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Low velocity impact and quasi-static in-plane loading on a graded honeycomb structure; experimental, analytical and numerical study

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ABSTRACT

Through the increasing development of technology in different industries, and the integral requirement of energy absorption, light shock absorbers such as honeycomb structure under in-plane and out-of-plane loads have been in the center of attention. The purpose of this research is to analyze the behavior of graded honeycomb structure (GHS) under low-velocity impact and quasi-static loading. To begin with using the lower-bound theorem, an analytical equation for plateau stress is represented, taking power hardening model into consideration. To compare the acquired analytical equations, empirical tests are conducted on test specimens made of aluminum 6061-O, under previously mentioned loading. Uniaxial tensile tests on each row material are performed to collect data on material properties. The low-velocity and quasi-static tests are conducted with Drop-weight and Santam compression machines, respectively. The quasi-static test is conducted to study the strain rate effect on behavior of the structure. Two experimental tests are simulated in ABAQUS/CAE. Based on the conducted comparisons, the numerical and analytical results indicate a satisfactory agreement with experimental results. Given the performed comparison between experimental and numerical mode shapes, a "V" deformation mode is distinguished for test specimen.

1. Introduction

Owing to the rapid development in automotive, transportation and aeronautics engineering, analyzing the energy absorption capacity in structures has became an important field of research. During the last decade, various materials and structures with high specific absorbing energy such as graded honeycomb structure and thin vessel structures have been studied [1,25]. One of the main applications of the cellular materials is in structural protection, due to their superior energy absorption and impact resistance. The basic applications pertaining to these characteristics are packaging of fragile components, with electronic devices as a dominant case, and various protective products such as helmets and shielding. Another emerging application is using cellular structures as, the core material for metal sandwich panels, which are proved to have superior performance over the counterpart solid plates of equal mass under shock loading [6,16,21,32,33].

In the quasi-static regime, the crushing response of most metal cellular structures indicates a typical stress–strain curve, including three regimes: an elastic response followed by a plateau regime with almost constant stress and eventually a densification regime of sharply rising stress [13,20]. The most important characteristic of graded honeycomb structures is that by changing the geometrical parameters of the structure such as height, thickness, cell size and inner angles, different mechanical characteristics could be obtained [2]. Low velocity impact can be treated as a quasi-static event, the upper limit of which can vary from 1 to 10 $\mathrm{m\,s^{-1}}$ depending on the target stiffness, material properties, and the impactor mass and stiffness [30]. Cantwell and Morton [4] classified low velocity up to 10 $\mathrm{m\,s^{-1}}$ by considering test techniques including Charpy, Izod and instrumented falling weight impact testing. Liu and Malvern [17] suggested that the type of impact can be classified according to the damage incurred. Abrate [1] and Robinson and Davies [29] defined a low-velocity impact as being one in which the through-thickness stress wave does not play any significant role in the stress distribution, and suggested a model to determine the transition to high velocity. A cylindrical zone under the impactor is considered to undergo a uniform strain as the stress wave propagates through the plate, resulting a compressive strain $\varepsilon_c = \frac{V_i}{V_s}$, where V_i is the impact velocity and V_s is the speed of sound in the material. For compressive strains below 1%, the low velocity condition can be considered. The speed of sound in a material is $V_s = \sqrt{\frac{E}{\rho}}$, where E and ρ are modulus of elasticity and density of the material, respectively.

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Nomenclature

GHS	Graded Honeycomb Structure
A	Cross section area of GHS perpendicular to loading direction
b	Depth of GHS cell
c	Cell horizontal wall length
d	Cell wall thickness
e	Specific absorbed energy
e_f	Elongation
K	Coefficient of strain-hardening relation
L	Height of GHS
l	Cell inclined wall length
W	Width of the GHS
m	GHS mass
m_c	Mass of each cell
M_p	Fully plastic moment
n	Strain-hardening index
u	Strain energy per unit mass
U	Strain energy
V	Volume of GHS
V_c	Volume of each cell
y	Distance from neutral axis
σ_u	Ultimate stress
σ_y	Yield stress
σ_p	Plateau stress
ρ^*	Density of honeycomb structure
ρ_s	Density of honeycomb structure material
ε	Bending strain
ε_c	Compressive strain
ε_d	Locking strain
ϕ	Cell wall angle
ψ	Inclined wall rotation

