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Materiomics: Multiscale Mechanics of Biological Materials and Structures

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Materiomics: Multiscale Mechanics of Biological Materials and Structures

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PREFACE

This book contains lecture notes from leading researchers in the field of mechanical sciences of biological materials and structures, with a focus on the behavior of biological materials under extreme physical, chemical, physiological and disease conditions, as well as on biomimetic and bioinspired material development for technological applications. To provide a thorough foundation for this research, the course will focus on the integration of advanced experimental, computational and theoretical methods applied to the study of biological materials across disparate length- and time-scales. Specific attention is paid to the integration of theoretical, computational and experimental tools that could be used to assess structure-process-property relations and to monitor and predict mechanisms associated with the function and failure of biological materials and structures composed of them.

The chapters provide overviews of emerging fields of research and highlight important challenges and opportunities. Hence, the three core objectives of this book are to: (1) Provide a clear description of methods and tools, (2) Present case studies that demonstrate the impact of multiscale modeling approaches, and to (3) Provide a carefully selected list of core references and citations for the interested reader. The case studies include the analysis of key biological materials, the biodegradation of implanted synthetics, the transfer of biological material principles towards bioinspired applications, and the exploration of diseases in which material failure plays a critical role. The approaches presented in this book emphasize the fundamental principles of physics, chemistry and mechanics, and they rely on quantum mechanics, molecular dynamics and continuum analyses. The use of basic sciences creates a powerful common platform regardless of the specific material system considered, and can therefore be transferred to other types of materials and structures.

The editors of this volume would like to thank the CISM team for their help and support in preparing this book. They are also grateful to the contributors of the various chapters for their time and efforts, and acknowledge the support of their research on the mechanical behavior of materials and structures over the years from the National Science Foundation, the Army Research Office, the Office of Naval

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Roberto Ballarini and Markus Buehler

CONTENTS

Introduction

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1 The promise of multiscale modeling and bioinspired engineering

The field of multiscale mechanics has witnessed an exciting development over the past decades, culminating in recent years in breakthrough discoveries that have blurred the boundaries between living and synthetic materials, and have enabled the first wave of high-impact applications of new materials and structures in biomedical, energy and structural engineering applications. Multiscale modeling offers promise for facilitating the creation of engineered materials and structures with properties that resemble those of biological systems, in particular the ability to self-assemble, to self-repair, to adapt and evolve, and to provide multiple functions that can be controlled through external cues. In addition to their potential for enabling the realization of advanced technological applications, the challenges posed by the complex behavior of hierarchical tissues and cells in biological systems represent terrific opportunities to open new chapters in the development of the mechanical sciences. It is remarkable how the mechanics practiced by da Vinci, Galileo, Newton and other great scientists has evolved to a point where now it interconnects intimately with the life sciences, and that it could ultimately contribute to the solutions of critical problems encountered in such disparate fields as medicine and the aging infrastructure.

Yet, in spite of significant advancements in the study of biological materials in the past decade, a lack of sufficient understanding of the fundamental physics of many phenomena in biology is hindering our progress towards the building of sufficiently robust models, simulation tools and experimentation. For example, the understanding of the mechanisms of failure in biological systems remains elusive, including those involved in the breakdown of diseased tissue, the failure of biological components due to injuries, and the ability of biological systems to mitigate adverse effects of damage through

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self-healing mechanisms. The cost-effective manufacturing of bioinspired products is also an enormous challenge, because humans have traditionally relied on top-down fabrication paradigms that simply cannot be used to efficiently produce the highly hierarchical structures that *Nature* builds from the bottom-up. Improved understanding of how biology originates from the molecular scale and proceeds to genes (DNA), proteins, tissues, organs and organisms can guide our development of self-assembly technologies that will allow mass production and utilization of bioinspired materials for daily life applications like consumer products, medical devices and large-scale systems in the aerospace, defense and building industries.

