A HONEYCOMB STRUCTURE ENHANCED BY NANOPOROUS MATERIAL FUNCTIONALIZED LIQUID

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1 Introduction

Developing advanced energy absorption materials and structures (EAMS) is of both fundamental scientific interest and great technological importance. As an EAMS is subjected to external loadings, the associated kinetic and strain energies are converted, often irreversibly, to other forms, such as heat, electricity, surface/interface tension, etc., based on which protection or damping devices, e.g. car bumpers, soldier armors, blast resistant layers, can be developed.

Due to its high energy absorption efficiency, cellular structure is one of the most attractive EAMS. Commonly used cellular structures include space filling foams and their two-dimensional counterparts, honeycombs, which are lightweight and can be made with relative ease by all major material categories. In these materials, performance is optimized by geometric arrangement of the solids in space to form interconnected or isolated cells. When compressive loadings are applied, the cell walls can buckle, which is the primary energy absorption mechanism. They are widely applied for shock mitigation, packaging, as well as cushioning. Comprehensive reviews of cellular structures have been given by a number of researchers.

Honeycomb is one of the most widely applied cellular structures. One of the major difficulties in further improving its energy absorption properties is that during the buckling process the working load is highly non-uniform, especially when the honeycomb is subjected to an out-of-plane loading. Very often, especially for a thin-walled structure, the wavelengths of wrinkles in cell walls are much smaller than the structural size. Initially, as the cell wall is straight, buckling initiation demands a large stress. As the cell wall becomes locally sigmoidal, the critical stress for the expansion of wrinkled zone becomes much lower. That is, while the cell-wall buckling is activated at a high stress level, the major portion of the energy absorbing process, which dominates the overall energy absorption efficiency, takes place at a relatively low stress level, significantly lowering the overall protection/damping capacity.

One method to solve this problem is to reinforce the honeycomb by a filler, particularly, a liquid filler. The mechanical property of liquid-containing cellular structures has been an active research area. Usually, compared with the network material, the liquid is of a relatively low weight density, and thus the structure is still lightweight. Moreover, the liquid can spontaneously fit well with the cell wall, avoiding possible problems of filler-network mismatch. The thermal, electrical, and magnetic properties of the structure can also be adjusted in broad ranges. However, since most of liquids are nearly incompressible and therefore cannot accommodate the cell-wall buckling, the liquid filled honeycomb often becomes rigid; that is, the major advantage of being cellular is lost.

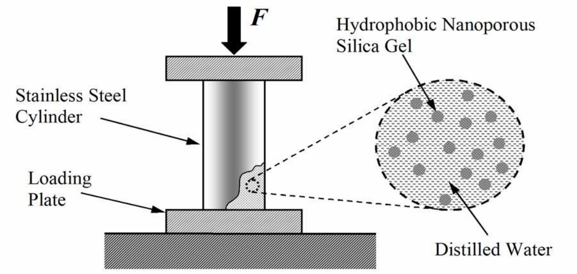

Fig.1 A schematic of the experimental setup.

Recently, through a set of pressure induced infiltration experiments [1-3], an energy absorbing, nanoporous material functionalized (NMF) liquid was developed. The system is formed by immersing a lyophobic nanoporous material in a liquid. Due to the capillary effect, the liquid can enter the nanopores only when a sufficiently high pressure is applied. Under the high pressure, as the large nanopore surface is exposed to the infiltrated liquid molecules, a significant portion of the external work is converted to the solid-liquid interfacial tension. Since the infiltration process is irreversible, i.e. the confined liquid does not defiltrate as the pressure is lowered, this part of energy is effectively "dissipated", leading to a high energy absorption efficiency at the level of 10-100 J/g. Furthermore, due to the pressure induced infiltration, the system compressibility is much larger than that of ordinary liquids. Hence, it is quite feasible to use NMF liquids to enhance honeycomb structures.

