ABSTRACT

Biological materials are built from a fairly small number of naturally occurring elements and compounds. To compensate for the lack of diversity in these building blocks, biological organisms, through millions of years of evolution and natural selection have evolved a wide range of innovative structures to achieve optimized performance in interacting with their natural environments. The focus of this work is on understanding the evolution strategies employed by natural organisms that encounter dynamic mechanical loads such as impact events, repeated cyclic loading events and structures that are tuned to harness mechanical vibrations. Insights gleaned from understanding the mechanisms involved can find potential applications towards lightweight structural materials and mechanical sensors.

We study cancellous bone, a naturally occurring lightweight micro-architected material and show that resistance to fatigue failure is sensitive to a microarchitectural trait that has negligible effects on stiffness and strength – the proportion of material oriented transverse to applied loads. Using models generated with additive manufacturing, we show that small increases in the thickness of the elements oriented transverse to the loading direction can increase fatigue life by 10 to 100 times. We show that the mechanism can be extended to synthetic microlattice structures, where fatigue life can be enhanced by 5 to 9 times with only negligible changes in stiffness and strength.

We then move our focus to natural structures tuned to harness mechanical vibrations. Mosquitos lack tympanic ears to detect sound. Instead, they rely on their plumose antennae, light-weighted sensory structures which detect sound induced air vibrations. Mosquitos use audition in different behavioral contexts. Here, we study the antenna of two species known to use hearing for different functions. Through the use of geometrically accurate computational models, we find that the mechanical design of the antenna is associated with the specific biological function of hearing in each species. Structurally, intersegmental variation and sensory hairs in the antenna are responsible for increased sensitivity and tuning of the mechanical response. Mechanical and neurophysiological mechanisms promote the detection of specific acoustic cues amidst the noise produced by their own wingbeats.

Finally, we focus our efforts on natural structures that encounter high-energy impact loading in their ambient environments. Woodpeckers are known to peck at trees every day through their

15-year lifespan while showing no evidence of brain damage. High fidelity finite element simulations in combination with an additive manufacturing experimental approach is utilized to unveil two main features in the woodpecker head that may contribute to the absence of brain damage; the bar structure of the jugal bone acting as a stress deflector and the high natural frequency in the skull bone acting as a frequency isolation tool.

Another natural organism that encounters high-energy impacts is the mantis shrimp. This aggressive marine crustacean utilizes a shield-like segment of its abdominal armor called the telson to defend itself from blows of conspecifics during ritualized fighting. We quantify the effect of ridges present on the dorsal surface of the telson. First, we show that ridges play a role in modulating stiffness of the mechanical system dependent on the point of application of the load. Second, under dynamic loading, ridges may act as wave traps retarding the propagating stress wave to prevent significant damage to the telson under impact. Finally, we extend the concept of the ridged geometry to bio-inspired curved shells, where we show an interplay between competing mechanisms that allows such structures to show the potential for large energy dissipation within controlled stiffness bounds.