STUDY OF LOW IMPACT PROPERTIES OF A COMPOSITE AND A HOMOGENEOUS CELLULAR STRUCTURE

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Abstract

In this paper, the energy absorbing characteristics of a composite cellular structure are compared with a homogeneous cellular structure through finite element simulations. Under low impact, deformation mode, collapsing load and collapsing mechanism, locking strain, and total energy absorbed are studied. The composite structure absorbs higher amount of energy than the homogenous structure of the same size and cell wall thickness due to higher initial collapsing load.

Introduction

Energy-absorbing materials dissipate kinetic energy during impact through a variety of means dependent upon the structure and material. Application of energy-absorbing structures includes automotive, highway, airplane, and personal safety. Energy-absorbers differ from classical structures, which are expected to undergo small amounts of elastic deformation prior to failure, whereas, energy-absorbing structures withstand intense impact loading and experience large geometric changes, strain-hardening effects, strain-rate effects and a variety of deformation modes [1]. Energy-absorbers are primarily designed to withstand impact loading over a short period of time. These loading conditions appear when objects travelling at a high velocity come to a rest in a short interval of time; a loading is considered impact when the time interval for which the loading is applied (on the structure) is shorter than half the natural time of oscillation of the structure [2]. For constant energy, the magnitude of the reactive force experienced by the object is a function of this time interval. Longer time intervals correspond to decreased impacts. An increased time interval is achieved through a longer deformation process, which occurs in high porosity materials, e.g., cellular materials, foams, etc [4].

Previous studies have shown that biomaterials can be used as energy-absorbing structures, such as wood, cork, bone, and the banana peel structure [2]. The purpose of the banana peel is to protect the soft inner core from being damaged from inevitable external impacts. The graded composite structure of the banana peel shows (Fig.1) that the stiffness and composition vary with thickness. The material around the inner big cells is spongy and soft as compared to that around the top closely packed cells. During an impact, the inner cells collapse first to protect the soft inner core [5]. This 'collapse mechanism' shifts up, and layers continue crushing until the whole structure is compromised, allowing structures to reduce the kinetic energy of the object in steps over a generous period of time, and the overall effect is impact mitigation. The presence of fluid in the cells enhances the integrity of the structure, and the widely dispersed biggest cells in the bottom layer do not communicate structurally with one another. Quasi-static and dynamic analysis showed that the peel's graded structure has a potential to be used as an effective energy absorber for compact, high impact protection systems [6].

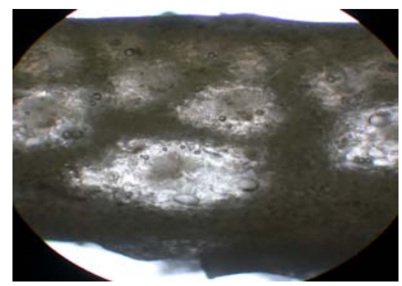

Fig. 1. Microscopic view of the cross-section of a banana peel (Medical University of Ohio). The peel thickness is 3 mm.

Due to graded and composite nature of the banana peel, some interest lies in understanding the impact behavior of peel structure if it is made out of fiber reinforced polymer matrix composite. Composite materials are used in many applications that require energy absorption. Much of their usefulness, which overlaps with cellular structures, comes from their relatively light weight to strength ratios. The automotive industry is relying more on composite materials for this benefit [3]. Other industries utilizing composite materials include aircraft, aerospace, marine, energy, biomedical and infrastructure [7].

In order to develop first order understanding of the low impact behavior of composite cellular structures, a single cell (called a unit cell) of the banana peel structure is selected for the finite element study. An arbitrary homogeneous material for cell wall material is chosen to provide basis for comparison with composite cell wall unit cell impact behavior. A detailed description of the finite element modeling and result interpretation is presented in next sections.

Finite Element Analysis

The Abaqus/CAE module was used to model two unit cells, termed as M1 and M2, respectively. The M1 is shown in Figure 2. The horizontal and inclined cell walls were 3 mm and 2.24 mm long with a unit depth in the transverse direction. An impact velocity of 10 m/s was assigned to the plate, A. The boundary conditions were assigned by fixing the plate 'B' and constraining all the degrees of freedom of the base horizontal wall of the unit cell except along the X direction. The M1 was meshed by using 4 node, hourglass control, reduced integration, quadrilateral shell elements, and plates, A, and, B, were discretized by using 4 node, 3D bilinear rigid, quadrilateral elements. Surface to surface contact condition with penalty contact method was defined between the rigid plate, A, and the top surfaces of M1, and general contact conditions were defined for the rest of the model. The (homogenous) material assigned to cell walls had modulus of elasticity of 69 GPa and yield strength of 76 MPa. The M2 modeling definitions were exactly the same as M1, except the material assigned to cell walls was $[0,45]_s$ fiber reinforced polymer matrix composite. The modulus of elasticity, tensile strength, and compressive strength (for each lamina) in the principal direction 1 were 55GPa, 700 MPa, 630 MPa, and for the principal direction 2, were 52 GPa, 640 MPa, 590 MPa. The in-plane shear modulus and shear strength were 4.2 GPa and 110 MPa. The thickness of each lamina was 0.1 mm. The ABAQUS CZone module was used to simulate deformation of M2, and TSAI-WU failure criterion was incorporated to model collapse and failure of cell walls.

