Compact energy absorbing cellular structure

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Abstract

The increasing demand of superior energy absorbing structures and materials to meet the stringent design criteria and higher safety standards for confined operating spaces leads to the advent of efficient compact cellular structures. This paper presents a detailed study of an intelligent and compact graded cellular structure that alleviates the impact damage(s) by undergoing a controlled stepwise deformation process by wisely utilizing the stroke. The structure's geometry is observed in the cross-section of a banana peel that has a specific graded cellular packing in a confined space. This packing enables the peel to protect the internal soft core from external impacts. The same cellular pattern is used to construct the structure. The energy absorbing characteristics of the structure are evaluated with respect to a solid section by means of non-linear finite element simulations using ABAQUS. The structure mitigates the dynamic collapse damage(s) and acts as an effective energy absorber over a solid section.
Keywords: graded cellular structure, banana peel, collapse mechanism, plastic deformation, energy absorbers.

1 Introduction

Energy absorbers are devices that convert kinetic energy into other forms e.g., pressure energy in fluids (e.g., varying cross-sectional area channels), elastic energy in deformable solids (e.g., springs), and combination of elastic and plastic energies in permanently deformable solids (e.g., sandwich panels). The primary objective of energy absorbers is to keep the reactive force below a threshold which will cause damage or injury. This objective is obtained by distributing the load over a long stroke. In other words, energy absorbers perform their function of reducing the load at the cost of long stroke and time. Other important characteristics of the energy absorbers include the irreversible impact energy

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conversion, stable and repeatable deformation modes, maximum specific energy-absorption capacity and low cost [1].

Many examples have been discovered where nature is addressing energy absorbing issues e.g., the presence of the cellular structure in a human femur (a cancellous bone) assists to reduce the bearing stress levels and the impact at the joint [2]. The cellular structure of wood has excellent energy absorbing properties in axial, radial and tangential directions [3]. The structures replicated from honeycombs are one of the prime candidates for reducing the impact in automobile, aerospace and packaging industries [4]. Another breakthrough is achieved by observing the cellular graded structure in a banana peel. The structure's geometry suggests that one of the functional requirements of a banana peel is to protect the internal soft core from external impacts.

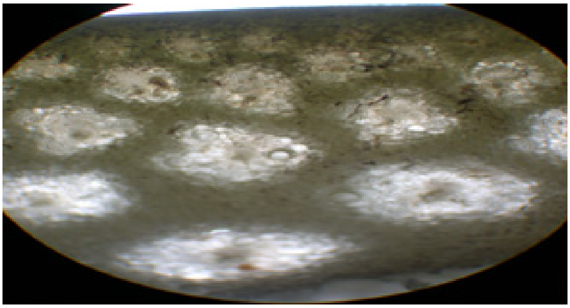

Figure 1: The graded cellular structure in a banana peel

Figure 1 shows the cross section of a banana peel. This structure has three unique features. First, it contains a graded cellular structure i.e., the size and the shape of the cells change along the thickness. Second, the composition of the material varies along the thickness. The material around the bigger cells is spongy and soft and stiffens uniformly in radial direction to the outer side of the peel. Third, the cells contain a fluid that, in context of energy absorbing characteristics, enhances the structural integrity. Technically, this type of material is called a Functionally Graded Material [5]. In FGM, the composition and structure gradually vary with depth, resulting in corresponding changes in the properties of the material.

The variation in size, shape and material of cells in a banana peel reveals the change in the collapsing load of cells. In other words, the big cells are less stiff than the small cells and consequently, collapse at lower load. This reflects that if a foreign object hits the banana peel, the layer of (biggest) cells adjacent to the internal soft core would collapse first and limit the impact load until it is completely crushed. This collapsing mechanism would smoothly flow up to the other layers until the whole structure is compromised. It is evident that such a type of a collapse mechanism allows structures to reduce the kinetic energy of the object over a finite period of time, and the overall effect is a reduction in the impact load [6].

In this paper, the hypothesis presented above is verified by executing the finite element analysis on the graded section representing the banana peel structure. Results are compared with the solid section and differences are discussed.

