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Temperature effect on non-stationary compressive loading response of polymethacrylimide solid foam

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ABSTRACT

This paper presents the results of experimental investigation and modeling the polymethacrylimide (PMI) solid foam response on slightly non-stationary compressive loads at different loading speed and temperature. The PMI represents a typical material used as a core component of composite sandwich structures. For all conditions, the strain–stress curves exhibit three definite regions, such as linearly elastic, plateau, and densification as it is known from the literature. However, it is shown in the present study that even minor fluctuations of the loading speed may lead to significant qualitative effects within the plateau segment. In particular, spike-wise load drops occur in a regular way during the loading phase when the specimen temperature is below −20 °C. Acoustic emission tests lead to the conclusion that the load drops are associated with generation of brittle fractures in the clusters of broken foam cells. Also, cyclic loading tests were conducted to evaluate the energy loss in cells permanent deformation during the loading cycle. The amount of energy dissipated for each cycle is reduced at higher temperatures. Finally, based on the experimental results, a phenomenological model of the foam load–displacement response at different loading speeds and temperatures is presented in the form of a single analytical expression.

1. Introduction

Solid foams represent an important component of lightweight composite structures. The major advantage of such structures is that they possess high strength and high stiffness to weight ratios. Many types of foam serve as core subcomponent in sandwich composite materials which are used in a rapidly growing number of applications such as high-speed marine vessels, aerospace applications and wind turbine blades. Solid foam exists either in the form of metallic-based, or polymer-based or hybrid-based materials. Examples of polymer-based materials include Polymethacrylimide (PMI), expanded polystyrene (EPS) and polyetherimide (PEI). Hybrid-based material foams include bioactive glass-polyvinyl alcohol (PVA), phenolic foams reinforced with glass and rubber and nanoclay reinforced hybrid syntactic foams.

Material Scientists are dealing with the mechanics of foam microstructure. For example Williams [1] showed that the average number of faces per cell is close to 14 and the average number of edges per face is 5.1. Mills and Zhu [2] proposed a Tetrakaidecahedral cell having six square and eight hexagonal faces. If cell faces do not rupture, there are contributions to the mechanical properties from the compression of the cell gas and from the stretching of cell faces. Young's modulus was found to depend linearly on the relative density (foam density to the polymer density) [3]. Rusch [4] suggested that the cell gas contribution to the stress would take place in the post-yield hardening of compressed cell foam. Cell faces were treated as membranes. Maiti et al. [5] argued that cell edges would touch each other at high strains as the length of the buckling element is decreased while the stress required for buckling would increase (densification).

Closed-cell foams have the solid material in edges and faces so each cell is sealed off from neighbors. That is why closed-cell foams have higher compressive strength due to their structures. Based on the results reported in the literature [6–10] a typical stress–strain curve of solid foams exhibits three definite regions: linear elasticity, plateau, and densification. Arezoo et al. [11] obtained experimental data pertaining to the quasi-static mechanical response of PMI foams of density ranging from 50 kg/m^3 to 200 kg/m^3. It was shown that foams of low density collapse by cell wall buckling while foams of high density undergo plastic cell-wall bending. As a result, both the elastic and plastic macroscopic responses of foam display a tension/compression asymmetry.

The acoustic emission (AE) responses during compression and indentation of two kinds of metal open cell foams (sponges): an aluminum–silicon foam (AlSi10) and Alporas foam (AlCa5Ti3) were

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examined by Kádár et al. [12]. They reported two types of AE signals, which can be distinguished according to the rising time of the amplitude of the AE signal. The signal revealed basically two different modes of deformation: namely fracture and plastic yield. Later, Kádár et al. [13] found that the yield stress of foam and deformation mechanisms during tension are governed by the cell-edge material and by the structure of the foam. Different deformation mechanisms were found to take place depending on the pore-size and the cell-edge thickness. In the case of large pores with thicker cell-edges, the deformation mechanisms were reported to be controlled by the structure, while for small pores (with thinner cell-edges) the microstructure of the cell-edge material governs the deformation. Ramsteiner et al. [14] carried out a number of tests to study the mechanical properties of open-cell and closed-cell foams. They showed that the foam density is the dominating parameter influencing its behavior. Brothers et al. [15] used AE methods to study the nature and evolution of microfracture damage during uniaxial compression of ductile amorphous and brittle crystalline metal foams made from a commercial Zr-based bulk metallic glass. They compared the results with those obtained for aluminum-based foam of similar structure. For the amorphous foam, acoustic activity revealed evolution of the damage process from diffuse to localized damage through the foam stress plateau region, and reversion back towards diffuse damage in the foam densification region.

