Mechanical Behavior of Steel and Aluminum Foams at High Temperatures

M. Tavares[a], J. M. Weigand, L. C. M. Vieira Jr.[a], S. J. C. Almeida[a], S. Szyniszewski[b,*]

[a] *Department of Structural Engineering, State University of Campinas, Campinas, Brazil*
[b] *Department of Engineering, Durham University, Durham, UK*

Abstract

The objective of this study is to quantify and understand the thermo-mechanical behavior of hollow sphere (HS) steel and powder metallurgy (PM) aluminum foams over a broad range of elevated temperatures. The mechanical properties of both the HS steel and PM aluminum foam are measured under compressive loading at ambient (24 °C) and temperatures of 100 °C, 150 °C, 200 °C, 300 °C, 400 °C, 550 °C and 700 °C, and results for the two foams are compared in terms of their rates of degradation in mechanical properties. The experimental work is underpinned by a computational micro-model, consisting of an assembly of hollow spheres, to link the cell geometry and base metal properties with the global mechanical performance. The computational model shows that plastic buckling of cells with progressive plasticity of the contact area is the key local failure mechanism. As expected due to the plastic buckling of the unit cells, thermal degradations of the tested metallic foams generally follow the same trends as does the yield stress of their bulk metals. The HS steel foam exhibits only minor elevated-temperature-induced degradation in its mechanical properties at or below 400 °C, while still maintaining 69 % of its capacity at 550 °C. Comparatively, the PM aluminum foam begins degrading at an elevated temperature of only 150 °C. Interestingly, the HS steel foam oxidized between 300 °C and 400 °C, resulting in increases in the quasi-elastic modulus

*Corresponding author
Email address: s.szyniszewski@gmail.com (S. Szyniszewski)

at elevated temperatures. Future work could explore how to design and take advantage of oxidation reactions at the surfaces of the cells because they could increase mechanical properties of metallic foams at high temperatures.

Keywords: Metallic foam, Deformation mechanism, Plastic buckling, Thermal analysis, Compression, Hollow-sphere steel foam, Aluminum foam, Mechanical properties, Thermal-mechanical analysis, Fire.

1. Introduction

Cellular materials are commonly found in nature (for example, bird bones, cork) because they are lightweight, and tissue can grow into their open cells enhancing biological interfaces. Metallic foam is an intentionally porous metal substratum largely made up of voids varying in size from nanometers to millimeters. Because the physical parameters of a metal foam, such as its porosity, can be readily controlled during manufacture, the metallic foam's Young's modulus and yield stress can be tuned to satisfy an engineering project's specific needs, especially in the context of multi-functional and multi-physical engineering applications.

Metallic foams have inherent fire retardancy, low thermal conductivity (relative to traditional metal structural components), and acoustic shielding. Open cell foams, albeit more expensive than conventional materials, also provide air, vapor, and fluid transport capabilities. Open cell foams act efficiently as heat exchangers due to the turbulent well-mixing flow that occurs within the foam's irregular micro-structural cavities, combined with the large surface area of their pores and high thermal conductivity of their base metals. The influences of various micro-structural properties of metal foams, such as their porosity, pore and fiber diameters, tortuosity, pore density, and relative density on the heat exchanger performance were discussed in [1]. [2] showed that a new composite material combining copper foam with wax was efficient in increasing the thermal conductivity of thermal energy storage systems. Cellular metals are also used as catalyst support in fuel cells. Their large surface area and mixing potential increases the intensity of the interaction between the catalyst and the fluid medium. [3] provides a review of the fabrication, characterization, and application of porous metal materials to fuel cells.

While existing applications for metallic foams reside largely in the mechanical, aerospace, and automotive domains [4], decreasing manufacturing costs and more widespread adoption of full-scale production techniques has ushered in the potential for using metallic foams in civil infrastructure applications. Metallic foams exhibit excellent stiffness-to-weight ratios, in comparison to conventional building materials, under a variety of loading conditions. For example, [5] showed that foam panels have higher bending stiffness than solid steel sheets of the same weight. Metallic foams are also renowned for their compressibility because they can reliably sustain 90 % engineering strain prior to failure [6], lending them extraordinary energy dissipation capacity [7]. Energy dissipation via large compressive deformations at low-amplitude stress levels has been explored by the automotive industry as a potential crash protection technology [8].

The ambient-temperature mechanical properties of metallic foams – specifically steel and aluminum foams – are characteristically different from those of their solid base metals. Steel foam is highly-compressible after yielding, unlike solid steel [9], which exhibits only shear deformations and is incompressible in the plastic regime. Also, foams tend to fracture under tensile strains that are noticeably lower than their crushing and compaction strains [10] thus warranting tailored respective failure criterions. [11] tested fifty hollow sphere (HS) steel foam bars to measure their compressive yield stress, densification strain, compressive plastic Poisson's ratio, compressive unloading modulus, as well as axial and shear mechanical properties at ambient temperature. [11] noted the importance of correctly assessing Poisson's ratio due to its link to foam compressibility as shown by [9].