2 Finite element modelling

ABAQUS/ PART module is used to develop the three dimensional solid models. In order to reduce the complexity of the problem, it is assumed that the material is homogenous and cells have a constant shape factor along the thickness. The shape of the cells is reverse engineered by utilizing the raster image capability of AutoCAD. Six models are developed as shown in Figure 2. Model 1 consists of a 50 mm square, 5mm thick solid aluminum plate. The isotropic elastic-power hardened aluminum has a strain hardening exponent of ‘0.2’, strength co-efficient of 180 MPa, yield strength of 48 MPa and Young’s modulus of 68000 MPa respectively [7]. The boundary conditions are assigned by fixing the base of the plate (by constraining all degrees of freedom) and hitting it from the top in a vertical plane at different impact velocities with a discrete rigid plate of zero thickness. The kinematic contact condition is defined between the rigid plate surface and the top element based surface of the solid plate. The contact properties assigned in the interaction are rough tangential behavior and hard contact in the normal direction. In order to ensure consistency in the mesh, the plate is discretized by the enforced advancing front mesh generation technique using reduced integration, hourglass control, hexahedral elements [8].

Models 2-6 are exactly the same with the exception of the graded structure as shown in Figure 2. Models 2 and 3 are constructed to study the effect of number of graded layers on the energy absorbing characteristics of the structure whereas Models 4-6 are developed to evaluate how the cell pattern and cell density per unit volume influence the reactive/contact force, stroke and structural integrity. It can be seen that Model 5, keeping in mind the assumptions made above, is the replica of banana peel structure. During the crushing process, cell surface elements may come in contact with one and other, ‘self contact interaction’ is defined on the internal cell surfaces using the ‘penalty contact method’.

3 Analysis

ABAQUS/ Explicit module is used to execute the nonlinear dynamic structural analysis that employs a method of central-difference time integration to solve ordinary differential equations. The ‘NIgeom’ parameter is turned on to include the large deformations effects (geometric non-linearity) during the analysis. Since, the solution is conditionally stable, ‘automatic global time increment’ is used to estimate the stable time step. The default values of linear and quadratic bulk viscosities are used to improve the dynamic modelling.

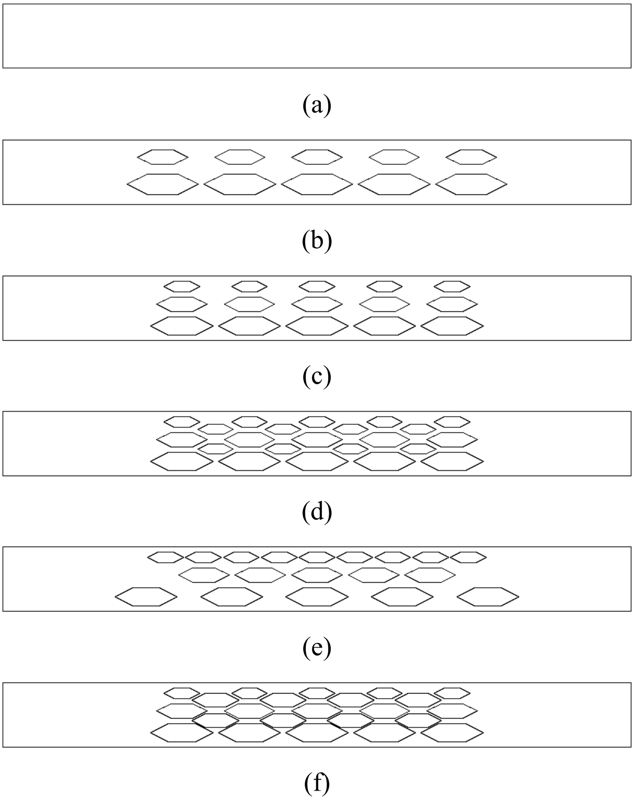

Figure 2: Solid and graded sections: (a) Model 1; (b) Model 2; (c) Model 3; (d) Model 4; (e) Model 5; (f) Model 6.

4 Results

4.1 Stress distribution and deformation modes

Figure 2 shows the deformation modes, distribution and magnitude of the dynamic Von Mises stresses at the end of the stroke at 3 m/sec impact velocity. The Von Mises stress levels in Models 2-6 are well above the yield strength of aluminium and are, on average, 25% higher than the maximum stress observed in Model 1. This indicates that graded structures undergo a higher equivalent plastic strain and absorbs most of the kinetic energy of the rigid plate in an irreversible form. The irreversible energy conversion and its effects will be discussed later.