2 Experimental Results

To validate this concept, the experimental setup depicted in Fig.1 was developed. The testing system consisted of a thin-walled stainless steel cylinder and a liquid phase sealed inside. Both ends of the cell were fixed on stainless steel loading plates using a J-B Weld epoxy glue. The cell was filled by an aqueous suspension of Fluka 100 C_8 reversed phase nanoporous silica gel. All the sample preparations were performed under water so that no air bubbles were entrapped. The stainless steel cylinder was employed as a close analog to an individual cell at the lateral surface of a honeycomb panel, which, due to the unbalanced pressure across the cell wall, is the most critical section dominating the buckling initiation.

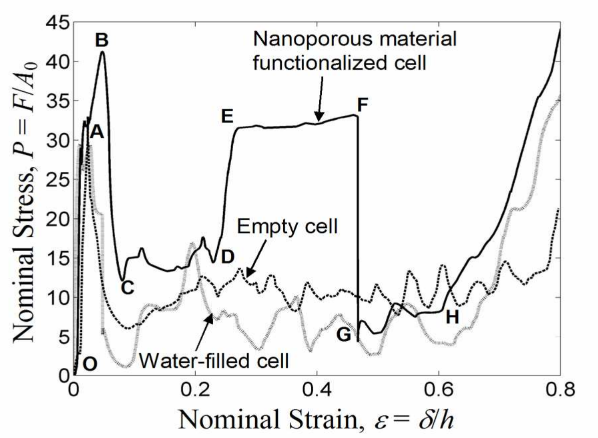

Fig.2 Typical load-displacement curves.

The prepared samples were tested in a type 5569 Instron machine. The compressive load, F, was applied and measured by an Instron 50KN loadcell and the displacement, δ, was measured by a linear variable displacement transducer. The crosshead speed was set to 0.5 mm/min. For comparison purpose, empty cells and cells filled by distilled water were also tested. For each type of cell, 3-5 samples were analyzed. Figure 2 shows typical stress-strain curves, where the nominal stress is defined as $P = F/A_0$, and the nominal strain is defined as $\varepsilon = \delta/h$, with A_0 being the cross-sectional area of the cylinder.

The solid curve in Fig.2 indicates the behavior of a cell filled by the NMF liquid. As the liquid phase starts to carry load, the nominal stress increases from "D" to "E". The effective stiffness of the system in this section is about the same as that in the initial linear compression stage, which is dominated by the modulus of elasticity of cell wall and the bulk modulus of water. When P rises to 32 MPa, the pressure induced infiltration is activated in the nanopores that remain unoccupied during the first loading. The energy absorbed by the NMF cell is 16.7 J. The mass and the volume of the NMF cell are 1.20 g and 940 mm^3, respectively. Hence, the mass based energy absorption efficiency, U/m, is 13.9 J/g, and the volume based energy absorption efficiency, U/V, is 17.8 J/cm^3. Compared with the energy absorption efficiency of an empty cell, the former is more than 20% higher and the latter is more than two times higher. That is, using NMF liquid can significantly enhance the energy absorption performance of the steel tube. Based on this technique, either structures of higher energy absorption capacities or structures of smaller sizes and masses can be designed.

It is clear that more detailed study on the rate dependence and the aggregate behaviors of multiple cells must be carried out to more accurately characterize the system performance and the interactions among the cell wall, the nanoporous gel, and the pressurized liquid phase. Nevertheless, the experimental data of the single-cell systems have provide a proof-of-concept result that the energy absorption efficiency of a honeycomb can be improved by using nanoporous material functionalized liquids. The energy absorption is achieved via cell-wall buckling, extended yielding, as well as pressure-induced infiltration. The buckling process is highly nonuniform.

References

[1] X. Kong, F. B. Surani, Y. Qiao, *J. Mater. Res.* **20**, 1042 (2005)
[2] F. B. Surani, Y. Qiao, *J. Mater. Res.* **21**, 1327 (2006)
[3] F. B. Surani, Y. Qiao, *Mater. Res. Innov.* **10**, 129 (2006)