

# Anisotropic Shear Properties of Organic Interfaces in Bio-composite Materials

Kian Tadayon, Benny Bar-On,\* and Igor Zlotnikov\*

Understanding the functional role of organic interfaces in highly mineralized biogenic composites remains a challenge in biological materials research. Here, a novel experimental and analytical approach is presented to directly probe the anisotropic shear properties of sub-micron interfaces in composite materials. Using focused ion beam (FIB) milling, specialized shear cantilevers containing a single organic interface is fabricated from the prismatic ultrastructures of two molluscan shells—*Atrina vexillum* and *Unio pictorum*. Nanoindentation-based bending experiments at distinct locations enable decoupling of anisotropic lateral and torsional shear responses. Analytical formulations, supported by finite element simulations, allow the extraction of the elastic, lateral, and torsional shear moduli. The findings reveal isotropic shear behavior in *A. vexillum*, contrasted by marked anisotropy in *U. pictorum*, where torsional shear modulus exceeds the lateral value by a factor of two. This is attributed to differences in the microstructural architecture of the organic interfaces. Despite similar compositions, structural differences result in distinct mechanical behaviors. Crucially, the developed methodology is not limited to biocomposites and can be applied to a wide range of composite materials where thin, confined interfaces critically influence performance. This work provides a novel, versatile tool for characterizing anisotropic interface mechanics across biological and engineered composite systems.

## 1. Introduction

The vast majority of highly mineralized biological materials have evolved to provide mechanical functions to organisms.<sup>[1–5]</sup> Mineralized walls of single-celled algae such as coccolithophores,

diatoms, radiolarians, and others afford protection and regulate interactions with the environment.<sup>[6,7]</sup> In multicellular algae, corals, and sponges, biominerals contribute structural stiffness.<sup>[8–10]</sup> The shells of mollusks, the endoskeletons of sea urchins, and avian eggshells support and protect the organism from predation.<sup>[11–13]</sup> In vertebrates, biominerals are critical components of skeletal structures and teeth, providing structural support, stiffness, wear resistance, locomotion, and protection.<sup>[14–16]</sup> In most of these examples, the biomineralized materials are hierarchically structured composites comprising mineral building units—typically crystalline calcium carbonate, phosphate, or amorphous silica—and an organic phase, such as proteins, polysaccharides, and lipids.<sup>[17]</sup> The organic phase is either incorporated into the mineral on a molecular scale or, at higher hierarchical levels, forms an independent structural component within the composite.<sup>[18]</sup> It binds the mineral units together, thereby contributing to structural integrity and playing a crucial role in the mechanical functionality of the biocomposite. Due

to its viscoelastic mechanical properties, the organic phase enables these stiff and tough structures to deform, move, selectively filter acoustic signals, absorb mechanical energy, and resist failure.<sup>[19–20]</sup>

The sustainable nature and functional efficiency of mineralized biological materials have attracted significant research attention to the relationships between properties, form, structure, and function in mineral-organic biogenic composites. Although this research has inspired numerous efforts to synthetically mimic natural structural motifs or to design materials inspired by these relationships,<sup>[21–23]</sup> a comprehensive understanding of the physical and mechanical mechanisms underpinning the remarkable performance of biologically formed materials remains elusive.

It is well established that, because the resources available to organisms for constructing mineralized tissues are very limited, functional efficiency is achieved through the 3D hierarchical organization of components.<sup>[24]</sup> These structures typically include relatively thin (sub-micrometer) organic interfaces that bind mineral components together.<sup>[25]</sup> Studying the mechanical performance of biological materials—particularly the role of relatively soft, compliant, and viscoelastic organic interfaces in highly mineralized biocomposites—is an active research area

K. Tadayon, I. Zlotnikov  
B CUBE – Center for Molecular Bioengineering  
TU Dresden  
01309 Dresden, Germany  
E-mail: igor.zlotnikov@tu-dresden.de  
B. Bar-On  
Department of Mechanical Engineering  
Ben-Gurion University of the Negev  
Beer-Sheva 84 10501, Israel  
E-mail: bbo@bgu.ac.il

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# Anisotropic Organic Materials

**Chemical Society (Great Britain)**



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