In all models (excluding Model 1), the crushing initiated in the middle layer of cells and transmitted smoothly to the bottom layer and eventually to the top layer of the stiffest cells. Note, this collapse mechanism contradicts the mechanism presented in the ‘introduction’ section because of the homogeneity of the material along the thickness. If a composite material of increasing stiffness from the fixed base to the top surface of the plate was assigned, the bottom layer (of the biggest cells) would have collapsed first.

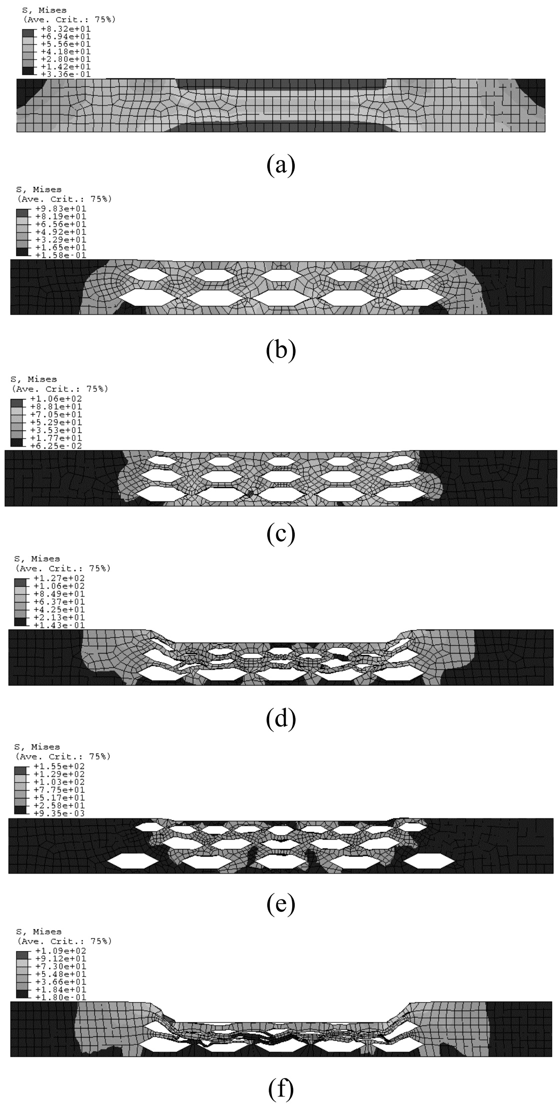

Figure 3: The deformation modes and distribution of Von Mises stresses at 3 m/sec impact velocity: (a) Model 1; (b) Model 2; (c) Model 3; (d) Model 4; (e) Model 5; (f) Model 6.

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4.2 Stress-strain curves

Figure 3 shows the stress-strain curves of models 1-6 at 3 m/sec impact velocity. The rigid plate experiences a stress of almost 205 MPa upon collision with the solid plate in Model 1. The steep curve shows that the rigid plate undergoes a high impact. Models 2-7 exhibits a traditional energy absorbing stress-strain curve that starts with a linear-elastic regime followed by a plateau regime of constant stress level. The linear-elastic regime reflects the uniform global elastic deformation of the graded structure that upon further increase in the applied load becomes localized to one of the layers of cells and leads to the plateau regime. The curves show that as the number of graded layers and cell density per unit volume increases, the contact force on the rigid plate reduces. However, it negatively affects the structural integrity of the structure. The graded structures in Models 4 and 6 undergo a gross plastic deformation (see Figure 3) and as a result keep the impact low as compare to Models 1-3 and 5. However, the simulations of models 4 and 6 show that structure is almost bottomed out in the process of stopping the rigid plate. This means any further increase in the impact velocity will lead to a densification regime where cell surfaces come in contact and sharp increase in the stress/load is observed.

