F4-J: Novel Cellular Structures and Sandwich Materials

ABSTRACT — We investigated the mechanical behavior of two-dimensional hierarchical honeycomb structures using analytical, numerical and experimental methods. Hierarchical honeycombs are constructed by replacing every three-edge vertex of a regular hexagonal lattice with a smaller hexagon. Repeating this process builds a fractal-appearing structure. The stiffness and strength of this structure is controlled by the iteration of dimensional ratios for different hierarchical orders. Hierarchical honeycombs of the first and second order can be up to 2 and 3.5 times stiffer than regular honeycombs at the same mass (i.e., same overall average density). The specific strength (based on plastic collapse) of the hierarchical honeycomb structures is similar to that of regular honeycomb structures.

I. PARTICIPANTS

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II. PROJECT OVERVIEW AND SIGNIFICANCE

The main goal of this project is to develop a novel class of Biomimetic Energy Absorbent Material Systems (BEAMS). We studied the energy absorption and structural behavior of different fundamental systems including cellular materials - encompassing structures with random heterogeneity and functionally graded variations; structures with protective layers; and structures with hierarchical organization. We used advanced modeling and numerical simulation of response of structures under blast and shock loading at different scales: from structural components to full-scale structural systems. We developed a robust failure material model for structures that enables us capture the material failure under dynamic loading. Our results could help better understand the behavior and function of engineered and biological cellular materials, and develop a new class of energy absorbent cellular structures. In this context, we have investigated the response of sandwich structures under high intensity dynamic loading, multiple shocks and combined shock and projectile loading to characterize the deformation and failure modes of the structure. We have also proposed a new class of honeycombs with hierarchical organization with enhanced mechanical properties over regular honeycomb structures.

A. State-of-the-Art and Technical Approach
Topic I: Mechanics of Biological and Biomimetic Cellular Structures

Cellular structures in nature: There are two structural features which can be found in many biological systems: Cellular organization with heterogeneity including functional gradient; and hierarchical organization. These features are believed to be largely responsible for the superior energy absorption of biological systems. As an example, elk antler is a tough structure capable of absorbing high energy impact, whose functionality is crucial to the animal's survival (Figure 1). According to (Chen et al. 2009) its heterogeneous and hierarchical structural organization are recognized as key factors in its superior behavior.

Heterogeneous and functionally graded structures: In general, the type and level of irregularity have significant effects on the properties of cellular structures. Figure 2 displays three biological systems with intricate cellular structures, arguably displayed in order of increasing structural and functional complexity (from left to right). In each system, the toughness and energy absorption of the cellular organization are crucial for the function and survival of the biological system. For example, cork is the outer bark of a tree, with heterogeneous cellular organization and remarkable energy absorption. Other examples of cellular biomaterials are elk antlers, banana peel and bone.

Structural hierarchy: Hierarchical structures are ubiquitous in nature and can be observed at many different scales in organic materials and biological systems (Aizenberg et al., 2005; Buehler, 2006; Espinosa et al., 2011; Fratzl and Weinkamer, 2007; Gibson et al., 2010; Lakes, 1993; Ortiz and Boyce, 2008; Qing and Mishnaevsky Jr, 2009). The hierarchical organization of these systems generally plays a key role in their properties, and hence survival (Fratzl and Weinkamer, 2007; Gibson et al., 2010). Hierarchy is also important in engineering and architectural design. Examples range from the Eiffel tower (1993) and polymers with micro-level hierarchical structures (Lakes, 1993), to sandwich panels with cores made of foams or composite lattice structures (Cote et al., 2009; Fan et al., 2008; Kazemahvazi et al., 2009; Kazemahvazi and Zenkert, 2009; Kooistra et al., 2007). There, hierarchical organization can lead to superior mechanical behavior and tailorable properties, as described recently for sandwich cores with hierarchical structure (Fan et al., 2008), for hierarchical cor-
rugated truss structures (Kooistra et al., 2007) and for fractal-appearing hierarchical honeycombs (Ajdari et al. 2012). The overall mechanical behavior of these structures is governed by the response at different length scales and levels of hierarchy; and increasing levels of structural hierarchy can result in lighter-weight and better-performing structures.