The highly complex nature of biological structures, which involve multiphysics and multiple length and time scales, has inspired the new field of study referred to as materiomics, which is defined in the next section and is reflected by the contents of this book.

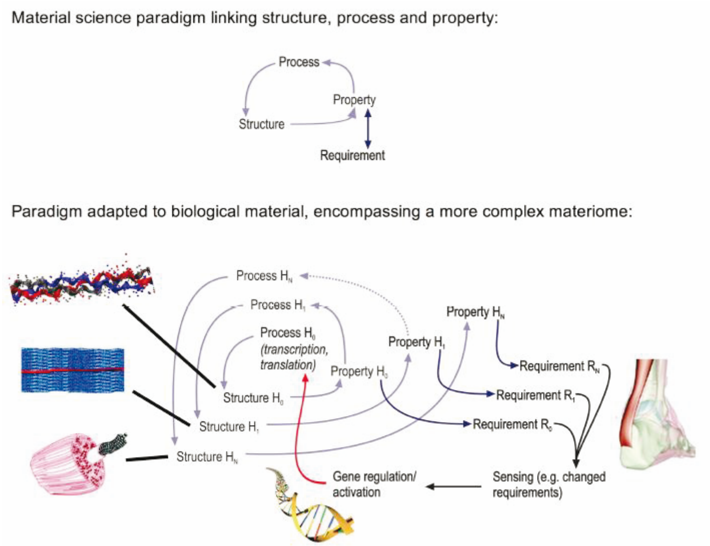

Figure 1. Schematic representing the materiomics approach (Cranford and Buehler (2012)).

2 Materiomics

What is materiomics? As illustrated schematically in Figure 1, it is an approach rooted in physics that extends the structure-process-propertyrequirement paradigm that has been developed by materials scientists to the analysis of highly complex biological and synthetic materials and structures. The schematic emphasizes that materiomics is a holistic systems approach to the theoretical, computational and experimental study of materials that aims to identify links between processes, structures, and properties across multiple scales, from nano to macro. The integrated view and description of the building blocks of a hierarchical structure and their fundamental interactions is referred to as the material's materiome. Materiomics thus provides a systematic description of universal mechanisms by which complex system functionality and failure can be explained from the materiome. As sketched in Figure 2, similar to the way music is created from a finite number of musical notes, the relationships between form and function found in natural materials provide the mechanistic basis to explain the remarkable mechanical properties of materials like nacre, bone, spider silk and collagen. For example, it has been determined that the toughness of bone and of sea shells of the crossed-lamellar type are the result of multiple and synergetic toughening mechanisms made possible by a half-dozen distinct microstructural features (Kamat et al. (2000); Ballarini et al. (2005)). In fact, for bone, sea shells and most other biological objects the traditional concepts of "structure" and "material" are blurred, and integrated in a vision that derives functional properties by systematically and strategically adapting multiple levels across numerous length- and time-scales (Figure 2). This viewpoint extends our current ability to engineer structures to the desired scale, and requires a multidisciplinary treatment of problems to incorporate physics, chemistry and advanced mathematics to develop complex models to design and predict performance.

New approaches that take advantage of mathematical tools such as material ologs (Spivak et al. (2011)) are important in arriving at a systematic analysis that reduces complexity to distill the essential features. Moreover, a range of experimental and computational tools is needed to measure and produce structures and properties at these variegated length- and time scales. A summary of key computational methods, synthesis, processing and experimental techniques is provided in Figure 3. It is evident that with modern tools a very broad range of scales can be seamlessly explored, thus allowing the realization of realistic multiscale analysis. Figure 4 depicts an impressive example of a precise experimental analysis of collagen microfibrils using the microtechnology-based material testing described in Chapter 3, something that would have been impossible just a few years ago.

