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Mechanical properties and energy absorption of heterogeneous and functionally graded cellular structures

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Abstract

The crushing behaviour and energy absorption of honeycombs made of a linear elastic-perfectly plastic material with constant and functionally graded density were studied up to large crushing strains using finite element simulation. Our numerical simulations showed three distinct crushing modes for honeycombs with a constant relative density: quasi-static, transition and dynamic. Moreover, irregular cellular structures showed to have energy absorption similar to their counterpart regular honeycombs of same relative density and mass. To study the dynamic crushing of functionally graded cellular structures, a relative density gradient in the direction of crushing was introduced in the computational models by a gradual change of the cell wall thickness. Decreasing the relative density in the direction of crushing was shown to enhance the energy absorption of honeycombs at early stages of crushing. We also developed detailed finite element models of a three-dimensional closed-cell rhombic dodecahedron structure subjected to dynamic crushing. We specifically quantified the distribution of plastic strain and energy absorption of the cellular structure and provided a comparison with the results obtained in analysis of 2-D cellular structures. The results provide new insight into the behavior of engineered and biological cellular materials, and could be used in development of a new class of energy absorbent cellular structures.

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Keywords: Cellular structures; honeycombs; energy absorption; functionally graded material

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1. Introduction

We developed finite element models of honeycomb structures with regular hexagonal cell shape to study their structural response under impact and in-plane crushing using ABAQUS (SIMULIA, Providence, RI). A mesh sensitivity analysis was carried out to ensure that the results are not sensitive to the mesh size. In all the calculations, we assumed the cell wall material to be linear elastic – perfectly plastic with Young's modulus, $E = 70\ GPa$, yield strength, $\sigma_Y = 130\ MPa$, Poisson's ratio, $\nu = 0.3$, and density, $\rho = 2700\ kg/m^3$, which are typical properties of aluminum. For a regular hexagonal honeycomb, the effective yield stress can be calculated from $\sigma_{Yc} = 0.5\,\rho_c^2\sigma_Y$, where ρ_c is the relative density of the honeycomb, defined as the area fraction of the cell walls with respect to the structure's dimensions [1]. In all the calculations presented in this study, the relative density of the honeycombs was varied by changing the thickness of the cell walls.

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2. Dynamic crushing of regular hexagonal honeycombs

To explore the energy absorption of honeycombs under dynamic crushing, we have simulated the honeycomb response under in-plane dynamic crushing at a constant prescribed velocity, V, as shown schematically in Fig. 1A. The honeycomb was clamped along its bottom edge and periodic boundary conditions were imposed at its sides. An important dimensionless parameter which governs the inertial effects is $\bar{V} = V/(c_0 \varepsilon_Y)$, where $c_0 = (E/\rho)^{0.5}$ is the elastic wave speed in the cell wall material, and $\varepsilon_Y = \sigma_Y/E$ [2]. Figures 1B shows the normalized plastic energy dissipation, $\bar{U}_P = U_P/\sigma_{Y_c} AL$ of honeycomb, where U_P is the plastic energy dissipation calculated directly from the numerical simulations for two different crushing velocities, $\bar{V} = 0.32$ and $\bar{V} = 6.35$. At low crushing rates, the normalized dissipated plastic energy increases slightly by increasing the structure relative density. However, all honeycombs have comparable normalized plastic energy absorption. In contrast at high crushing velocities, the normalized plastic energy dissipation of a honeycomb strongly depends on its relative density and is higher for a honeycomb with lower relative density, which is due to dynamic effects and the nonlinearity caused by cell walls contact. In Fig. 1C, we have quantified the normalized plastic energy dissipation of regular honeycombs with $0.01 \leq \rho_c \leq 0.10$, under dynamic crushing. The results are presented in the log-log scale and at $\varepsilon = 0.5$ or 50% crushing. At low crushing rates, $\bar{V} < 1$, the normalized plastic energy dissipation of the honeycomb increased by increasing its relative density. For $\bar{V} > 1$, honeycombs with smaller relative density have remarkably higher normalized plastic energy dissipation at the same level of crushing strain.