Research has shown that elevated temperatures have a significant influence on the compressive behavior of metallic foams. [12] conducted a series of compressive tests on ALPORAS, a commercially-available closed cell aluminum foam manufactured by the Shinko-wire Company, at temperatures ranging from 25 °C to 620 °C. They found that the foam's compressive strength decreased both with decreased density and increased temperature. [13] tested the mechanical properties of powder metallurgy steel foams at ambient and elevated temperatures, and reported an increase in compressive yield strength and stiffness for temperatures at or below 400 °C, and a decrease in compressive yield strength and stiffness above that temperature. [13] concluded that the ageing effect (i.e., dynamic age-hardening) was responsible for the increase in mechanical properties up to 400 °C. [14] examined the high-temperature compressive behavior of powder metallurgy aluminum foams at temperatures ranging from 20 °C to 500 °C. They observed that increased temperatures resulted in decreased compressive strength and decreased energy absorption capacity, but increased densification strain (plateau length) at constant density. [14] also reported that exposure time i.e., the amount of time which the specimen was held at a constant elevated temperature before compressing it, did not influence the foam's compressive behavior. As part of a broader study on the behavior of ex-situ aluminum-alloy filled tubes under elevated temperatures (see [15]), [16] performed one quasi-static compressive test of a closed-cell aluminum foam specimen at temperatures of 25 °C, 150 °C, 300 °C, and 450 °C. Their results found only minor degradation in yield stress at or below 300°C, after which, because it passing through its transition temperature, the degradation was more pronounced. [16] notes that, as the aluminum cell-walls began softening at higher temperatures, the morphology of the compressive stress-strain behavior becomes smoother, such that the aluminum foam behaves in a similar manner as a ductile metal.

Many additional studies have investigated the compressive behavior of composite or alloyed metallic foams at elevated temperatures. After testing the compressive behavior of cenosphere-filled aluminum syntactic foams at elevated temperatures of 100 °C and 200 °C, and strain rates ranging from 10^{-3}/s to 1/s, [17] found that plateau stress decreased with temperature irrespective of strainrate. [18] tested Distaloy (Cu-Ni-Mo) and Astaloy (Mo) foams having different degrees of porosity at elevated temperatures of 200 °C, 400 °C, and 600 °C. They found that the length of the yield plateau (in units of compressive strain) was appreciably affected by porosity but not temperature. They also observed that compressive yield strength increased up to a temperature of 400 °C, after which it sharply decreased at 600 °C. [19] investigated the compressive behavior of composite Al-Si-SiC foams at elevated temperatures, evaluating the influence of temperature on energy absorption and type of fracture. They reported a decrease in compressive strength with increasing temperature, as well as a decrease in the absorbed energy when a ductile-type fracture mode occurred. [20] tested expanded perlite-aluminum syntactic foam cylinders in compression at elevated temperatures, comparing the foam's resulting temperature-degraded mechanical properties against those of the matrix materials, tested under the same conditions. Their results showed that the high-temperature behavior of the foams was controlled both by temperature-dependent softening of the matrix materials and a transition of the deformation behavior of the foam from brittle at low temperatures to ductile at high temperatures. [21] investigated the effect of temperature on the microstructure, failure mechanism, and compressive mechanical properties of commercially-available zinc-aluminum alloy syntactic foams with expanded perlite or expanded glass filler particles at four elevated temperatures of 100 °C, 200 °C, 300 °C, and 350 °C. The results showed that while the foam with expanded perlite was stronger than the foam with expanded glass across all elevated temperatures, the relative reduction of plateau stress of the two foams was similar.

As a continuation of the work presented in [11], this study examines the thermo-mechanical behavior of hollow-sphere (HS) steel foam samples removed from the same rectangular prism. Specifically, this paper characterizes and compares the mechanical properties of HS steel and powder-metallurgy (PM) aluminum foam specimens both exposed to a wide range of elevated temperatures, up to 700 °C and 500 °C, respectively, for durations of 15 min and 30 min. Consistent with ISO Standard 13314:2011, the yield strength and plateau stress are calculated for each specimen. To permit additional characteristics of their compressive stress-strain responses to be calculated, for example the strain at which densification begins, a nine-parameter phenomenological equation fitted to the compressive stress-strain response of each specimen. Finally, to examine the plasticity that localized at sphere interfaces due to contact forces, high-fidelity computational models of hollow-sphere foams were also conducted using LS-DYNA. These models showed that under increased deformation plasticity spreads toward the equators of the spheres, gradually increasing diameter of the plastic hinge hoop moving outwards from the initial contact area until buckling of the sphere-walls occurred. This result lends validity to the idea that thermal degradation of the global mechanical properties of HS foam is primarily controlled by the influence of elevated temperatures on the base metal's yield stress.

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