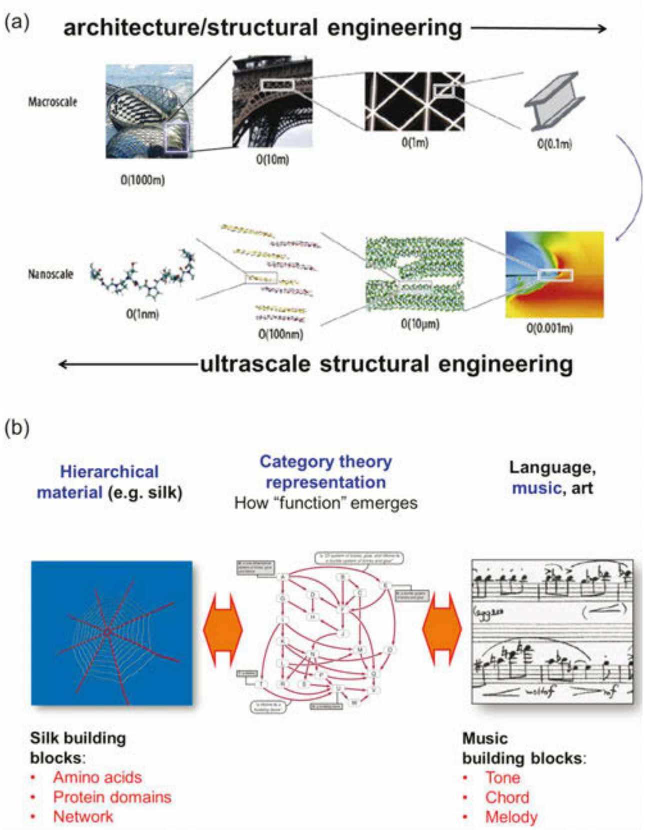

Figure 2. Common principles of biological and bioinspired material design, showing the merger of "structure" and "material" across different length scales in hierarchical materials (Buehler and Ackbarow (2007)).

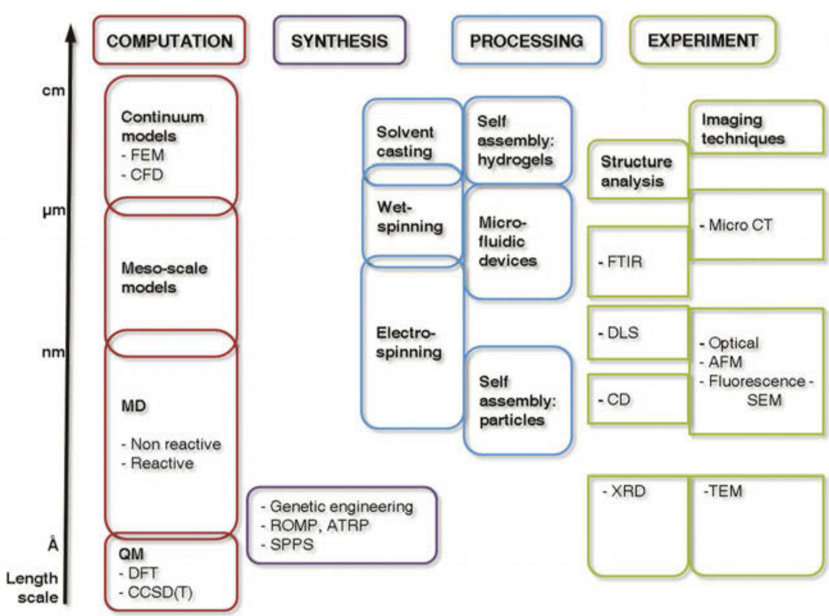

Figure 3. Overview of various computational and experimental tools, including synthesis, processing and imaging/manipulation techniques. The emergence of tools operating at different length scales now enables the analysis of materials across all relevant scales (Gronau et al. (2012)).

