Abstract

Auxetic materials, characterized by their negative Poisson's ratio (NPR), exhibit unique deformation mechanisms such as lateral expansion under tension and contraction under compression, enabling enhanced stiffness, energy absorption, and adaptability compared to conventional materials. These properties have made auxetic meta-structures highly attractive for advanced engineering applications, including vibration mitigation, impact resistance, and lightweight structural design. Despite their potential, realizing both tunable dynamic performance and efficient energy dissipation in auxetic systems requires systematic investigation across multiple scales of design and material gradation.

This thesis presents a comprehensive study on the vibration control and energy absorption performance of architected auxetic meta-structures, encompassing smart sandwich plates and tubular/rectangular auxetic systems. The first part focuses on active vibration control (AVC) of smart auxetic sandwich plates with tetrachiral and butterfly-inspired cores. Dual-functionally graded (dual-FG) nanocomposite and CFRP-type face sheets, combined with piezoelectric sensor-actuator layers, are modeled using a serendipity interpolation-based finite element framework with first-order shear deformation theory (FSDT) kinematics. The effective anisotropic properties of the auxetic cores are obtained via RVE-based homogenization. Parametric studies reveal that core geometry, ligament length, wall thickness of tetrachiral core, and CNT reinforcement in FG skins enable precise tuning of stiffness, auxeticity, and vibration suppression in auxetic sandwich structures. In addition, butterfly-inspired cores are found to offer superior auxetic behavior and enhanced dynamic controllability compared to conventional re-entrant designs. Closed-loop velocity feedback control effectively mitigates induced vibrations, demonstrating the synergy between auxetic geometry and active control.

The second part addresses energy absorption and crashworthiness of auxetic meta-structures under quasi-static compression. Hybrid auxetic tubular and rectangular configurations are optimized for stiffness, stability, and progressive collapse. In tubular designs, elliptical-hole auxetic tubes with central rib reinforcements exhibits up to 500% improvement in yield strength and 87% increase in plastic energy dissipation. However, in rectangular hybrid designs, infill-based rectangular chiral auxetic honeycombs (RCAH) demonstrates the highest peak force and energy absorption under identical material volume. Parametric studies highlight the critical role of ligament rotational flexibility and chiral angle on crushing performance. Selective reinforcement with PU foam further enhances specific energy absorption and plastic dissipation, illustrating the potential of hybrid auxetic-foam architectures for advanced impact-resistant applications.

Collectively, this work establishes clear design guidelines linking auxetic microstructure, material gradation, and macroscopic mechanical response. It demonstrates that smart sandwich plates with various auxetic core topologies and advanced composite face sheets can achieve precisely tunable dynamic performance and effective vibration suppression. Separately, tubular and rectangular hybrid auxetic structures can be optimized for high stiffness, stability, and superior energy absorption, providing a framework for lightweight, adaptive, and impact-resilient structural applications.

Keywords: Auxetic meta-structures; Advanced composite face sheets; Active vibration control (AVC); Finite element modeling (FEM); Crashworthiness; Tubular and rectangular auxetic structures; Progressive collapse; Tunable stiffness.