Architected Cellular Materials: Designing Lighter and Stronger Materials

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For thousands of years, humans have developed ever lighter and stronger materials, including alloys, polymers, and composites. Recently, these efforts have been accelerated through the introduction of carefully engineered open structure into solid materials to create cellular materials. This presentation will show how the properties of cellular materials can be tailored by changing the solid constituents and the cellular architecture, i.e., the spatial configuration of voids and solids. For example the random cellular architecture of foams and aerogels results in bending-dominated deformation of the ligaments, resulting in a rapid decrease in strength and stiffness as porosity is increased. In contrast, certain ordered lattice-type cellular architectures can have nearly optimal stretching-dominated properties, resulting in materials in which the strength and stiffness scale proportionally to the solid volume fraction of the material.

The importance of architecture is illustrated readily in large, familiar structures such as buildings or wheels. The first wheels were made out of solid stone or wood and had no notable porosity. In contrast, modern bicycle wheels have a sophisticated architecture, in which more than 95% of the material has been replaced with air. Excellent strength and stiffness is achieved despite the light weight by loading the spokes in tension, where their performance is stretch-dominated, not in compression, where they would buckle and bend easily.

This presentation will show how this concept can be applied on the materials level. By designing the cellular architecture at the nanometer, micrometer and millimeter scales we have fabricated metallic microlattices with densities as low as 0.9 mg/cm^3 and unprecedented mechanical behavior.

Traditionally, the properties of materials have been altered by varying the composition and microstructure. Changing the cellular architecture provides an array of additional degrees of freedom when designing a material. In lattice materials, the unit cell configuration and symmetry, ligament size and shape, and node topology can be altered independently. Our studies of have shown that by independently changing these different architectural parameters, conventionally linked properties such as density, stiffness, and strength can be decoupled.

Cellular materials with specifically designed architecture can address many challenges in aerospace applications and some examples will be presented, including lightweight load-bearing structures and multi-functional components. Multi-scale modeling is applied to optimize these materials from the nano- to the micro- and macro-scale. Whereas the design of alloys or polymers is generally still hindered by limited scientific understanding and computational power, that of cellular materials is more tractable: Cellular architecture and suitable constituent solid materials can be combined using known structural engineering principles.

Powerful computational tools to optimize structures for mechanical efficiency allow the most structurally efficient and lightweight architecture for a complex part and load case to be computationally determined, but today's manufacturing capabilities still impose limits on what can be made. New fabrication routes for cellular materials are exemplified by 3D printing, but considerable progress must still be made to enhance the scale, throughput, reliability, and palette of materials available. This presentation will describe a rapid manufacturing method developed at HRL Laboratories for ordered polymer lattice materials and the use of these polymer lattices to create ultralight metallic microlattices.

Architected cellular materials are already finding applications beyond the aerospace industry, which will lead to improvements in fuel efficiency, performance, and convenience for automobiles, sporting and consumer goods.