Abstract

Load bearing biomaterials are typically structured as composites, which comprise of rigid, elastic crystalline reinforcements and a more compliant, and energy-dissipating biopolymeric phase. The biopolymeric phase is found as interfacial regions (matrix) between adjacent crystalline elements, and/or as near-surface layers (film-coating) that overlay much more massive bulk material. As example, sutural interfaces in mineralized tissues (e.g., between the skull bones, and between the rigs of the turtle shell) are structured as zig-zag regions, filled by a biopolymeric material, and function as compliant joints that allow the biomaterial a certain degree of deformability that substantially stiffen the biomaterial beyond a certain deformation threshold (lock-in effect). As other example, film coatings of biomaterials are structured as a single or multi-layer of soft and viscoelastic biopolymers, which serve as an energy dissipating buffer upon local contact loadings. Both interfacial and film-coatings biopolymers provide the biomaterials diverse mechanical functions, including absorbing impact, detaining cracks, and filtering mechanical signals. Identifying the mechanical properties of these biopolymers are considered the key toward understanding the underlying structure–function relationships in various load-bearing biological materials; however, many of these relationships are yet unknown. Moreover, due to the small dimensions and irregular shapes of this biopolymers in the biomaterial (as interfacial or coating regions)—measuring their mechanical properties is a prime challenge in biomaterials science. In the first part of my study, I employ mechanical modelling, analytical formulations and numerical simulations, by which I analyze the interfacial force–depth relationships, stress distribution, and indentation modulus of the interfacial region in biomaterials; consequentially, I establish an analytical framework that connects these results to the elastic properties of the underlying matrix and reinforcement components, which is generally applicable for a broad range of biomaterials. In the second part of this study, I introduce a theoretical framework that links the interfacial dynamic modulus of a biomaterial to the extrinsic dynamic modulus of a larger-scale biomaterial segment. This theoretical framework enables to back-calculate (via simple linear scaling) the interfacial dynamic modulus of biomaterials from their far-field dynamic mechanical analysis— demonstrated on zigzag-shaped sutural interfaces. In the third part of the study, I analyze the dynamic indentation modulus of viscoelastic film-coatings and introduce a theoretical modelling that provide analytical relationships between the dynamic modulus of the viscoelastic film, the film thickness, and the overall dynamic indentation modulus of the film-substrate laminate. Accordingly, I propose a methodological approach to back-calculate the film dynamic modulus from dynamic indentation measurements on the laminate. The modeling outcomes and its analytical relationships are insensitive to tip shape variations, independent of the absolute moduli magnitudes of the film and substrate— and are thus generally applicable for the broad dimensional range of laminates with mechanical characteristics. In the last part of the study, I used experimentally based structural modelling and FE simulations to analyze the mechanical significance of the soft bi-layer skin coating of the turtle shell in terms of resistance to surface damage upon extensive indentations. I identify that the functional bi-layer skin of the turtle shell (soft-softer-hard) serves as a bumper–buffer mechanism upon local indentation loadings. This material-level adaptation protects the inner core from the highly localized indentation loads via stress delocalization and extensive near-surface plasticity. The practical and conceptual outcomes of my study can potentially be adapted into various other materials science disciplines including nanocomposite-, bio-inspired–, and biomedical-materials, and to pave the way to the design of new architectural engineering materials with exceptional load-bearing capabilities.