In our work, we replaced the vertices of a regular hexagonal lattice with a smaller hexagon, to achieve a structure with one level of hierarchy (which has superior stiffness compared to its regular hexagonal counterpart). This vertex-replacement procedure can be repeated at smaller scales to achieve honeycombs with a higher order of structural hierarchy. Figure 3A shows the evolution of a regular honeycomb cell as the structural hierarchy is introduced. The structural organization of the honeycomb at each level of hierarchy can be defined by geometrical parameters, \( \gamma_1 \) and \( \gamma_2 \), defining the ratio of the smallest hexagonal edge length (b for 1st order hierarchy and c for 2nd order hierarchy), to the original hexagon’s edge length, a, as described in Figure 3A (i.e. \( \gamma_1 = b/a \) and \( \gamma_2 = c/a \)). Figure 3B shows samples of regular and hierarchical honeycombs with \( \rho = 10\% \) and \( a = 2 \) cm fabricated using 3D printing (Dimensions 3D printer; Stratasys Inc., Eden Prairie, MN). In addition to a limited set of experiments, we developed analytical and finite element models to calculate the effective elastic modulus and yield strength of the honeycombs. In the analytical part, we estimated the deformation of honeycombs with one or two levels of hierarchy under uniaxial loading using Castigliano’s second theorem. To validate the theoretical results we have simulated the structural response using finite element analysis. Models of two-dimensional hierarchical honeycombs are simulated using Abaqus 6.10 (SIMULIA, Providence, RI).

The resulting isotropic in-plane elastic properties (effective elastic modulus and Poisson’s ratio) of this structure are controlled by the dimension ratios for different hierarchical orders. By increasing the order of hierarchy we can reach stiffer structures at the same overall average density. For example, hierarchical honeycombs of first and second order can be up to 2.0 and 3.5 times stiffer than regular honeycomb at the same mass (i.e., same overall average density). Our study showed that depending on relative density of the structure, there is a limit for stiffening the structure by increasing the order of hierarchy. The work provides insight into the role of structural organization and hierarchy in regulating the mechanical behavior of materials, and new opportunities for developing low-weight cellular structures with tailorable properties. Figure 4 shows the contour map of normalized effective stiffness of hierarchical regular honeycomb structures with second-order hierarchy for all possible values of \( \gamma_1 \) and \( \gamma_2 \). The x-axis is \( \gamma_1 \) and ranges from 0 to 0.5, while \( \gamma_2 \) is limited by the two geometrical constraints, \( \gamma_2 \leq \gamma_1 \) and \( 0 \leq \gamma_2 \leq (0.5 - \gamma_1) \).

**Figure 3 – Hierarchical honeycombs.** (A) Unit cell of the hierarchical honeycombs with regular structure and with 1st and 2nd order hierarchy. (B) Images of honeycombs with \( a = 2 \) cm fabricated using three-dimensional printing.
The results show that a relatively broad range of elastic properties, and thus behavior, can be achieved by tailoring the structural organization of hierarchical honeycombs, and more specifically the two dimension ratios. For example, the hierarchical honeycombs with one order and two orders hierarchy are shown to have specific stiffness up to 2.0 and 3.5 times of the regular hexagonal honeycomb. Increasing the level of hierarchy provides a wider range of achievable properties. Our study showed that maximum achievable stiffness (stiffness limit) of hierarchical honeycombs depends on the overall relative density of the structure. Figure 5 summarizes these results. The plot shows the maximum stiffness of the hierarchical honeycomb for different densities, n, and relative densities, ρ, normalized by the stiffness of regular honeycomb of same mass. The limit for the maximum stiffness of hierarchical honeycombs are shown by dashed lines. For example, for hierarchical honeycomb with , ρ =0.01, the stiffness limit of the honeycomb is E/E0 = 15 for n = 9. Further increase in the order of hierarchy, does not yield to stiffer structures. Further optimization should be possible by also varying the thickness of the hierarchically introduced cell walls, and thus the relative distribution of the mass, between different hierarchy levels. The proposed work focused only on the elastic properties of hierarchical honeycombs, and the collapse/yield and instability properties of these structures are currently under study.

