Effect of Unit Cells Networking and Topology on Stiffness and Energy Absorption in Zero Poisson's Ratio Metamaterials

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Abstract

Stiffness and energy absorption are critical characteristics in mechanical structures, influencing their performance, safety, and durability under diverse loading conditions. While traditional materials derive these properties from their chemical composition, metamaterials – engineered materials with unique internal structures – achieve tailored mechanical properties through geometric design rather than the properties of their base materials. Recent advancements have focused on chiral metamaterials, where chirality-defined as the interaction between tensile/compressive and torsional forces that introduces additional rotational freedom-manifests through twist deformation under uniaxial compression, a property rarely observed in uniform materials. Thus, unlike uniform materials, these metamaterials exhibit a unique behavior: their structure rotates while undergoing compression or tension.

Building on previous work that introduced a novel compression-torsion coupled (CTC) metamaterial unit cell design with six defining geometrical parameters – capable of varying degree of chirality and transitioning from semi-achiral to highly chiral behavior through modifications to the infill ratio – this study shifts focus from individual cell design to the impact of cell networking and arrangement on the overall mechanical properties of metamaterial structures. The unit cell's design supports both clockwise (CW) and counterclockwise (CCW) configurations, offering flexibility in achieving tailored deformation responses.

A key focus of this research is the development of zero Poisson's ratio structures, achieved by combining CW and CCW unit cells in equal proportions. Thirty-two distinct configurations of a 4×4×4 unit cell assembly were analyzed to explore the variability in stiffness and energy absorption resulting from different unit cell arrangements. Finite Element Analysis (FEA) conducted in COMSOL Multiphysics 6.0 was complemented by experimental validation using 3D-printed samples produced via selective laser sintering (SLS) with Nylon 12. The stiffness and energy absorption of each configuration were measured under quasi-static compression by 10% of the sample's initial height.

Results revealed substantial differences in mechanical properties across configurations, despite identical geometrical parameters and unit cell counts. The configuration with an "oxox/oxox/xoxo/oxox" pattern in the XY direction and an "xoxo" pattern in the Z direction exhibited the lowest stiffness and energy absorption, while an "oooo/oooo/xxxx/xxxx" pattern in the XY direction and an "ooxx" pattern in the Z direction demonstrated the highest values. The comparison between these two configurations shows a difference exceeding 40% in both stiffness and absorbed energy. These findings underscore the significant impact of network arrangement on metamaterial properties, enabling the design of structures with a wide range of stiffness and flexibility to meet specific application requirements.

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