MECHANICAL AND SELF-SENSING PERFORMANCE OF SELECTIVELY LASER SINTERED CNT/PA12 HONEYCOMBS SUBJECT TO MONOTONIC AND CYCLIC COMPRESSION

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Keywords: 3D printing, Selective laser sintering, Strain sensing, Damage sensing, Multifunctional composite.

Abstract

Architected cellular materials, also known as lattice structures, have attracted significant interest from researchers in recent years due to their unique mechanical and functional characteristics. Among various types of cellular structures, honeycombs are widely studied as core materials for sandwich structures in different fields due to their high weight-specific stiffness and strength, as well as excellent energy absorption and thermal insulation properties. Honeycombs can support loads in multiple directions, and their mechanical properties are highly anisotropic, which can be beneficial in a range of applications.

In recent times, there have been rapid advancements in the fabrication of lightweight cellular fiber composites, especially through 3D printing methods. Depending on the fiber concentration and processing conditions, polymer-based composites may contain manufacturing defects at different length scales which can limit the performance and lifetime of a component, particularly under cyclic loading. Hence, real-time monitoring of the material condition is essential for spotting early signs of damage and enabling prompt remedial action. An innovative approach for structural health monitoring is to integrate the sensing function into the material itself. This is often achieved by adding highly conductive fillers to the polymeric base material which form a percolating network whose electrical resistance is highly sensitive to the induced deformation. Carbon nanotubes (CNTs) have been widely used as functional fillers in polymers to create electrically conductive and piezoresistive polymer composites due to their remarkable electrical properties and high aspect ratio which facilitates the formation of conductive networks at low nanofiller concentrations.

To explore the feasibility of integrating self-sensing capabilities in honeycomb structures, this study examines the mechanical and piezoresistive attributes of selectively laser-sintered CNT/PA12 honeycomb structures under both monotonic and cyclic compressive loading. The honeycomb structures considered herein are composed of hexagonal unit cells with different relative densities (20%, 30%, 40%), and are fabricated through 3D printing of ball-milled CNT/PA12 nanocomposite powder with 0.3 wt.% CNTs. The process parameters (laser power, scan speed and print bed temperature) are fine-tuned to obtain samples with high surface quality and minimal porosity.

Microstructural observations show that the cell walls of the CNT/PA12 honeycomb structures had a higher porosity as compared to the neat PA12 honeycombs. The CNT/PA12 composites were printed at a lower bed temperature than the neat PA12 to avoid undesired fusion of particles in the non-laser irradiated powder bed (also known as hard caking) which contributed to the increased porosity in the composite. Consequently, the CNT/PA12 honeycombs show reductions in both in-plane and out-of-plane mechanical properties (i.e. elastic modulus, collapse strength and energy absorption), particularly at higher relative densities (30% and 40%). Under in-plane loading, the collapse of the honeycomb structures is triggered by the formation of plastic hinges near the nodes, while under out-of-plane loading, the structures collapse by localized buckling and wrinkling of the cell walls. In most tests, the samples exhibit relatively flat and stable stress plateaus, and achieve energy absorption efficiencies up to 53% and specific energy absorption capacities up to 24 J g^{-1}.

Regarding self-sensing performance, the CNT/PA12 structures demonstrate exceptional strain sensitivities within the linear elastic region, reporting gauge factors of up to 25. However, their capacity to monitor damage progression during the collapse phase is limited under monotonic loading due to the percolation of contacts across the collapsed cell layers, mitigating the damage-induced elevation in electrical resistance. Nevertheless, cyclic tests with incrementally increasing strain amplitudes show that the zero-load resistance increases significantly during the collapse phase and corresponds well with the progression of damage in the cellular structure, due to the lack of contact percolation in the unloaded state. This allows concluding that reliable monitoring of material damage in cellular or porous structures can only be performed when the structure is fully unloaded. Moreover, the nanocomposite lattice structures show a stable and reliable piezoresistive response when subjected to 100 repeated compression cycles at low strain amplitudes ($\leq$ 1%), suggesting that the developed nanocomposite structures exhibit considerable promise for use in smart lightweight structures equipped with integrated functionalities for strain and damage sensing.