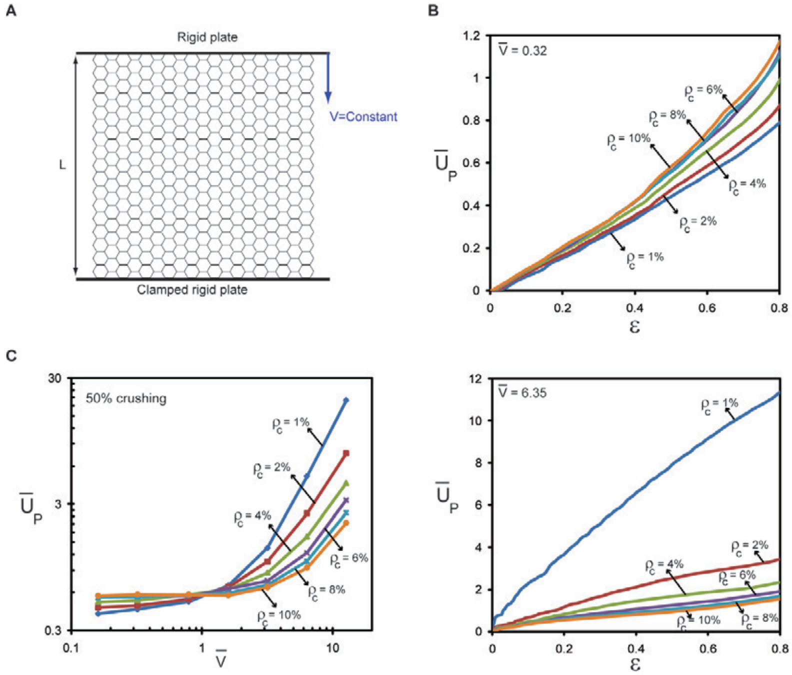

Figure 1 - Dynamic crushing of a hexagonal regular honeycomb. (A) Schematic of the finite element model. (B) Normalized plastic energy dissipation versus the crushing strain for $\bar{V} = 0.32$ and $\bar{V} = 6.35$. (C) The normalized plastic energy dissipation of regular honeycombs versus the normalized crushing velocity at 50% crushing. The results in (C) are presented in the log-log scale.

3. Functionally graded cellular structures

Functionally graded cellular structures are novel class of materials, where variations in cell size, shape and wall thickness results in a functional variation in the relative density and organization of the cellular structure. Examples of functionally graded cellular structures in nature are bamboo, banana peel and elk antler [3,4]. Previous studies on impact resistance and energy absorption of functionally graded cellular structures have shown their potential for creating impact resistant structures and cushioning materials [5,6]. Cui et al. [7] suggested that a functionally graded foam can exhibit superior energy absorption compared to a uniform foam with equal mass. In another effort, Wadley et al. [8] constructed a multilayered pyramidal lattice from stainless steel and investigated the quasi-static and dynamic compressive response of these structures. The developed method allows fabrication of functionally graded cellular structures by varying the relative density of the pyramidal lattice at each layer.

In this study, we constructed finite element models of functionally graded cellular structures by changing the thickness of the cell walls - and thus, the relative density - in the direction of crushing – See Fig. 2A. $\gamma = 0$ gives a honeycomb with constant relative density, and a positive density gradient gives a cellular structure with a relative density that gradually decreases in the crushing direction. The total relative density of the structures was kept constant (here, $\rho_c = 0.05$), as the density gradient is introduced. Figure 2B and 2C show the energy absorption of functionally graded regular hexagonal honeycombs with different density gradients subjected to low velocity and high velocity dynamic crushing. At low crushing velocity ((i.e. quasi-static mode), introducing the density gradient decreases the energy absorption of the honeycombs up to crushing strains ~ 67%, and the honeycomb with $\gamma = 0$, has the maximum energy absorption for this crushing strain range. There are minimal differences between the response of functionally graded honeycombs with positive and negative density gradients, as quantified in Fig. 2B and expected in the quasi-static regime. In contrast at high velocity crushing, the density gradient has a remarkable influence on the energy absorption of the honeycomb (Fig. 2C). Up to ~ 50% crushing, the functionally graded cellular structures with positive density gradient, $\gamma > 0$ - where the cellular structure relative density is high at the crushing side and changes gradually to its lowest value at the clamped side - have higher energy absorption compared to a honeycomb with $\gamma = 0$. The negative density gradient, $\gamma < 0$ results in reduction of the honeycomb energy absorption.

