams tested with and without radial constraints show a clear strain rate sensitivity. The densification of the foam occurs earlier (showing lower densification strain) under radial constraints. The radial constraints enhance the energy absorbed per unit volume of the open-cell aluminum foam.

Keywords
open-cell aluminum foam, compression behavior, energy absorption, radial constraints, strain hardening

Introduction
Aluminum alloy foams, as an important class of cellular materials, have good mechanical and physical properties, such as crash energy absorption, sound absorption, and vibration damping structures. In practical engineering applications, especially when the aluminum foam is used to fill hollow structures, its deformation occurs under constrained stress conditions. These hollow structures will act as a barrier for unconstrained transversal displacements. The description of compressive response of the aluminum foams under constraint loading conditions is essential for designing new foam-filled components. Some studies of compressive mechanical properties of lateral and radial constrained closed-cell aluminum foams have been carried out. The uniaxial quasi-static and dynamic compression tests under free radial boundaries for the aluminum alloy foams have been studied. Nonetheless, for the open-cell aluminum foams, there is limited information available about the compressive response and energy absorption with constrained transversal boundaries. To close this research gap, the compressive tests of unconstrained and constrained open-cell aluminum foams were conducted and the compressive behavior and energy absorption were discussed.

Materials and experimental methods
The open-cell aluminum alloy foams are characterized by spherical cells and circular air holes on cell walls, which were produced by Beijing Foam Metals Co., Ltd (China) in the present study. The spherical open-cell aluminum foam material was prepared by counter-gravity infiltration casting. The diameters of spherical pore and circular hole are 3.0–4.0 mm and 1.0–2.0 mm, respectively. The densities $r^*$ of specimens are 0.95–1.16 g cm$^{-3}$ (the relative densities $r^*/r_s$ are 0.35–0.43). The cylindrical aluminum foam specimens were subjected to uniaxial quasi-static and dynamic compression tests without radial constraints (free lateral displacements) and compressive loading with radial
constraints (constrained lateral displacements) using an MTS-810 material testing machine provided by MTS Systems Corporation (USA) and a Split-Hopkinson pressure bar (SHPB) set-up at room temperature. The ISO 13314: 2011 standard indicates a sample height-to-diameter ratio \( \frac{H_0}{D_0} \) of between 1 and 2. Andrews et al. reported that the specimen’s height of aluminum foams is at least seven times the pore size to avoid edge effects. Therefore, the selected specimens are circular cylinder diameter of 37 mm and height 37 mm in consideration of avoiding edge effect and constrained dynamic compression (the diameter of the incident bar of SHPB set-up was 37 mm). The experimental set-up for constrained compression is shown in Figure 1. In all constrained compression tests, the inner die and punch surfaces were coated with high pressure-resistant silicone-based lubricant. The uniaxial quasi-static and dynamic compression tests were conducted under the radial constraint and free boundaries and the strain rate of 0.001 and 2000 \( s^{-1} \) was expected for the dynamic compression.

Results and discussion

The quasi-static and dynamic compressive stress–strain responses of open-cell aluminum foam specimens under the radial constraint and free boundaries are shown in Figure 2. According to the ISO 13314: 2011 standard, the plastic strength \( \sigma_p \) is defined as the first stress peak value in the plastic region and the plateau stress \( \sigma_{p0} \) was calculated as the arithmetic mean of the stress values at the strain of 0.2 and 0.4, as listed in Table 1. The stress–strain curves under radial-restraint compression are nominally higher and steeper than that under free-state compression. The results of Figure 2 and Table 1 clearly indicate a significant influence of the radial constrained boundary on the compressive response of open-cell aluminum foams, which according with the results of closed-cell aluminum foams reported by Duarte. The results imply that the onset of open-cell foam densification occurs relatively earlier under radial constrained boundary as well. From Figure 2, all the open-cell aluminum foam specimens show distinct strain hardening behavior as with the compressive stress–strain response of the closed-cell aluminum foams reported in the literature. The effect of the foam density on the strain hardening to the densities of foam specimens with radial constraints is not clearly observed in this study.

The energy absorbed by the foam per unit volume is the area under stress–strain curve up to the densification strain and is estimated by integrating the compressive stress–
strain data. The upper limit of the compressive strain 0.5 is recommended when energy absorption of specimens calculated.\textsuperscript{10} The quasi-static and dynamic compressive energy absorption density for unconstrained and constrained open-cell aluminum alloy foam are shown in Figure 3. From foregoing compressive stress–strain curves (Figure 2), the specimens of open-cell foam with radial constrained boundaries have higher stress levels. Consequently, the specimens with radial constraints have a stronger abilities of energy absorption density than the specimens without constraints. Figure 3 shows clearly that the energy absorption density curves of specimens tested with constraints are above the curves of the specimens tested without constraints. The energy absorption density is about 16.44 MJ m\textsuperscript{-3} with radial constraints and 10.01 MJ m\textsuperscript{-3} without radial constraints, respectively, while the compressive strain is 0.5 under quasi-state compression. It was also observed that the energy absorption density curves of foam tested with and without radial constraints under dynamic loading conditions are slightly higher than the ones subjected to quasi-static loading conditions. The results of energy absorption curves indicate that the densification strain values of open-cell aluminum foam specimens decrease and at the same time, the energy absorption values per unit volume increase under the radial constrained boundaries compared to the free boundaries. That is to say, the radial constrained boundaries are highly advantageous to energy absorption of open-cell aluminum foam, as with reported for the closed-cell aluminum foam by Duarte et al.\textsuperscript{6} Therefore, in the practical engineering applications, the open-cell aluminum foam can be used as the core material of energy absorption structures to fill the hollow structures with enough strength, which acts as a barrier to restrain the transversal displacements, and then, the deformation of the foam occurs under constrained stress conditions and more energy can be absorbed.

**Conclusions**

The experimental work was reported in this article to examine the effect of the radial constraints on the mechanical behavior of an open-cell aluminum alloy foam under quasi-static and dynamic uniaxial compression tests. The radial constraints impart significant strain hardening to the foam and a clear indication of strain rate sensitivity of the foam tested with and without radial constraints is observed. The densification of the foam occurs earlier (showing lower densification strain) under radial constraints. The performance of the foam absorbing energy per unit volume is greatly improved by the radial constraints. The observed hardening effect offers important practical and applicative significance for the open-cell aluminum alloy foam.

**Declaration of conflicting interests**

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