3 Motivation for studying biological structures: The superior performance of natural structures conferred by their hierarchical designs

Why should humans study biological structures and paradigms? Because *Nature* has created an extremely large number of high-performance prototypes that humans can reverse engineer and in turn use as inspirations for creating synthetic products with similar superior performances. This section focuses on but one strategy used by *Nature* to create materials and structures whose survival requires superior mechanical properties and structural behavior, namely highly hierarchical design.

The structures created by organisms, although made from rather mundane materials, show impressive properties that are clearly well-suited for

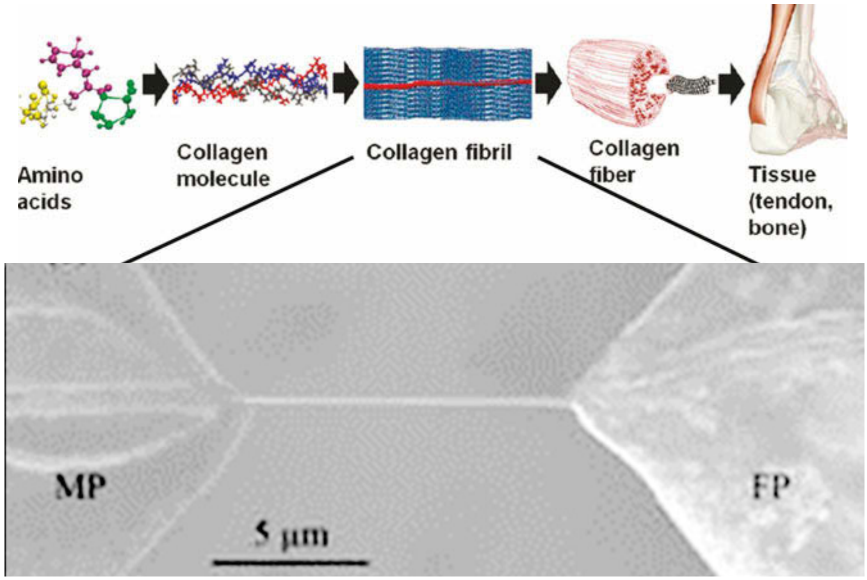

Figure 4. Example of advanced experimentation applied to test the nanomechanics of individual collagen fibrils. Results from such experiments can be compared to molecular modeling and enable us to ask fundamental questions about the physiology and disease of key construction materials in nature (adapted from Eppell et al. (2006)).

their intended functions. Structure/function/performance correlations have been assumed by scientists to be a result of evolutionary pressures inherent in natural selection. While proponents of "intelligent design" offer other explanations, the diversity of microstructure in structures such as molluscan shells and bone and their remarkable mechanical properties and self-healing mechanisms testifies to the flexibility and power of this approach. *Nature* achieves robust structures using as little mass as possible, through judicious arrangements of mundane polymeric and ceramic components. Be they primarily ceramic (tooth enamel, mollusc shell), polymeric (insect exoskeleton, plant cell walls), or more evenly balanced composites (antler, bone), biological materials are virtually all composites utilizing different proportions of the basic components and a variety of hierarchical structural architectures.

It is very instructive to compare the mechanical properties of biological structures with materials created by humans through the performance index paradigm pioneered by Ashby (Ashby (1992)). First, a brief primer on basic structural mechanics. Consider the simple extension of a rod of length, L, and cross-sectional area, A, made of a material with density, ρ (Figure 5). In terms of the applied force, F, and the elongation, δ , the stress and strain are defined as $\sigma = \frac{F}{A}$ and $\varepsilon = \frac{\delta}{L}$. For most engineering materials, the relation between σ and ε is linear at small values of strain, with a slope defined as the elastic (Young's) modulus, E. At the elastic limit, σ_f, the curve ends abruptly for brittle materials and is nonlinear for ductile materials up to the ultimate stress required to fracture the rod, σ_u. The area under the linear part of the curve up to a given strain, $\frac{\sigma^2}{2E}$, is defined as the elastic strain energy density and represents the potential energy conferred to the rod by the work performed by the applied force. If the strain is limited to values less than the yield strain, $\varepsilon_f = \frac{\sigma_f}{E}$, then the tie will return to its original length upon removal of the force. This behaviour is referred to as elastic, in that no energy is dissipated during a loading-unloading cycle. The total area under the $\sigma - \varepsilon$ curve represents the work done by the force to fracture the rod into two pieces; the work of fracture is defined as this work divided by the area of the surfaces created by fracturing the rod into two pieces.