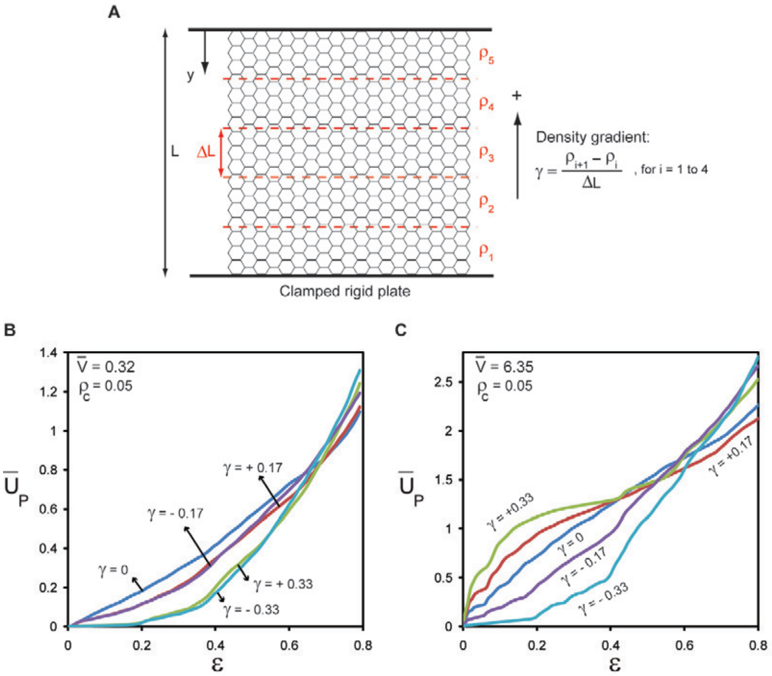

Figure 2 - Dynamic crushing of a functionally graded regular hexagonal honeycomb. (A) Schematic of the model. (B) Normalized plastic energy dissipation versus the crushing strain for honeycombs with different density gradients at low crushing rates, $\bar{V} = 0.32$ and (C) at high crushing rate, $\bar{V} = 6.35$. The overall relative density of the honeycombs were kept constant, $\rho_c = 0.05$.

To explain these observations, we studied the deformation modes and the distribution of equivalent plastic strain of functionally graded honeycombs with $\rho_c = 0.05$ under crushing. In the quasi-static regime, the deformation of the honeycomb with constant relative density is mainly concentrated along two bands, forming the X-Shape. In contrast, for a functionally graded honeycomb, the deformation is limited to the part of the structure with low relative density, while the rest of the structure stays almost undeformed. At high velocity crushing, the deformation mode is quite different: For a regular honeycomb with $\gamma = 0$, the deformation is highly localized to the crushing side thus, only the cells close to crushing side undergo considerable deformation and contribute to the energy absorption of the honeycomb as it gets crushed. For cellular structures with $\gamma < 0$, the deformation mode is similar to that of regular honeycomb with $\gamma = 0$, and since the structure has a lower relative density at the crushing side, its overall energy absorption is even lower than its counterpart honeycomb with $\gamma = 0$. For a functionally graded honeycomb with $\gamma > 0$, the deformation is focused at both crushing and clamped sides of the honeycomb and thus, a higher number of cells deform and contribute to the overall energy absorption of the cellular structure.

