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Stress waves in layered cellular materials—Dynamic compaction under axial impact

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, SP, Brazil

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ABSTRACT

Theoretical analysis of the propagation of stress waves in layered cellular solids with different densities, and consequently strengths, is carried out to deepen the understanding of their dynamic compaction due to impact loading. The cellular topology is neglected and homogeneous properties are assumed. Two types of plastic waves are distinguished depending on the layers density arrangement. Only waves of strong discontinuity occur when the layers' densities increase in the direction of propagation of the primary wave. Multiple reflections of the stress waves from the layer interfaces are identified and studied for this type of the layers density arrangement. Simultaneous propagation of a wave of strong discontinuity in the proximal layer and a simple wave in the subsequent layers occur when the layers' densities decrease in the direction of propagation of the primary wave.

Two types of loading conditions: an impact of a stationary cellular block by a rigid mass and an impact of a cellular block on a rigid wall are analysed. It is assumed that the constituent materials in the layered solids exhibit strain hardening. The plastic strain is sought as a function of the impact velocity and material properties when using the characteristic Hugoniot strain–velocity relationship. FE models using ABAQUS are constructed and numerical simulations are carried out to verify the predictions of the theoretical analysis. The potential of layered cellular materials to design more efficient structural components when subjected to intensive dynamic loading is briefly discussed when comparing the response of some layered configurations with their uniform density counterparts of equal mass.

1. Introduction

There has been a growing interest in the recent years in finding design solutions for efficient energy absorbing lightweight structures and materials. In particular, the response of sandwich structures, comprising two layers of stronger materials (metals or polymers) and soft core, to quasi-static and dynamic loading have been extensively studied. It became clear that the core material properties play a crucial role in the dynamic behaviour of sandwich structures when they are subjected to intensive loading as blast or impact. Therefore, the responses of sandwich components comprising e.g., metal foams and honeycomb [1–4], polymer foams [5,6], truss and corrugated plate structures [7–9], etc. have been examined. The overall conclusion based on the behaviour of various sandwich structures is that they outperform the response of their monolithic counterparts under uniform dynamic load. However, the response of sandwich components to localized load is not always in favour of these structures and the stress–strain characteristics of the core become more important.

In order to control better the core response to a compressive load, core materials with non-homogeneous properties including density graded materials – continuous or stepwise – have been recently receiving an increasing attention. Since the material properties can vary gradually or layer-by-layer within the core material, sandwich composites can be designed to achieve higher energy absorption efficiency thus improving the overall blast resistance of sandwich and protective structures. Studies have been reported on different kinds of graded materials like polyurethane [10], polypropylene [11], polystyrene [12,13], syntactic epoxy [14], polymeric hollow sphere agglomerates [15].

The behaviour of sandwich composites with stepwise graded core under low-velocity impact was studied in [10] where it was shown that a reasonable core design can effectively reduce the shear forces and strains within the structures. Consequently, structures with such layer arrangement can mitigate or completely prevent impact damage on sandwich composites.

Shock tube experiments were performed to study the dynamic response of layered sandwich panels with E-Glass Vinyl Ester

* Corresponding author. Tel.: +359 2 979 6482; fax: +359 2 870 7498.
E-mail address: d.karagiozova@imbm.bas.bg (D. Karagiozova).

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composite face sheets and stepwise graded styrene foam cores [13] where the importance of the sequence of the layers' density was demonstrated. The core layers were arranged according to the density of the respective foam; configuration 1 consisted of low/middle/high density foams and configuration 2 consisted of middle/low/high density foams. The experimental results showed that configuration 1 outperformed configuration 2 in regards to their blast resistance. Significant core material compression was observed in configuration 1 which led to a reduced dynamic pressure on the back face sheet. In configuration 2, the core compression was limited, and thus the specimen showed a heavy amount of damage.

A study on the response of graded polymeric hollow sphere agglomerates with various density gradient profiles to a quasi-static and dynamic compressive loading was reported in [15]. It was found that the density gradient profile had a rather limited effect on the energy absorption capacity for the loading velocities up to 50 m/s used in the tests. A numerical model was built to examine the response to higher impact velocities when the influence of the density gradient was established. This study showed that placing the hardest material as the first impacted layer and the weakest material as the last layer has some benefits in terms of maximum energy absorption with a minimum force transmitted to the protected structure.

