Chapter 1

Introduction to Materials Engineering

The science of biology differs from other basic sciences in one important manner. Whereas all fields ask the fundamental questions: what, where, when, and how, only in biology do we also ask why. This is because the things studied in chemistry, physics, geology, etc., have complex structures that lead to interesting and often important properties, but these things do not have inherent functions in the sense that their properties are organized to achieve specific goals. For example, the physical interaction of photons with a crystal of quartz creates interesting optical effects, but it is difficult to ascribe any purpose to this interaction. In biology, however, we recognize that all living things are organized around a complex set of goals that lead to the growth and reproduction of organisms and to the survival and evolution of species. Further, our observations clearly indicate that the complex structures in organisms have properties that are strongly associated with these goals; that is, they have important functions. Once we accept this notion that function is the essence of biology, we can understand the importance of design, which is simply the relationship between the structure and the function of the various components that exist in living systems.

Applied science or engineering provides a strong parallel to biology in that the objects produced in engineering are all inherently functional. That is, synthetic structures have been designed for a specific purpose. Indeed, engineers have spent many years studying how to create good designs, and the principles of design derived for synthetic structures can provide us with interesting insights into the way that organisms have solved similar problems. Here we must recognize that the word “design” can be used in two ways. Firstly, design can represent the process by which a functional structure is created, and in this sense engineers are designers. In biology, we recognize that evolution is the designing process, and evolution works in a very different manner from engineering design. Most importantly, for engineers the process of design is a series of conscious decisions about the method of approaching some predetermined goal, and engineering design principles provide a guide for attaining these goals. For evolution as designer there are no predetermined goals, with the exception of survival. Thus, selection of various, possibly random, alterations in the structure of an organism may lead to a change in the organism’s function, which then presumably has an effect on the fitness or survival of that organism. The second definition of design may simply be, as stated above, the relationship between structure and function of a machine or an
organism. This is an important distinction, and this second definition of design is the one that will be used here because we are not concerned with the process of evolution, rather we are interested in understanding how organisms function. In this context, we should recognize that design is a rather neutral term in that there can be good designs and bad designs. Hopefully the design process will lead to the creation of good designs, and a major goal of biomechanics is to use engineering design principles to analyze biological systems to evaluate the quality of biological designs. For example, materials science provides a conceptual basis for understanding the design of structural materials, which can be applied to an analysis of the design of materials that have evolved in plants and animals. This is the focus of the current chapter.

Consideration of the effective use of energy by living organisms is an important unifying principle that can be used to link biomechanics to animal performance, behavior, ecology, and evolution. We pay considerable attention to locomotor energetics in this book. This linkage is generally expressed with the concept of a balanced energy budget for an organism, which states that there must be a balance of energy input and utilization for an animal to survive, reproduce, and prosper. The key to energy budgets is that net energy input (energy intake as food less metabolic waste) must be partitioned between a variety of conflicting uses, including basal metabolic costs, activity costs, somatic growth, and reproductive growth. Somatic growth is necessary for animals to reach sexual maturity, and reproductive growth is necessary to produce offspring for the next generation, and in general animal fitness is directly linked to success in producing offspring. Thus, any reduction in activity costs leaves more energy available for growth and reproduction. Locomotion in most animals is an energy-demanding form of activity, but because feeding usually involves locomotion, it is also rather directly linked to food intake. Thus, biomechanical designs that reduce the energetic cost of movement could play a crucial role in the overall energy balance for an animal by making more energy available for reproduction, hence improving the fitness of the animal.

Biomechanics can also reveal insights into the design of animal skeletons, an approach that treats animals as machines and allows us to develop an understanding of the internal mechanisms that underlie structural support and locomotion. Thus, we can investigate the materials that skeletons are constructed from and the shapes and interactions of the skeletal elements that together form the functional whole of the animal machine. Materials scientists have developed an extensive set of design principles that relate the molecular and microscale structure of materials to functionally important mechanical properties, such as strength, stiffness, and toughness. This is the subject of chapters 2–8. Before we delve into the details of biomaterials design, it will be useful to consider some of the general features of the structural materials that have evolved in living systems.

1. NATURE BUILDS WITH POLYMERS. This statement probably best represents the nature of biomaterials, as there are few, if any, biomaterials that are completely devoid of organic polymers. The polymers are typically protein or polysaccharide in general chemical structure, but the details of the macromolecular structure in any particular material are both complex and elegantly tailored to the specific function of the material in a living organism. One of the dominant themes we will follow is the relationship between biopolymer sequence and three-dimensional polymer conformation.
In the case of structural proteins, which dominate in animal materials, the amino-acid sequence to protein conformation relationship provides the clearest link between genetics and a biomaterial's structure and function. Protein polymers in structural biomaterials are exceptionally complex and diverse, and this diversity of microstructure provides amazing control over material properties. Polysaccharide polymers are dominant in plants but also common in animal materials, although their structural diversity is less than is found in proteins. Again, polymer sequence controls microstructure, and hence determines material properties.

2. THE VAST MAJORITY OF NATURAL MATERIALS ARE FIBER-REINFORCED COMPOSITES. Many of the structural biopolymers mentioned above are assembled into fibrous structures that play dominant roles in the materials where they are found. For example, the protein polymer collagen self-assembles into nanoscale filaments that organize into parallel arrays. In the composite we call bone, collagen filaments are infiltrated by inorganic (calcium phosphate) crystals to form a stiff and strong composite material. Similarly, cellulose molecules self-assemble into nanoscale filaments that associate with other, less structured, polysaccharides or with lignin to form a completely organic fiber-matrix composite, such as that found in plant cell walls. These two examples illustrate a broad diversity of rigid composite materials in biology, but other materials combine protein or polysaccharide filaments with softer matrices that create soft composites, with very different properties.