4. Three-dimensional closed-cell rhombic dodecahedron cellular structure

In this section, We have studied the crushing behavior of closed rhombic dodecahedron cellular structure (Voronoi tessellation of the face-centered cubic lattice) to understand the response of the structure in broad range of crushing rates and relative densities. The results for this monodisperse structure with 10% relative density are shown in Fig. 3. At low crushing rate (quasi-static mode), the layers of the structure are crushed slowly and X-shape mode is created in 3-direction. By increasing crushing rate (transition mode), crushing is started from the layer close the crushing edge and the X-shape is also created. In the high crushing rates (dynamic crushing) since the plastic wave does not have enough time to propagate through the structure, get to the bottom surface and move back to the top surface, the bottom layers do not deform and just the top layers are crushed in 2-direction. To further understand the deformation mechanism, we have plotted the equivalent plastic strain in the direction of crushing and the results are summarized in Fig. 3B and 3C.

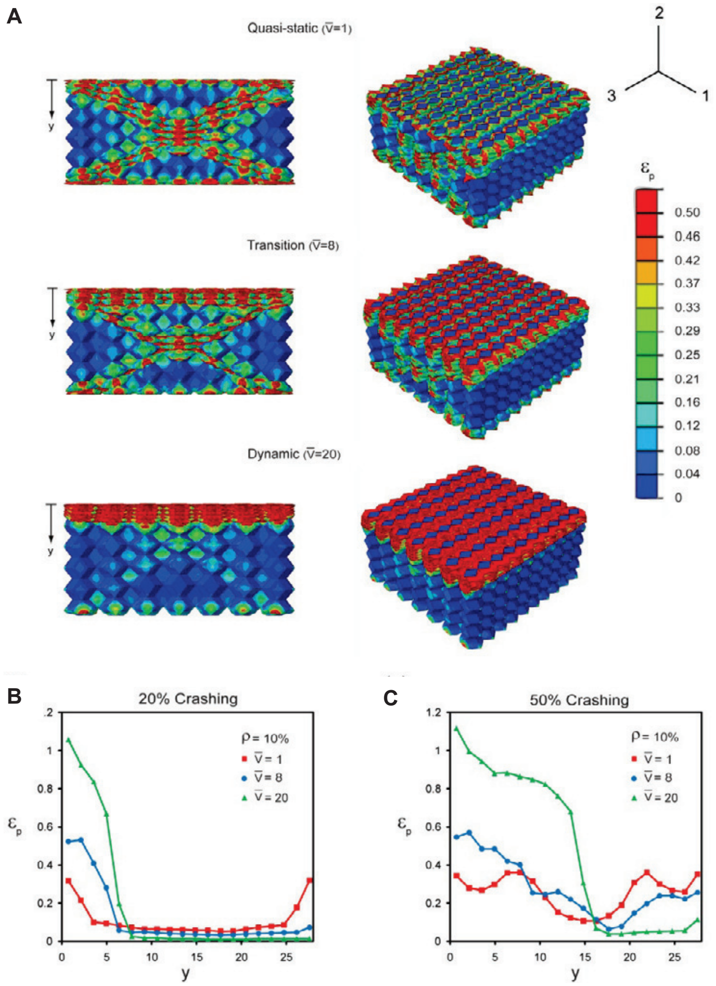

Figure 3 – (A) Deformation modes of a closed Rhombic dodecahedron cellular structure at 50% crushing and 10% relative density. (B) and (C) Equivalent plastic strain versus the height of the structure at different crushing rate for 20% and 50% crushing.

5. Conclusions

Finite element method was employed to study the in-plane crushing of regular and functionally graded honeycombs. Insights into the role of 'dynamics effects' on the overall energy absorption and impact resistant of cellular structures are provided, and different deformation modes for honeycombs subjected to dynamic crushing were identified. We also studied the dynamic crushing of functionally graded cellular structure with regular cellular arrangements. Our results show that introducing a density gradient could significantly change the deformation mode and energy absorption of cellular structures under both low and high crushing velocities. A limited number of functionally graded cellular structures were analyzed and no effort was made to obtain the cellular structure with maximum energy absorption at a constant average density. However, enough insight is provided to understand the mechanism of energy absorption in functionally graded cellular structures under dynamic loading. Our results could help better understand the behavior and function of some of the engineered and biological cellular materials. Our study also complements recent studies on performance of sandwich panels with graded cores [9,10] and could help develop a new class of energy absorbent cellular materials and blast resistant structures.

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