If a relatively brittle structure contains a crack-like flaw and is treated as linear elastic, the stresses along the crack front are singular and therefore cannot be directly used to predict load carrying capacity. Instead, the force required to fracture the structure is determined by the stress intensity factor, K, which characterizes the stress and strain intensities in the vicinity of the crack front. The stress intensity factor depends on the geometry of the structure, the type of loading, and the specific crack shape; according to linear elastic fracture mechanics theory the crack will extend across the specimen when K reaches a critical value defined as the fracture toughness, K_c. The stress intensity factor is directly related to J, the energy available to overcome the material's resistance to crack extension, by the equation $K = \sqrt{EJ}$. Therefore the fracture toughness can be expressed in terms of the energy required to create the fracture surfaces, J_c, by the relation $J_c = \frac{K_c^2}{E}$.

Quantitative comparisons between materials can be made using the concept of material performance indices, parameters that quantify a material's ability to perform a certain function. The higher the value of the index, the better suited is the material for a given application. For a thorough discussion of the mechanical properties of natural materials and the origins of their superiority, the reader is referred to Ashby et al. (1995) and Wegst and Ashby (2004). Here we borrow from their discussions.

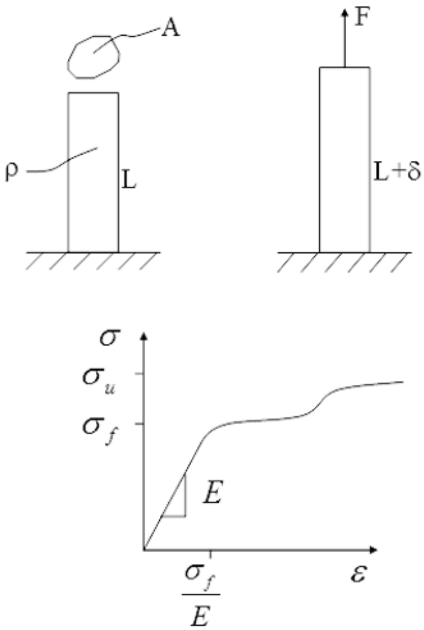

Figure 5. Simple elongation experiment and representative stress-strain curve.

Table 1. Performance indices for different types of structural elements.

Design	Tie in tension	Beam in flexure	Plate in flexure
Maximum strength to weight	$\frac{\sigma_f}{\rho}$	$\frac{\sigma_f^{2/3}}{\rho}$	$\frac{\sigma_f^{1/2}}{\rho}$
Maximum stiffness to weight	$\frac{E}{\rho}$	$\frac{E^{1/2}}{\rho}$	$\frac{E^{1/3}}{\rho}$
Large recoverable deformation	$\frac{\sigma_f}{E}$	$\frac{\sigma_f}{E}$	$\frac{\sigma_f}{E}$
Spring with minimum volume	$\frac{\sigma_f^2}{E}$	$\frac{\sigma_f^2}{E}$	$\frac{\sigma_f^2}{E}$
Fracture safe displacement controlled design	$\left(\frac{J_c}{E}\right)^{\frac{1}{2}}$	$\left(\frac{J_c}{E}\right)^{\frac{1}{2}}$	$\left(\frac{J_c}{E}\right)^{\frac{1}{2}}$