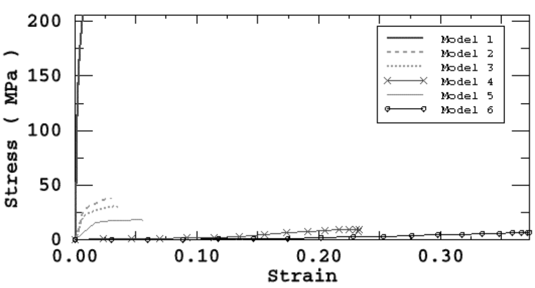

Figure 4: Stress- strain curves of Models 1-6 at 3 m/sec impact velocity.

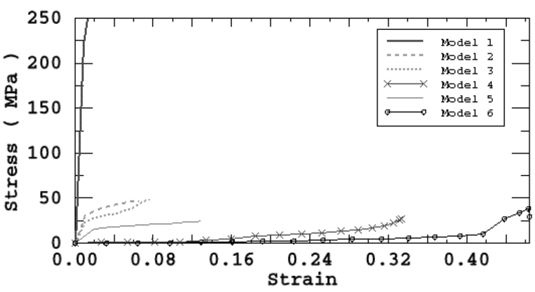

Figure 5: Stress- strain curves of Models 1-6 at 5 m/sec impact velocity.

The banana peel structure in Model 5 exhibits a balanced response between the load reduction and the stroke utilization. It acts superior to models 1-3 in reducing the impact and utilizes the stroke wisely as compare to Models 4 and 6. Figure 4 depicts the response of models 1-6 at 5 m/sec impact velocity. It can be seen that banana peel structure out performs all the structures and the solid plate, in terms of keeping the peak reactive force low. Further more, intact layers of cells at the end of the deformation process reveal the potential of reducing the load for higher range of impact velocities. Figure 5 evidently shows the peak reactive stress of banana peel structure at higher impact velocities.

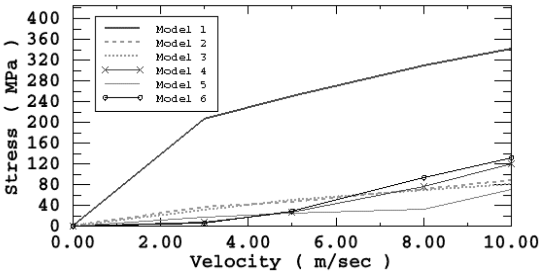

Figure 6: Contact stress on the rigid plate at different impact velocities.

4.3 Energy

Table 1 lists the plastic energy absorbed by the solid and graded plates, the rebound velocity of the rigid plate and the percentage decrease in the rebound with respect to solid plate, in Models 1-6 at 3 m/sec impact velocity. The plastic energy not only reduces the contact force but also dictates the amount of energy consumed in negative work done by the solid and graded plates on the rigid plate. The work appears as a rebound of the rigid plate from the solid and graded plates. The higher the absorbed plastic energy, the lower the rebound and consequently, the better the energy absorber. Other forms of energy like entrapped elastic energy, frictional energy (not listed here) also implicitly contributed to the reduction of the rebound.

Table 1: The energy absorbed by solid and graded plates at 3 m/sec impact velocity.

	Plastic Energy (J)	**Rebound Velocity (m/sec)**	**% decrease in rebound w.r.t solid plate**
Model 1	2.965	1.53	0
Model 2	4.296	.55	64
Model 3	4.356	.51	66
Model 4	4.343	.51	66
Model 5	4.364	0.5	66
Model 6	4.347	.51	66

The values in Table 1 indicate that all graded structures absorb approximately equal amount of plastic energy which is 44% higher than the solid plate. As a result, the rigid plate rebounds with lower velocity and undergoes less severe transition from retardation to acceleration in graded structures.

Stress wave propagation and strain rates also affect the energy absorbing characteristics of the graded cellular structure [9]. However, due to low dynamic effects and strain rates, it is reasonable to assume that their contribution to the magnitude of collapse load and energy is small and hence neglected [10].

5 Conclusions

The graded cellular structure found in a banana peel acts as an efficient compact energy absorber. The structure exhibits superior energy absorbing characteristics for a wide range of impact velocities in a confined space with a same space/stoke constraint over a solid section. The structure maintains a balance among the load reduction, structural integrity and stroke utilization. The plastic collapse of cells keeps the reactive stress approximately constant and reduces the impact significantly. The structure absorbs most of the kinetic energy in the form of plastic energy that indirectly alleviates the impact and lowers the rebound which results in less severe retardation-acceleration phase.

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