Abstract

Load-bearing biomaterials are typically structured as composites. They comprise of rigid, elastic crystalline reinforcing layers and a more compliant, energy-dissipating biopolymeric phase. The biopolymeric phase is found as part of an interfacial matrix between adjacent crystalline elements, and/or as a coating in near-surface that overlay a bulk material. As an example, the sutural interfaces in the mineralized tissues like those found in the skull or between the rings of a turtle’s shell are structured as zig-zag regions. They are filled with a biopolymeric material and function as compliant joints that allow the biomaterial a certain degree of deformability. They 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 multiple layers of soft and viscoelastic biopolymers, which serve as an energy dissipating buffer to local contact loadings. Both interfacial and film-coating biopolymers provide biomaterial’s diverse mechanical functions, These functionsinclude absorbing impact, detaining cracks, and filtering mechanical signals. Identifying the mechanical properties of these biopolymers is considered key to understanding the underlying structural–functional relationships in various load-bearing biological materials. However, many of these relationships are currently unknown. Moreover, due to their small dimensions and irregular shapes of biopolymers in a biomaterial— measuring their mechanical properties is a primarty challenge for biomaterials science. In the first part of this study, mechanical modelling, analytical formulations and numerical simulations are employed to analyze the force–depth relationships, stress distribution, and indentation modulus of the interfacial region in biomaterials. This analysis is used to establish an analytical framework that connects these results to the elastic properties of the underlying matrix and reinforcement components. This framework is generally applicable to a broad range of biomaterials. In the second part of this study, a theoretical framework is introduced which links the interfacial dynamic modulus of a biomaterial to the extrinsic dynamic modulus of a larger-scale biomaterial segment. This theoretical framework enables the calculation (via simple linear scaling) of the interfacial dynamic modulus of biomaterials from their far-field dynamic mechanical analysis This approach is demonstrated on zigzag-shaped sutural interfaces. In the third part of the study, the dynamic indentation modulus of viscoelastic film-coatings and analyzed and a theoretical model is introduced. This model provides 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, a methodological approach to calculate the film dynamic modulus from dynamic indentation measurements on the laminate is proposed. These modeling outcomes and analytical relationships are not sensitive to variations in tip shape and are independent of the absolute moduli magnitudes of the film and substrate. They are thus generally applicable for the broad range of laminate dimensions with mechanical characteristics. In the last part of the study, experimentally-based structural modelling and FE simulations is used 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. The functional bi-layer skin of the turtle shell (soft-softer-hard) is identified as serving 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 this study can potentially be adapted into various other materials science disciplines including nanocomposite, bio-inspired, and biomedical-materials. This study may also support the design of new architectural engineering materials with exceptional load-bearing capabilities.