**Topic II: Sandwich Structures Subjected to Complex Dynamic Loading**

We developed detailed numerical models to study the behavior of sandwich panels with low density core constructions, as well as sandwich-walled structural system under complex dynamic loading. The numerical models allows studying the behavior and fracture of sandwich panels under complex dynamic loading condition. The loading scenarios considered were 1) a single high intensity shock loading, 2) multiple shocks, and 3) a shock followed by a projectile loading. Figure 6 shows an example from our study on the failure of panels under multiple shocks. The results quantify the failure mechanism of honeycombs sandwich panels made of two different steel alloys (AH36 and HY80) under multiple shocks. The figure also shows the deformed configuration of a panel after impingement by three shocks of equal intensity. In this example, the honeycomb sandwich panel detaches from its support after impingement of the third shock.

**Sandwich-walled Structural Systems**

The previous studies related to understanding the mechanics and structural performance of sandwich structures are mainly focused on studying the behavior of the core construction or the performance of a single isolated sandwich panel. Here, we extended these studies to explore the behavior and performance of structural systems made of sandwich-walled panels. Our objective was to explore the potential benefit of
sandwich configurations in enhancing the overall behavior of structural systems under shock loading. As an example, Figure 7 shows the displacement response of frames made of solid and sandwich panels. In addition to a traditional frame made of solid panels, two frame configurations with sandwich-walled panels, were considered. In one configuration, the two side walls of the frame were replaced by sandwich panels. In the second configuration, both sides walls and the top panel of the frame were replaced by sandwich panels. The response of these sandwich-walled frames were compared with the response of traditional frame, made of solid panels with equal mass. The results show that the sandwich-walled panels have significantly less maximum displacement compared to the frame made of solid panels. In addition, the sandwich-walled panels have negligible residual deformation, compared to the frame made of solid panels which undergo significant residual deformation. The results highlight the potential of sandwich panels in creating novel threat-resistant structural systems.

![Failure Map](image1)

**Figure 6** – (Left) The failure map for square honeycomb plate subjected to one, two and three shocks made of AH36 and HY80 as dependant on the critical effective plastic strain at fracture. (Right) Deformed configuration and contour map of plastic strain of square honeycomb plate made of HY80. In all diagrams, square honeycomb core plate has $M=156 \text{ kg/m}^2$, $L=1 \text{ m}$ and $\rho_c = 0.04$.

![Normalized Deflection](image2)

**Figure 7** - Normalized deflection of sandwich walled frames type I and II compared with solid plate walled frame. Plates have mass/area $M=156 \text{ kg/m}^2$ and made of HY80 and no failure incorporated for that. sandwich plates have core relative density of $\rho=0.04$. 
B. **Major Contributions**

Our results provide new insight about the energy absorption mechanisms of lightweight cellular structures, as well the failure and impact mechanics of structure under high intensity loading. The results will pave the way to develop novel lightweight energy absorbent materials and threat-resistant structures that can be used to protect both civilian and military structures, as well as military vehicles, ships and flight structures.

II. **FUTURE PLANS**

We will focus on understanding the behavior of sandwich-walled structural systems, and biomimetic hierarchical cellular structures.

III. **RELEVANCE AND TRANSITION**

The development of new materials systems and novel structural concepts for safety and protection is highly relevant to ALERT's objective. Work is under way to develop cost effective methods for creation of these materials at a large scale to transfer the development knowledge to industrial partners.

IV. **LEVERAGING OF RESOURCES**

Dr. Vaziri has received the 2010 Air Force Office of Scientific Research (AFOSR) Young Investigator award, the 2011 NSF CAREER award and four multinational grants from Qatar Foundation. The four grants from Qatar provides funding of more than $4M, with direct funding at Northeastern > $1.1M (Period of Performance 10/2011-10/2015). Dr. Vaziri is also pursuing several additional funding opportunities, including submission of an international grant to DHS in collaboration with University of Cambridge and a joint NSF proposal application with faculty members of ALERT.

V. **DOCUMENTATION**

A. **Journal publications**


B. **Seminars, Workshops and Short Courses (in 2011-2012)**

complex Dynamic Loading”, Plasticity, Bahamas, 2013


VI. REFERENCES


