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Design and Fabrication of Bioinspired Hierarchical Dissipative Elastic Metamaterials

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Hierarchical structures with constituents over multiple length scales are found in various natural materials like bones, shells, spider silk and others, all of which display enhanced quasistatic mechanical properties, such as high specific strength, stiffness, and toughness. At the same time, the role of hierarchy on the dynamic behavior of metamaterials remains largely unexplored. This study numerically and experimentally assesses the effect of bioinspired hierarchical organization as well as of viscoelasticity on the wave attenuation properties of continuous elastic metamaterials. We consider single-phase metamaterials formed by self-similar unit cells with different hierarchical levels and types of hierarchy. Two types of structures are considered: a hub-spoke geometry with thin connecting elements and nested hierarchical organization, and a crosslike porous geometry with external hierarchical organization. In the first, hierarchical elements occur at similar size scales, while in the second they differ by one order of magnitude. Results highlight a number of advantages through the introduction of structural hierarchy. Band gaps relative to the corresponding nonhierarchical structures are mostly preserved in both types of structures, but additional hierarchically-induced band gaps also appear, and the hierarchical configuration allows the tuning of band-gap frequencies to lower frequencies in the crosslike porous geometry, with a simultaneous significant reduction of the global structural weight. We show that even small viscoelastic effects are essential in determining the overall attenuation behavior, including between band gaps. Finally, we verify the numerically-predicted multifrequency band gaps by experimental characterization of the transmission properties of crosslike structures. The approach we propose allows the incorporation of hierarchical organization in existing metamaterial configurations, with the corresponding improvement of wave-damping properties, thus extending application possibilities for elastic metamaterials to multiple frequency scales.

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I. INTRODUCTION

Biological structural materials are renowned for their exceptional mechanical characteristics, often surpassing synthetic high-performance materials [1]. Spider silk, bone, enamel, limpet teeth are examples of materials that combine high specific strength and stiffness with outstanding toughness and flaw resistance [2–4]. Many studies have shown hierarchical structure to be responsible for these properties, e.g., providing many energy dissipation and crack deflection mechanisms over various size scales to contribute to high toughness [5]. However, studies in biomechanics linking material structure to function have mainly been limited to the quasistatic regime while the dynamic properties of these materials have been somewhat less investigated although notable examples of impact tolerance (e.g., the bombardier beetle's explosion chamber [6]) or vibration damping (e.g., the woodpecker skull [7]) have been observed.

A systematic study of the dynamic properties of composite structures such as those found in biomaterials can exploit analysis tools and methods widely applied in

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