Consider first the minimum weight design of three simply loaded structures; a rod in tension, a flexed beam, and a flexed plate. The first two rows of Table 1 list the performance indices relevant to a minimum weight design of these structures that does not specify the shape of the element's cross-section. The fact that the most efficient material for a strong and light tie (or similarly stiff and light) subjected to simple elongation is the one that possesses the largest value of $\frac{\sigma_f}{\rho}$ (or similarly $\frac{E}{\rho}$) is perhaps obvious and can be guessed by someone that has never taken a course in mechanics. However, those that have studied structural mechanics know that beam and plates experience spatially varying stress and strain distributions that lead to performance indices that involve different rational exponents to the strength and stiffness.

Table 2. Stiffness to weight performance indices. The parentheses reflect the elastic modulus along the stiffer direction, and therefore are not representative of a stiff plate in bending that requires equal moduli in all directions (adapted from Ashby et al. (1995); Wegst and Ashby (2004)).

Material	E/ρ $(GPa/Mg/m^3)$	$E^{\frac{1}{2}}/\rho$ $(GPa^{\frac{1}{2}}/Mg/m^3)$	$E^{\frac{1}{3}}/\rho(GPa^{\frac{1}{3}}/Mg/m^3)$
Palm (Iriartea)	23	12.5	(10.1)
Mild steel	27	1.8	(0.8)
Balsa wood	20	14.1	(12.6)

Consider specific materials. Table 2 shows that for the stiff and light design, the performance index of mild steel is comparable (actually slightly higher) to that of the two representative woods. However, steel is not nearly as efficient as Palm or Balsa for beams or plate elements subjected to flexure. This data suggests that the various hierarchical microstructures of wood have evolved to ensure that trees are efficient in their response to the principal loads they must carry; bending of branches under their own weight and bending of trunks under wind loads. Similar insights are provided by Table 3 for the strong and light design criterion.

We now turn our attention to material choices for an elastic hinge, a component that is required to undergo relatively large deformation when loaded, and to return to its original shape when the load is removed. The performance index for the design of elastic hinges is $\frac{\sigma_f}{E}$, and it as listed in Table 4, leather, cartilage, and to a lesser extent, skin, are the best choices. To man's credit, rubber edges out its biological counterparts, although rubber is not usually thought of as a bioinspired material.

Table 4 also shows that silk fibre is the top choice for springs that are required to absorb the most energy per unit volume. In fact, it out performs

Table 3. Strength to weight performance indices.The parentheses reflect the elastic modulus along the stiffer direction, and therefore are not representative of a stiff plate in bending that requires equal moduli in all directions (adapted from Ashby et al. (1995); Wegst and Ashby (2004)).

Material	σ_f/ρ $(GPa/Mg/m^3)$	$\sigma_f^{\frac{2}{3}}/\rho$ $(GPa^{\frac{2}{3}}/Mg/m^3)$	$\sigma_f^{\frac{1}{2}}$ $(GPa^{\frac{1}{2}}/Mg/m^3)$
Mild steel	51	6.9	2.5
Balsa wood	160	64	(40.0)

man-made spring steel , and the natural elastic hinges leather and cartilage by significant margins. Its molecular design guarantees that silk can absorb, without fracturing, the energy introduced by the excursions of the spider and/or the desperate movements of its entangled prey.

Table 4. Performance indices relevant to hinges and springs (adapted from Ashby et al. (1995); Wegst and Ashby (2004)).

Material	σ_f/E	σ_f^2/E (MJ/m^3)
Spring steel	0.01	19.0
Soft butyl rubber	1.40	19.6
Single silk fiber	0.14	290.0
Cartilage	1.00	10.0
Skin	0.25	2.5
Leather	1.00	45.0

The last example involves cracked structures. Consider the specific case of choosing a material for a cracked structure that is required to survive large elastic deformation. Table 5 indicates that skin has the best performance index, despite having a much lower fracture toughness than steel or highly mineralized mollusc shell. Interestingly, the microstructural design of skin may have evolved to make it ideally suited for being stretched around our knuckles and elbows without tearing. We could not enjoy such movements if our skin had the fracture properties of man-made alloys or other biological materials.