In order to explore the properties of non-homogeneous foam beyond the available materials, numerical models were developed to study the properties and loading response of these materials. Models of two dimensional graded Voronoi structures were used in [16] to examine the effective elastic modulus and yield strength. It was observed that the overall elastic modulus of functionally graded structures was more sensitive to density gradient than the overall yield strength. Moreover, the yield stress is a strong function of applied stress in the gradient direction and independent off applied stress in the not graded direction.

Numerical analysis was also used in [17] to examine the influence of the foam density gradient on the energy absorption of graded materials when subjected to various impact energies. It was shown that functionally graded foam can exhibit superior energy absorption over equivalent uniform foams under low energy impacts, and that convex gradients perform better than concave gradients. This advantage is however negated when the impact energy becomes significantly high such that low-density regions of the graded foam become ineffective at bearing the higher load and they densify after absorbing only a small fraction of the total energy.

The dynamic response and blast resistance of all-metallic sandwich panels with multi-layered aluminum foam cores were studied in [18] using finite element simulations and compared with those of ungraded single-layer sandwich plates. The results demonstrated that relative to conventional ungraded panels subjected to identical air blast loading, the graded plates possess smaller central transverse deflection and superior blast resistance when the layers density decreases from the front sheet to the back sheet of the panel.

The above experimental and numerical studies show that a winning strategy in terms of more absorbed energy with a low transmitted force could consist of placing the "hardest" layer as the first impacted layer and the "weakest" layer in contact with the protected structure to reduce the transmitted force. However, the reported studies on dynamic loading of density graded foam suggest that the advantages of using density graded foam are not always obvious, particularly when a high intensity load is applied [17] and substantial kinetic energy remains after the core compression. Therefore, a better understanding of the process of compaction and force transfer between the layers and to the distal end of the graded material would assist the selection of the layers arrangement for optimized energy absorption.

Theoretical analysis was carried out to reveal the phenomena related to the dynamic compaction of cellular rod with non-homogeneous properties considering a finite length strength-graded rod [19] and density graded rod [20] subjected to an impact loading. A simultaneous compaction was revealed in the case of a negative gradient while the propagation of a single compaction wave was observed in rods with a positive gradient. The analytical results indicated that the negative gradient weakened the capacity of energy absorption while positive gradient had a little influence.

Although easier to produce, a graded layer-by-layer cellular structure can respond to dynamic compression in a considerably more complex manner in compassion with the continuously graded one. A large strength disparity between the layers can lead to a significant stress increase at the layer interfaces as shown in [21], which could be a reason for damage as observed for the particular layer arrangement reported in [13].

In the present paper, a theoretical analysis of the dynamic compaction of layered cellular solids is carried out to deepen the understanding of their response to a high velocity impact. The analysis is based on the propagation of compaction waves when using the characteristic Hugoniot strain–velocity relationship [19]. Multiple reflections of the stress waves from the layers interfaces are analysed in order to better understand the phenomena at these interface. Two types of loading conditions: an impact of a stationary cellular block by a rigid mass and an impact of a cellular block on a rigid wall are examined in the present study.

FE models using ABAQUS are constructed next and numerical simulations are carried out to verify the predictions of the theoretical analysis. Finally, comparison between the responses of some layered configurations with their uniform density counterparts is discussed.

2. General characteristics of the analysed cellular solids

The theoretical analysis is carried out of the uniaxial compression of layered cellular materials with piecewise varying density under different loading conditions. The analysis is focused on materials like metal foam and metal hollow sphere agglomerates etc., which do not exhibit local structural softening. The approach based on Hugoniot strain–velocity curves proposed in [22] is used to analyse the compaction of cellular materials with the emphasis on the history and final strains fields within the compacted zones. In contrast to the commonly used concept of a predefined densification strain [23–25], the plastic strain is sought as a function of the impact velocity and material properties. The dependence of the plastic strains behind the wave front on the particles velocity in cellular materials was recently revealed in dynamic tests [26] and numerical simulations [27,28] considering the material microstructure.

No details of the cellular topology are analysed here and it is assumed that the cell size is small in comparison with the analysed layer thickness, so that the studied class of materials can be modelled as a harmonized material which exhibits strain hardening. The stress–strain dependencies for the examined constituent materials of the layered solid are characterized by a strictly concave curve which has a general expression

$$\sigma = g(\varepsilon), \quad g''(\varepsilon) > 0, \quad \varepsilon > \varepsilon_Y \tag{1}$$

where ε_Y is the strain at yield. Curves in terms of nominal stress and strain with characteristics defined by Eq. (1) and used in the current study are presented in Fig. 1. The elastic portion of deformations is neglected and plastic stresses and strains are taken positive in compression.