Foam core composites with different types of skin architectures were considered in Ref. [16]. The failure modes of the various foam core composites at the skin, skin-to-core interface and the core under three-point loading were assessed in light of AE testing parameters and rapid vibration-based elastic moduli measurements. In situ AE and post test microscopic analysis of quasi-static and flexural fatigue testing of sandwich composites conducted by Shafiq and Quispitupa [17] indicated core damage to be the predominant failure activity while fiber rupture served as a precursor to catastrophic failure. The study revealed that multiple crack initiation sites were observed under fatigue loading conditions in the vicinity of the notch tip. Both modes I and II cracking were observed in the core and along the interface between the core and the face-sheets. Damage assessment of foam core sandwich composite panels due to slamming water as a function of slamming energy (161–779 J) and deadrise angle (0–45°) was studied by Charca et al. [18]. They found that higher slamming energy and lower deadrise angle resulted in greater damage to the material. Catastrophic failure was observed to occur beyond a threshold strain of 0.0035 mm/mm. Core shear along the interface with the face-sheets and local buckling of the face-sheet and resin fragmentation were observed to be the dominant modes of failure under slamming.

The effect of temperature as well as strain rate on the quasi-static compressive response of polyvinyl chloride (PVC) closed-cell foams was examined by Thomas et al. [19]. Foams with densities 75, 130, and 300 kg/m^3 were tested at room and elevated temperatures. A reverse trend in failure modes was observed when moving from room to elevated temperatures at high strain loading, which was not found in quasi-static testing at elevated temperatures. Post-impact tests were conducted to evaluate the residual strength of the foam cores subject to elevated temperatures. The energy absorption of all cores was found to be proportional to the strain rate. At elevated temperatures, the change in the foam stiffness was found proportional to the relative density. Deschanel et al. [20] reported tensile failure experiments on polyurethane (PU) foams by imposing a constant strain rate. For heterogeneous materials the failure does not occur suddenly and can develop as a multistep process through a succession of microcracks that end at pores. The acoustic energy and the waiting times between acoustic events follow power-law distributions. This remains true while the foam density is varied. Tensile tests at different temperatures (from room temperature down to −65 °C) were performed by Deschanel et al. [20] on PU foams of relative density 0.58. It was found that the foam becomes increasingly brittle with temperature decreasing. The Young's modulus was found to increase as the temperature decreases, likewise the maximum stress which almost doubles between room temperature and −65 °C. It was reported that the plastic plateau disappears with decreasing temperature, and that the failure strain is less important as the material becomes more brittle. The behavior in AE at room temperature and at −10 °C was found almost identical, where acoustic activity begins late when the material is already in the plateau stage and a divergence of the number of AE events occurs at the end. On the contrary, for the tensile tests at −30 °C and −60 °C the AE activity was found to start at the very beginning, indicating the early occurrence of damage. The number of events rises gradually as the load increases.

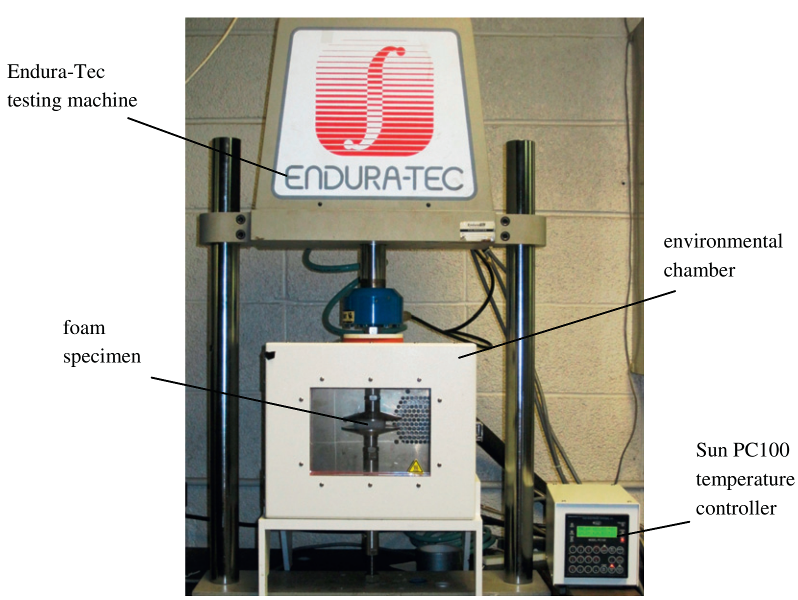

Fig. 1. Experiment setup showing environmental chamber and temperature controller.