F4-J: Novel Cellular Structures and Sandwich Materials

ABSTRACT — Military systems and structures must survive, as well as function in, harsh environmental conditions and extreme loads (e.g. sudden changes in temperature, intense winds and drag forces, fire, projectile impact and explosion). In order to withstand these loads, lightweight and volumetrically-efficient protective and structural concepts must be devised that are highly reliable and structurally efficient. To address those challenges, we developed a new class of ultralight cellular structures by exploiting topological hierarchy, self-similarity and fractal geometries. Using a blend of analytical, numerical and experimental techniques, we explored the behavior and deformation mechanisms of these structures over a range of loadings. In addition, we continued our work related to studying the behavior and performance of sandwich panels and sandwich-walled structural systems.

I. PARTICIPANTS

<table>
<thead>
<tr>
<th>Faculty/Staff</th>
<th>Name</th>
<th>Title</th>
<th>Institution</th>
<th>Email</th>
<th>Phone</th>
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<tbody>
<tr>
<td></td>
<td>Ashkan Vaziri</td>
<td>Professor</td>
<td>NEU</td>
<td><a href="mailto:vaziri@coe.neu.edu">vaziri@coe.neu.edu</a></td>
<td>617.373.3474</td>
</tr>
<tr>
<td></td>
<td>Jim Papadopoulos</td>
<td>Research Associate</td>
<td>NEU</td>
<td><a href="mailto:j.papadopoulos@neu.edu">j.papadopoulos@neu.edu</a></td>
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<tr>
<th>Students</th>
<th>Name</th>
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<th>Institution</th>
<th>Email</th>
<th>Intended Year of Graduation</th>
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<tbody>
<tr>
<td></td>
<td>Hamid Ebrahimi</td>
<td>PhD</td>
<td>NEU</td>
<td><a href="mailto:ebrahimi.h@husky.neu.edu">ebrahimi.h@husky.neu.edu</a></td>
<td>2015</td>
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II. PROJECT OVERVIEW AND SIGNIFICANCE

A. State-of-the-Art and Technical Approach

Topic I: Self-Similar and Hierarchical Cellular Structures

Architecture-Property Relationship in Self-Similar Hierarchical Honeycombs

We studied the behavior of a new class of fractal-appearing hierarchical honeycombs, which was recently shown to exhibit superior in-plane stiffness to mass ratio (i.e., specific Young’s modulus). Analytical and numerical investigations were carried out to study the in-plane plastic collapse behavior of hierarchical honeycombs at one order of hierarchy, for arbitrary biaxial in-plane loading in the principal structural directions. The analysis is based on an upper bound estimate from competing plastic hinge mechanisms defined for the unit cell, and also on a lower-bound strength estimate derived from elastic beam analysis of a unit cell. Next, an extensive numerical investigation was performed to study the in-plane stiffness and plastic collapse strength of hierarchical honeycombs with up to four orders of hierarchy. The results showed that a wide range of specific stiffness and specific strength can be achieved by changing the architecture of honeycombs. The results provide new insight into the relationship between the structural organization and mechanical be-
behavior of cellular-based materials and lattice structures and suggest novel avenues for creating low density materials with desired properties and function.

**Novel Self-Similar Honeycombs**

Figure 1 shows examples of self-similar honeycombs with fractal-like geometries developed in our group, where topological modifications and hierarchy are used to tailor properties and enhance function. A selected set of results is displayed that shows the large increase in the achievable range of stiffness and plastic collapse strength permitted by increasing the order of hierarchy. Our results offer insights into the potential value of iterative structural refinement for creating low-density materials with desired properties and function.

![Self-Similar Hierarchical Honeycombs](image)

**Spiderweb Honeycombs**

![Relative stiffness and strength of Self-Similar Hierarchical Honeycombs](image)

Figure 1- Structural models of the unit cell of hierarchical self-similar and spiderweb honeycombs. Specimens with 1st and 2nd order hierarchy were made using three-dimensional printing. The plot shows the map of normalized collapse strength versus normalized stiffness for regular, 1st, 2nd, 3rd and 4th order self-similar hierarchical honeycombs. It should be noted that a \( n \)th order hierarchical honeycomb is a special configuration of honeycombs with higher order of hierarchy. Thus, the entire colored area in the plot displays the range of achievable stiffness and strength with introducing four orders of hierarchy in the architecture of a regular honeycomb.

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

Current literature related to impact mechanics and blast resistance of sandwich panels generally consider a single impulsive pressure loading (shock) or single projectile loading impinging on the panel. However, the application of sandwich panels in critical structures requires consideration of other possible extreme events and loading scenarios. Examples of such events are: (i) impingement of multiple shocks, (ii) shock loading followed by projectile impact (for example due to debris that gets airborne as the shock wave travels towards the structure), (iii) multiple impacts by non-explosive projectiles, (iv) shock or projectile loading followed by an internal fire (e.g. World Trade Center Collapse in 2011) and (v) shock or projectile loading followed by internal explosion (e.g. in pipeline networks and fuel tanks). In our recent published work, we studied the behavior and performance of sandwich panels as they are impinged by multiple shocks. In the current work, we have focused on the second scenario mentioned above, that of shock loading followed by a projectile impact on a sandwich structure. This type of loading typically occurs when a primary explosion fragments parts of the enclosing or surrounding structure launching a major fragment in air like a projectile. Thus, the initial shock wave of the blast is followed by a projectile strike.

**Residual Structural Capacity of Shock-Loaded Panels**

We developed detailed numerical models to study the residual structural capacity of sandwich panels sub-
jected to shock and projectile impact. The goal of the study is to assess the mechanical behavior, stability and load carrying capacity of structural systems damaged due to shock or projectile impact.

**Sandwich-walled Structural Systems**

We have continued our work related to studying 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. In this context, we have started a collaboration with Harbin Institute of Technology (Harbin, China) to develop and manufacture sandwich-walled structural systems made of fiber reinforced composites.

**B. Major Contributions**

Our results provide new avenues to develop threat resistant structures that can withstand extreme loading conditions (e.g. impact, blast, thermal shock) without diminishing their functionality. Development of these structures require innovative design and manufacturing involving high performance multifunctional materials and structural systems, as well as understanding their behavior under various loading conditions. These two topics have been the focus of our study. Examples of such developments are cellular structures with functionally graded and hierarchical structural organization, shown to have superior mechanical properties compared to conventional cellular structures of same overall mass. Another example is the ongoing efforts in the development of sandwich-walled structural systems.

**III. FUTURE PLANS**

We will focus on understanding the behavior of sandwich-walled structural systems, and hierarchical cellular structures with self-similar and fractal architecture.

**IV. 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.

**V. LEVERAGING OF RESOURCES**

Dr. Vaziri has received the 2010 Air Force Office of Scientific Research (AFOSR) Young Investigator award, the 2012 NSF CAREER award and four multinational grants from Qatar Foundation. The four grants from Qatar Foundation provide funding of more than $4M, with direct funding at Northeastern > $1.1M (Period of Performance 10/2011-10/2015). Dr. Vaziri has also submitted a 5 year grant to the AFOSR titled "Ultralight cellular structures with self-similar, fractal and reconfigurable architecture", which is currently pending.

**VI. PROJECT DOCUMENTATION AND DELIVERABLES**

A. Journal Publications

B. Seminars, Workshops and Short Courses


VII. REFERENCES