The main purpose of energy absorbers is reduction the effect of impact load by its distribution within a time period. The main characteristics of energy absorbing cellular structures are absorbing energy in an irreversible manner, reducing reactive load, undergoing repeatable deformation mode, being compact, being light in weight, and having higher specific energy absorption capacity, being inexpensive and the ease of installation. The common forms of cellular structures are (1) open cell structures in which cells are arranged in a two dimensional regular or irregular array, and (2) closed cell structures in which plates are inter-connected and formed three dimensionally, partially open or closed with regular or irregular shaped cells. Honeycomb structures, considered as one of the primary shock absorbers, are widely used in automotive, aeronautics and packing industries. Scientifically speaking, banana peel which is a Functionally Graded Material (FGM) is a type of energy absorber [22]. Moreover, the human and bird bones are natural shock absorbers. The cancellous structure of bone leads to the absorption of applied shock as well as the reduction of bearing stress in joints [24]. Extensive research has been conducted in understanding the in-plane and out-of-plane behaviors of honeycombs. Deqiang et al. [5] analyzed the behavior of this type of structure under impact loads using LS-Dyna software. Song et al. [31] used a finite element model where the values of plateau stress and strain energy were obtained to investigate the influence of cells shape, impact load, relative density and strain hardening on the deformation mode and plateau stress. The results indicated that the values of plateau stress and energy absorption increased with a raise in cells' irregularity. Zou et al. [36] analyzed the in-plane dynamic destruction of regular honeycomb structures using FEM, and compared the obtained plateau stresses by analytical and numerical methods to each other. They also studied different mechanisms of structure cells deformation, and represented the stress-velocity diagrams. Ajdari et al. [3] analyzed the dynamic destruction behavior and the value of energy absorption in regular, irregular and FG honeycomb structures. They studied different modes of deformation and the value of energy absorption in these structures by FEM. Papka and Kyriakides [26,27] studied the load–displacement response of hexagonal-cell aluminum honeycombs, as well as circular polycarbonate honeycombs under in-plane uniaxial loading. They observed various deformation patterns (modes), which were related to the particular ratio between the components of the applied displacements or forces. Galehdari et al. [8,9] have compared the time history of reaction force of two honeycomb structures, i.e. the graded and with the same thickness. In another article, they have studied the effect of power hardening model for the GHS material on the plateau stress. Moreover, an optimization method has been introduced to maximize the specific absorbed energy. Fan and Zou [7] have studied the functionally graded honeycomb structures with defects. In this paper, the patterns and locations of defects, as well as the density gradients which affected the in-plane dynamic crushing behavior of honeycombs were studied. Based on the numerical results, the energy-absorption curves for systems with positive and negative densities were symmetric about the homogeneous structures. As the compression proceeds, for the honeycombs with positive and negative density gradients, the trends of energy-absorptive abilities went into reverse. Gunes et al. [12] investigated the damage mechanism and deformation of honeycomb sandwich structures reinforced by functionally graded plates under ballistic impact effect by means of explicit dynamic analysis using ANSYS LS-DYNA. The effect of material composition of functionally graded facesheets on the ballistic performance of honeycomb sandwich structures was investigated and the penetration and perforation threshold energy values which were the most considerable parameters on ballistic performance and ballistic limit of the sandwich structures were determined. Ghalami-Choobar and Sadighi [10] have investigated the high velocity impact response of sandwich specimens with FML skins and polyurethane foam by experimental and numerical approaches. The 3D finite element code, LS-DYNA was used to model impact of cylindrical projectile with clamped boundary condition. The results show the facesheets have major contribution on energy absorption of the sandwich specimens. Moreover, increasing core density did not significantly change absorbing energy in comparison with the effects of other parameters.

Muhammad et al. [23,24] simulated the behavior of graded honeycomb structure under impact load and presented an analytical equation for dynamic plateau stress corresponding to high velocities. The results of analytical equation were compared to those of numerical solution. In addition, to reduce the layer thickness in direction of panel sandwich thickness, the material hardness was also decreased. In another study, they investigated the in-plane response of the graded structure under medium and high velocity impacts. Different critical energy absorbing characteristics, e.g. deformation modes, collapsing mechanism, crushing stress, locking strain and total energy absorbed have been discussed. In above mentioned studies, the ideal elastic-perfectly plastic material model has been used to derive the plateau stress and specific energy of structure. However, a relatively large difference has been noticed between numerical and analytical results [22]. Zhu [35] has studied the large deformation pure bending of a wide