Nonlinear Mechanical Response of Rotation-Dominated Chiral Lattices

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Abstract. Cellular materials are classified under one of two topologies – the stretch-dominated geometry, that has higher specific modulus, or the bending-dominated geometry, which tends to exhibit better energy absorption efficiency. Here, we show that chiral materials, a relatively new class of cellular materials, fall into a third category – the rotation-dominated topology, where lattice strain is dominated by joint rotation. The key characteristics of this new topology include (i) a nonlinear elastic stress-strain response that is derived entirely from the geometry (ii) multiple relative modulus – relative density relationships that can be linear or nonlinear (iii) a anisotropic-to-isotropic transition with increasing lattice size. The results of this study are expected to be of interest to the architected materials community and we will also show how it relates to the microstructure of materials manufactured from powder-based methods (*e.g.* selective laser sintering, powder metallurgy).

Introduction

With the advent of 3D printing, complex geometries can now be fabricated with ease. This has led to a renewed interest in the mechanical properties of cellular materials. Previous analysis by Ashby has shown that such materials tend to have 1 of 2 possible topologies – one that has its deformation dominated by stretch/ compression and another, dominated by bending deformation. Stretch-dominated topologies, such as the octet-truss geometry, tend to offer better stiffness at the same solid fraction (*i.e.* higher specific modulus), while bending-dominated geometries, such as the tetrakaidecahedron (*i.e.* Kelvin Cell) offers better cushioning properties (*i.e.* higher energy absorption efficiency).

This classic analysis has informed structural designers for decades and acted as the key to understanding stochastic foams and a new generation of architected materials, which has exhibited lighter densities, higher stiffness, higher strength and better recoverability than previous designs. Despite the wealth of new designs generated, however, the classification of cellular materials into stretch-dominated and bending-dominated has not been challenged. Here, we demonstrate, through analytical, experimental and numerical means that novel chiral designs, with unit cells that cannot be superimposed onto its own mirror image, belongs to a third class of topology, the rotation-dominated topology.

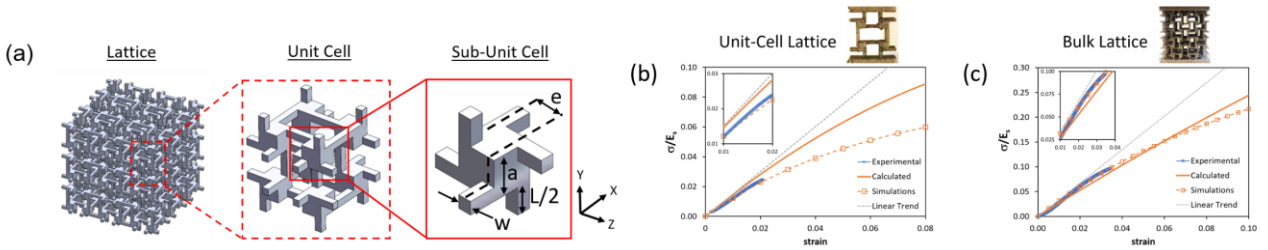

Figure 1: (a) Schematic diagram illustrating the 3D anti-tetrachiral geometry (3ATC). The simulated, experimental and analytically calculated elastic stress-strain relationship for (a) a single unit cell of 3ATC (c) a 3 x 3 x 3 lattice of 3ATC (*i.e.* bulk lattice). Notice the deviation of the elastic response from a linear trend (gray line) that is typical for most geometries.

Results and Discussion

The mechanical properties of a chiral structure, the 3D anti-tetrachiral (3ATC) geometry, was rigorously derived without empirical parameters for a single unit cell and a bulk lattice. The predictions were compared with results from numerical simulations and experiments and found to agree very well. There are 3 unique features about the 3ATC geometry that are yet to be observed in other structures. Firstly, it exhibits a nonlinear elastic stress-strain response that is derived entirely from the joint rotation, which is the main contributor to overall strain in the lattice. Secondly, its relative modulus – relative density relationship can either be linear or non-linear; the nonlinear trend does not conform to a power law as well, unlike other structures. Thirdly, the 3ATC geometry is mechanically anisotropic as a unit cell but isotropic as an infinite lattice. Based on our preliminary analysis, it seems to be the only structure that is capable of undergoing such an anisotropic to isotropic transition. These results are expected to be of interest to the architected materials community and we will also show how they can be relevant to powder-based 3D printing methods commonly employed for metals and polymers today.

References

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