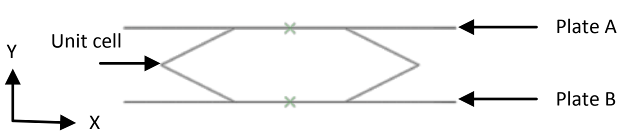

Fig 2. Unit cell for model M1. The wall thickness is 0.3 mm.

Results and Discussion

Deformation mode

Figure 3 shows the deformation of M1 and M2 at 12.6 ms time instant. The collapsing mechanism is primarily governed by the bending of inclined walls. The deformation mode shape is linear in M2 (composite) and partially convex in M1 due to some extra buckling of top horizontal wall, which results in a complete contact of plate, A, with the surface of top inclined and horizontal walls.

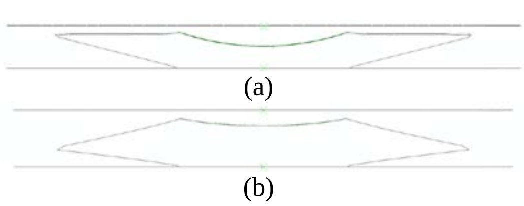

Fig 3. (a) Deformation of M1 (convex mode, strain rate = 4800 s^{-1}); (b) deformation of M2 (linear mode, strain rate = 4324 s^{-1}).

Force vs. Displacement Curves

Fig 4. shows the plot of reactive force experienced by the plate, A, when it impacted M1 and M2. Due to noise in the reactive force data for model M2, the data was filtered using a cut-off frequency of 10 Hz. The plateau force for M1 is 4 N, and the (homogenous) unit cell bottoms out at 1.6 mm displacement. The initial collapsing load for M2 is 25.5 N, which is 6.37 times larger than the collapsing load in M1; the effect of initial peak load in M1 at time 0s is attributed to some instability in kinematic contact formulation, and therefore, is neglected in this analysis. The distinct global plateau regime is absent for M2, and the reactive force, after initial peak, decreases monotonically as the deformation progresses in the unit cell (until locking strain effects become dominant at 1.6 mm displacement).

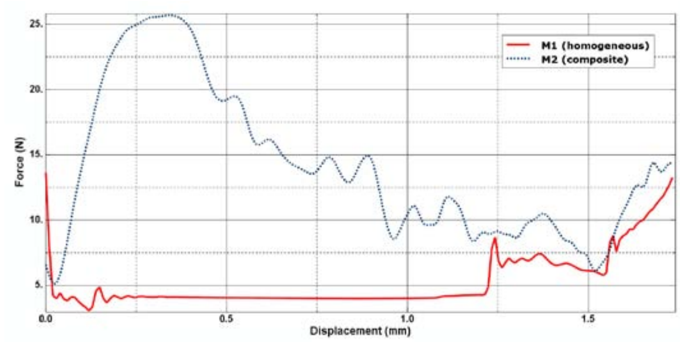

Fig 4. The force pulse on the plate 'A' during deformation of homogenous and composite unit cells.

Energy

The area under the force-displacement curves is equal to the total energy absorbed by the unit cells from the inception of collapsing of cell walls to the exhaustion of deformation. The energy absorbed for M1 was 8.97 mJ, and for M2, was 24.21 mJ. It may be noted that the major fraction of the total energy absorbed was plastic energy for M1 and elastic energy for M2.

Conclusion

The impact properties of homogenous and composite unit cells are studied. For low impact velocities, the composite unit cell crushes in a linear mode, and convex mode is dominant in homogenous unit cell. The initial collapsing load for composite unit cell is (approximately) 500 % larger than the load for homogenous unit cell. Instead of global plateau regime (observed for homogenous unit cell), several local plateau regimes, decreasing in magnitude with the progression of deformation, are observed. The total energy absorbed by the composite unit cell is 3 times larger than the energy absorbed by the homogenous unit cell. However, the form of energy is mostly elastic in composite cell and mostly plastic in homogenous cell.

References

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