International Journal of Impact Engineering 108 (2017) 153–170

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

On the dynamic compression of cellular materials with local structural softening

D. Karagiozova[a,*], M. Alves[b]

[a] Institute of Mechanics, Bulgarian Academy of Sciences, Acad. G. Bonchev St., Block 4, Sofia 1113, Bulgaria
[b] Group of Solid Mechanics and Structural Impact, Department of Mechatronics and Mechanical Systems Engineering, University of Sao Paulo, Sao Paulo 05508-900, Brazil

ARTICLE INFO

Article History:
Received 31 December 2016
Revised 6 April 2017
Accepted 7 April 2017
Available online 8 April 2017

Keywords:
Metal honeycomb
Structural softening
Out-of-plane impact
Inertia effects
Shock wave
Energy absorption

ABSTRACT

Analytical and numerical analyses are carried out in order to reveal the importance of the cellular materials topology for their dynamic compaction. The aim is to distinguish between the deformation and energy absorption mechanisms of materials which exhibit local structural softening, such as out-of-plane loaded honeycomb, and materials with local structural hardening (foam). It is shown that the dynamic out-of-plane compaction of honeycombs does not obey the law of shock wave propagation and a new phenomenological model of the velocity attenuation is proposed. It is revealed that the absorbed energy by the honeycomb is proportional to the area under the dynamic stress-strain curve, which is defined by the foil material properties, in contrast to the shock-wave propagation model where the absorbed energy is proportional to the area under the shock chord. Comparisons with the predictions of the Rigid Perfectly-Plastic Locking (RPPL) model, which approximates well the average quasi-static stress-strain characteristic of a honeycomb, are discussed. Special attention is given to the effects of neglecting the honeycomb topology on their response to impact loading.
Finite element simulations are carried out to verify the proposed theoretical model revealing the major factors which influence the dynamic response of out-of-plane loaded honeycombs to high velocity impact.

1. Introduction

Cellular materials, including metallic honeycombs and foams, are often used as structural sandwich components in transportation industries due to their high strength to weight ratio and good energy absorption capacity. Ample studies on the quasi-static and dynamic compression of these materials have been conducted to reveal the relations between the relative density, plateau stress and dynamic stress enhancement due to the loading rate. Numerous experimental and numerical studies revealed the inertia sensitivity of metal-based foam with different topologies and metallic honeycombs [1–6], which is the major reason for their increased dynamic strength.

Despite the large number of studies on the dynamic stress enhancement and energy absorption of cellular materials with different topologies however, a limited number of theoretical studies on the influence of the local structural softening response of the cellular materials on their dynamic characteristics has been reported. Since the pioneering work of Reid and Peng [1], major attention in the theoretical analyses has been paid to the modeling of the dynamic compaction of cellular materials which do not exhibit structural local softening (foam, metal hollow sphere, in-plane loaded honeycomb, etc.). The dynamic response of these materials is well described by the shock wave propagation theory when models based on the pre-defined densification strain [1,7] or velocity dependent densification strain [8–10] were used in the analysis.

A theoretical analysis of the out-of-plane compression of hexagonal metallic honeycomb was carried out by Wierzbicki [11] in order to predict the quasi-static plateau stress of these materials. The proposed closed form solution is based on the deformation mechanism of the honeycomb and the plateau stress is obtained as a function of the base material properties and honeycomb geometry. Subsequent experiments on out-of-plane impact loading of honeycombs revealed that their dynamic plateau stress is higher than that under quasi-static loading. Goldsmith and Louie [2] reported experimental works on out-of-plane crushing and on the ballistic perforation of honeycombs where it was shown that the mean crushing load sometimes increases by up to 50% compared to the static results. Zhao et al. [3] have also found the similar phenomenon for metallic honeycombs with an enhancement ranging from 10% to 50%. Dedicated analyses of the strength increase of out-of-plane loaded honeycomb were also reported, for example, by Deqiang et al. [4], Xu et al. [5] and Hu et al. [6].

* Corresponding author.
E-mail address: d.karagiozova@imbm.bas.bg (D. Karagiozova).

http://dx.doi.org/10.1016/j.ijimpeng.2017.04.007
0734-743X/

Despite the increased application of honeycombs as core materials in sandwich structures and analysis of their response to different types of loading, e.g., [12–14], the existing theoretical analyses of the dynamic compression of cellular material with structural softening are rather limited. The theoretical studies are usually limited to the best-fit approximation of the dynamic stress based on numerical simulations [4] and experimental results [5] or the propagation of a shock wave is *a priori* assumed [6] in order to estimate the dynamic stress enhancement.

In general, the deformation of the quasi-statically in-plane loaded honeycomb with relatively thin walls are characterized by local bending deformations while more localized plastic deformations associated with the development of plastic hinges at the connections between the adjacent walls are observed in honeycomb with thicker walls. In both cases, the local force-displacement curve under a uniaxial compression is an increasing function reaching eventually a constant value. This response type is recognized as “Type I” structure [16]. This type of behavior could be also associated with the compressive behavior of rings, spheres, etc. When loaded dynamically, these cells respond by the same type of the load-deflection curve locally while reaching higher values due to some inertia effects. Therefore materials containing cells, which are characterized by a local deformation behavior resembling the “Type I” structural response, are referred to as materials with local structural hardening in the present study.

On the other hand, the response of out-of-plane compressed honeycomb is associated with the behavior of the so called “Type II” structures [16] which tend to develop a higher peak load before the load drops during the formation of the particular buckle and fold. Materials containing cells, which are characterized by a local deformation behavior resembling the “Type II” structural response, are referred to as materials with local structural softening.