The biological materials just described can therefore be considered prototypes of successful structural designs that *Nature* has provided to gratis and that can inspire us to create our own tailor made materials with similar performances. The major challenge is the development of methods for fabricating such highly hierarchical structures.

Nature is indeed impressive and inspiring.

Table 5. Performance indices for structures containing cracks (adapted from Ashby et al. (1995); Wegst and Ashby (2004)).

Material	$K_c = (EJ_c)^{\frac{1}{2}}$ $(MPa - m^{\frac{1}{2}})$	$\left(\frac{J_c}{E}\right)^{\frac{1}{2}}$ $(mm^{\frac{1}{2}})$
Mollusc shell	9.5	0.4
Mild steel	90.0	0.4
Skin	0.4	38.7

Bibliography

M.F. Ashby. *Materials selection in mechanical design.* Pergamon Press, 1992.

M.F. Ashby, L.J. Gibson, U. Wegst, and R. Olive. The mechanical properties of natural materials. i. material property charts. *Proc. R. Soc. Lond. A*, 450:123–140, 1995.

R. Ballarini, R. Kayacan, F.J. Ulm, T. Belytschko, and A.H. Heuer. Biological structures mitigate catastrophic failure through various strategies. *International Journal of Fracture*, 135:187–197, 2005.

M.J. Buehler and T. Ackbarow. Fracture mechanics of protein materials. *Materials Today*, 10(9):46–58, 2007.

S. Cranford and M.J. Buehler. *Biomateriomics.* Springer, 2012.

S. Eppell, B. Smith, H. Kahn, and R. Ballarini. Anano measurements with micro devices: Mechanical properties of hydrated collagen fibrils. *Journal of the Royal Society Interface*, 3:117–121, 2006.

G. Gronau, S. Tarakkad Krishnaji, M.E. Kinahan, T. Giesa, J.Y. Wong, D.L. Kaplan, and M.J. Buehler. A review of biopolymer structure-process-property relationships at multiple scales via integration of modeling and experimentation. *Biomaterials*, accepted for publication, 2012.

S. Kamat, X. Su, R. Ballarini, and A.H. Heuer. Structural basis for the fracture toughness of the shell of the conch strombus gigas. *Nature*, 405: 1036–1040, 2000.

D. Spivak, T. Giesa, E. Wood, and M.J. Buehler. Fracture mechanics of protein materials. *PLoS ONE*, 6(9):e23911, 2011.

U.G.K. Wegst and M.F. Ashby. The mechanical efficiency of natural materials. *Philosophical Magazine*, 21:2167–2181, 2004.

Multi-scale modeling of biomaterials and tissues

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Abstract

Computer simulation has emerged as a powerful tool to investigate and design materials without ever making them. Predicting the properties and behavior of materials by computer simulation from the bottom-up perspective has long been a vision of computational materials scientists and, as computational power increases, modeling and simulation tools are becoming crucial to the investigation of material systems. The key to achieving this goal is using hierarchies of paradigms that seamlessly connect quantum mechanics to macroscopic systems. Particular progress has been made in relating molecular-scale chemistry to mesoscopic and macroscopic material properties essential to define the *materiome*. This chapter reviews large-scale atomistic and coarse-grain modeling methods commonly implemented to investigate the properties and behavior of natural and biological materials with nanostructured hierarchies. We present basic concepts of hierarchical multiscale modeling capable of providing a bottom-up description of chemically complex materials and some example applications related to the study of collagen material at different hierarchical levels.

1 Introduction to the multi-scale modeling paradigm

In recent years, researchers consider computer simulations as a tool to design new materials, new structures, or to develop new drugs, without the need to synthesize them. A vision of materials scientists has long been to

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