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# Theoretical and finite element study of a compact energy absorber

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## Abstract

In this paper, a compact energy absorbing structure is presented, analyzed, and compared with a regular honeycomb structure by means of finite element simulations using ABAQUS. The structure's geometry is observed in a banana peel that contains a specific graded structure in a confined space. The structure is responsible for protecting the internal soft core at low impact velocities. Deformation modes, plateau stress, stroke, cell shape and impact energy absorption capabilities are studied on different models and the theoretical expressions are presented to predict the behavior of the structure at low velocities. This structure proves its worthiness over a regular honeycomb structure over a higher range of impact velocity under the same space/stroke constraints.

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*Keywords:* Regular honeycomb structure; Graded honeycomb structure; Banana peel; Collapse mechanism; Plastic hinge; Energy absorber; Plateau stress

## 1. Introduction

Energy absorbers are devices that convert kinetic energy into another form (e.g., pressure energy in fluids, elastic energy in solids, and plastics energy in deformable solids). The primary objective is to reduce the impact by distributing the load over a finite time period [1,2]. Honeycombs, in addition to possessing a high strength to weight ratio, exhibit excellent energy absorption properties. Extensive work has been done to predict the behavior of regular honeycombs under static and dynamic loading. Papka and Kyriades [3–6] studied the experimental response of in-plane uniaxial and biaxial crushing of metal honeycombs and compared the results with finite element simulation. Ashby and Gibson presented [7] the theoretical expression for calculating the stiffness moduli and plateau stress of periodic and regular honeycombs under quasi-static loading. Silva, Hayes and Gibson [8,9] investigated the effects of non-periodic two-dimensional arrangements of cells on the elastic properties and strength to get good insight into the crushing process of irregular honeycombs that are prevalent in nature.

Honeycombs behave differently under dynamic loading in terms of mode shape and plateau stress. Honig and Stronge [10,11] analyzed the in-plane dynamic behavior of honeycombs. They studied the dynamics of crush band initiation and wave trapping under impact loading using ABAQUS and presented expressions for critical velocity by employing theory of wave trapping. Ruan, Lu, Wang and Yu [12] studied in-plane dynamic crushing of honeycombs and explored the influence of cell wall thickness and impact velocity on the deformation mode and plateau stress by using ABAQUS. They also proposed an empirical formula for computing the dynamic plateau stresses at high impact velocities. Zhao and Gary [13] examined the in-plane and out of plane dynamic response of honeycomb using viscoelastic split bars. These studies mainly focused on honeycombs with uniform cell wall thickness throughout the structure. However, in nature, cellular structures vary in cell wall thickness, size and shape and therefore open another venue to explore energy absorbing properties.

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**Nomenclature**

| | |
|---|---|
| RHS | regular honeycomb structure |
| GHS | graded honeycomb structure |
| $A$ | the cross-sectional area of the unit cell |
| $Y$ | Cartesian co-ordinate axis for vertical loading direction |
| $P$ | load in the $Y$-direction |
| $F_a$ | axial load on inclined cell wall |
| $F_c$ | Euler's critical load |
| $M_p$ | plastic bending moment of honeycomb cell wall |
| $\sigma_p$ | plateau stress |
| $\sigma_y$ | yield strength of honeycomb cell wall material |
| $c$ | length of horizontal cell wall |
| $l$ | length of inclined cell wall |
| $d$ | honeycomb cell wall thickness |
| $b$ | depth of honeycomb cell wall |
| $\phi$ | angle of inclined walls w.r.t. the $Y$-direction |
| $\psi$ | angular deformation of inclined walls w.r.t. the undeformed position |
| $\Delta$ | displacement |
| $T$ | time |
| $v$ | impact velocity |
| $\rho^*$ | density of honeycomb |
| $\rho_s$ | density of cell wall material |
| $\varepsilon_d$ | densification or locking strain |

In this paper, the static and dynamic response of the hexagonal graded honeycomb structure (GHS) found in a banana peel is studied by using ABAQUS. The structure's energy absorbing properties under compression are explored. The relation of the plateau stress for constant wall thickness hexagonal honeycombs presented by Ashby and Gibson [7,14] is modified to predict the static and low dynamic response of the individual layers of cells. The response of individual layers is superimposed to achieve the global response of the structure. The model is tested at different impact velocities and the response is presented in the form of stress–strain and energy curves. Results are compared with the hexagonal regular honeycomb structure (RHS) of uniform wall thickness and differences are discussed.

## 2. Energy absorbing characteristics of a banana peel

Fig. 1 shows the cross-section of a banana peel. In technical terms, such kinds of materials are called functionally graded materials (FGM). In FGM, the composition and structure gradually vary with depth, resulting in corresponding changes in the properties of the material [15]. Observations suggest that these types of functionally graded structures are highly adaptive to all boundary and loading conditions defined by their environment. For example, the interior structure of a bone has an optimized shape with respect to the direction of principal stress and the magnitude of shear stress [16]. The structure found in bamboo gives a high strength to weight ratio [15]. The studies have shown that these biological systems have a sensing mechanism (e.g. piezoelectric effects in bone) that allows them to undergo modeling and remodeling to adopt the most favorable structure that meets all the functional requirements under intense environment and energy conditions [17–20]. The structure of a banana peel, by using some mechanosensor system, adopted an optimized shape to meet one of its intended functions of protecting the internal soft core from the external environment in a limited space.

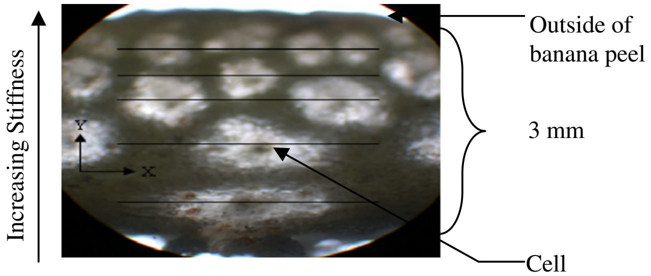

Fig. 1. Cross-section of a banana peel.

The arrangement of cells can be broken down into layers in the $X$-direction and grading (difference in sizes) in the $Y$-direction as shown in Fig. 1. The word 'cell' means a structural cavity of roughly hexagonal shape in the banana peel cross-section filled with a viscous fluid whose properties are still unknown (see Fig. 1). Five layers of cells are easily identifiable. These layers are indicated by horizontal lines. The first layer is composed of closely packed cells. The second layer is composed of bigger cells with more spacing between the two cells. This variation in the pattern continues until the last layer where cells are widely dispersed. The graded structure indicates the variation in stiffness along thickness. According to structural mechanics, two different sized structures with the same shape factor have a different stiffness. The bigger the structure is, the lower the stiffness, provided all the cross-sectional dimensions remain constant. The composition of the material changes with the depth in the $Y$-direction. Material around the larger inner cells is spongy and soft as compared to the one around the top, closely packed cells. Furthermore, the presence of fluid in the cells enhances the integrity of the structure.

The non-homogenous material and the graded structure show that if the foreign object hits a banana peel (or a banana falls on another object), the least stiff inner cells would collapse first to limit the load on the soft core. The collapse mechanism would shift smoothly to other

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