Indeed, an effect due to the eventual shock front propagation cannot be anticipated in the material with local structural softening, as it was pointed out in [1]. Experimental tests on the dynamic compression of honeycomb made of aluminum alloy AA5052 and 3003 accompanied by a thorough numerical analysis [15] revealed that the lateral inertia in the successive folding of thin-wall tube structures can explain the observed dynamic enhancement of the out-of-plane crushing pressure and it is the major reason for this phenomenon. Dynamic enhancement from 10% to 60% of the out-of-plane crushing strength was reported for the analyzed honeycomb in [15].

The aim of the present study is to explore the differences between the compaction and energy absorption mechanisms of cellular materials with local structural softening and structural hardening. It should be noted that the studies on the impact response of cellular materials are often related to a constant impact velocity. While these analyses can reveal some dynamic characteristics of the cellular materials, their application to real loading situations is rather limited. The analysis of the dynamic loading due to a mass impact or blast often requires an estimation of the velocity attenuation and force transfer to the distal end of the structure. From this prospective, it is important to analyze the response of honeycomb configurations that are able to entirely absorb the initial kinetic energy. For example, an intense uniform blast on a protective structure comprising a thin cover plate and a cellular material core can be modeled as a small mass impact having a high initial velocity V_0. In this scenario, the velocity of the cover plate will vary between V_0 and zero while the initial kinetic energy is absorbed by the compression of the cellular structure for optimized thicknesses of the cover plate and core. For that reason, the analysis of an impact by a relatively small mass can be of a practical importance and it will be the focus of the present study.

2. Observations from the numerical simulations

From a macro-structural point of view, the averaged quasi-static stress-strain characteristic of the out-of-plane loaded honeycomb represents a good example of a cellular material with a well-defined constant plateau stress and densification strain [17]. These characteristics satisfy the requirements of the Rigid Perfectly-Plastic Locking (RPPL) material model proposed in [1], so that this model is often used to determine the dynamic strength enhancement of honeycombs in order to estimate theoretically the impact energy absorption. However, the RPPL model is based on the shock wave propagation phenomena for which the conditions on the wave front are well described in [7]. Strong discontinuities of the particle velocity, stress and strain occur at the wave front while the strain and velocity ahead of the wave front remain zero when a high velocity impact acts on a stationary cellular block. Thus, the strain remains virtually zero until the arrival of the shock wave.

Numerical simulations are carried out in order to analyze the dynamic compression of low density honeycomb and to verify the assumptions of the RPPL model with respect to the dynamic honeycomb response. Hexagonal honeycomb with branch angle of 120° (Fig. 1a) and out-of-plane thickness $L = 0.1$ m is compressed in the longitudinal direction due to an impact of a rigid mass with initial velocity V_0 when the distal end of the honeycomb block is stationary.

Honeycombs with material and geometrical characteristics close to the commercially available honeycomb materials [18] have been selected for the analysis. In addition, the quasi-static strength of some analyzed honeycomb configurations ware selected to be comparable to the strength of a cellular material with significantly different topology (foam) in order to reveal the importance of material topology. Strain rate insensitive aluminium alloys with density $\rho_{Al} = 2700$ kg/m^3, Young’s modulus $E = 70$ GPa, Poisson’s ratio 0.35 are used as foil materials. Several honeycomb configurations are analyzed in order to examine the influence of the hardening characteristic of the base material and cell size on the velocity attenuation and energy absorption of honeycomb blocks. The geometric and material characteristics of the honeycombs are given in Tables 1 and 2. The aluminium alloy AA5056 has yield stress $\sigma_Y = 435$ MPa and hardening modulus $E_h = 575$ MPa while $\sigma_Y = 325$ MPa and $E_h = 464$ MPa characterize the aluminium alloy AA5052. The strain hardening of AA5056 is artificially neglected for the honeycomb configurations given in Table 2 thus assuming an elastic perfectly plastic base material. The honeycomb density is defined by the cell geometry as [11]

$$\rho_0 = \frac{8}{3\sqrt{3}}\frac{h}{D}\rho_{Al} \tag{1}$$

and the relative honeycomb density in Tables 1 and 2 is $\rho* = \rho_0/\rho_{Al}$. Honeycombs having three different relative densities are analyzed. The honeycombs marked as F56 ($D = 2.75$ mm, $h = 0.0255$ mm) and G56 ($D = 5.5$ mm, $h = 0.051$ mm) are made of aluminium alloy AA5056 and have relative density of 0.0143; honeycombs A56 ($D = 5.5$ mm, $h = 0.08$ mm) and D56 ($D = 2.75$ mm, $h = 0.04$ mm) made of aluminium alloy AA5056 and A52 ($D = 5.5$ mm, $h = 0.08$ mm) made of aluminium alloy AA5052 have relative density of 0.0224; honeycombs B56 ($D = 5.5$ mm, $h = 0.127$ mm) made of aluminium alloy AA5056 and B52 ($D = 5.5$ mm, $h = 0.127$ mm) made of aluminium alloy AA5052 have relative density of 0.0355.

FE code ABAQUS/Explicit is used to simulate the quasi-static and dynamic response of the honeycomb. Symmetric boundary conditions in the local in-plane coordinate system are applied to the representative unit in Fig. 1 in order to define the repeatability of this block in the *x-y* plane. No initial imperfections are introduced in the *x-y* plane or longitudinal direction as it was anticipated that the influence of the initial imperfections can be disregarded for the purposes of the present study. In fact, the major effect that the initial