3. BIOMATERIALS EXHIBIT HIERARCHICAL COMPLEXITY OF STRUCTURE. That is, nanoscale structures, which arise from the self-assembly of individual protein or polysaccharide molecules within or in association with individual cells, assemble into several levels of structural organization in the formation of macroscale materials and structures, such as a tendon or a bone or a hoof. There are at least two possible roles for hierarchical complexity. First, it may provide structural mechanisms for fine-tuning mechanical properties and for controlling anisotropy of properties. Second, the hierarchical organization of structural materials may arise from mechanisms that allow the cellular synthesis of macromolecules to be organized into macroscopic material systems that are orders of magnitude larger than the cells and the molecular building blocks that they synthesize. At present we can recognize hierarchical organization in many structural biomaterials, but we are only beginning to understand the roles that the various levels in the structural hierarchy play in the formation and the function of the hierarchical materials.

4. BIOMATERIALS ARE REMARKABLY DIVERSE. However, they can be grouped into three structural-design motifs. The majority of artificial structures that we encounter every day are essentially rigid. Stationary structures, like classic Greek temples and the vast array of buildings and bridges we see in the modern world, are supported by large columns or beams that are made from rigid materials, such as stone, steel, concrete, or wood. These columns and beams function by resisting compression and bending forces, created largely by gravitational loading, with minimal deformation. Most artificial mobile structures are also rigid and are built largely from rigid materials, but mobile structures, such as airplanes, are frequently built from lightweight,
high-performance materials such as aircraft aluminum and, more recently, carbon-fiber composites. The key feature of rigid-material designs is that they have high stiffness and hence resist deformation under all loading regimes, which means they strongly resist deformation under compression, tension, and shear loading. The horse shown in fig. 1.1A may seem to be supported by rigid columns of bone, but this is a gross oversimplification because animals are highly mobile, and they achieve mobility by having structural systems that are deformable. Individual bones are indeed rigid structures, and are made from a stonelike mineralized organic composite. However, in order to achieve mobility of support, animals employ a wealth of highly deformable components that are made of two very different alternate material-design motifs (fig. 1.1B). These motifs will be called tensile materials and pliant materials, to clearly distinguish them from the rigid materials that are highlighted in fig. 1.1A.

Because most biomaterials can be described as fiber-reinforced composites, we will start by thinking about the design of tensile materials because they are generally constructed as parallel arrays of essentially pure polymeric fibers, so their design is relatively simple. In addition, these tensile materials provide the fiber phase for many of the rigid and pliant composites we see in nature. Tensile elements play a unique set of roles in both artificial and natural structures. Their function, generally, is to be sufficiently stiff and strong to effectively transmit large forces in tension with little deformation and hence little energy storage. At the same time, they must be flexible (i.e., have little resistance to bending) so that the tensile forces can be transmitted, through suitable devices, around corners. The common artificial devices that meet this requirement are called ropes or cables, and sailboats and sailing ships employ numerous tensile structures that play key roles in the boats’ propulsive systems. Masts and spars were traditionally made of wood, a rigid biological composite; although in modern vessels they are made from aluminum or carbon-fiber composites. But masts must be supported by “stays,” spars must be controlled by “sheets,” and sails must be raised by “halyards.” In sailboats the ropes that form the sheets and halyards pass through pulleys so that their tensile forces can be transmitted around corners. Pliant composites are not often found in artificial structures, but they are abundant in animals.

If we look inside the horse’s forelimb in greater detail (fig. 1.1B) we see a combination of rigid, tensile, and pliant structural materials that form its skeletal support system. The rigid bones do indeed form structural-support columns, but the bones alone do not form a stable column. The individual bones are arranged at angles, and they would simply collapse under their own weight if not stabilized by other structural elements. A dynamically stable vertical column is created by structural components that control the rotation and translation of the angled bones. Tensile structures called ligaments hold the bones together in structures we call joints, so that compressive forces can be transferred from bone to bone. Ligaments prevent bones from sliding apart (i.e., dislocating) because they are rigid in tension, and at the same time the ligaments allow the bones freedom of rotation because they are flexible. Tendons, another tensile structure, attach muscles to bones, and this allows active muscular contractions to stabilize the limb column in static loading and to move the limb in locomotion. Ligaments and tendons are made from the tensile material collagen, in the form of rope-like bundles of essentially parallel collagen fibers. In addition to collagen, silk and silklke protein fibers are also abundant in tensile systems, although collagen is the primary fiber-forming biopolymer in animals.
Bone, the rigid composite material that forms the major structural elements in the vertebrate skeleton, is a composite of collagen fibers infiltrated by mineral crystals of calcium phosphate, but there is a broad diversity of rigid composite materials in biology. The fiber-forming polysaccharide chitin is the reinforcing fiber in the rigid composite that forms arthropod cuticle, and cellulose is the ubiquitous fiber-forming

Figure 1.1. Skeletal materials. The bony skeleton of the horse when viewed on its own might lead one to believe that the animal is supported by stone columns, rather like the marble columns of Greek temples. In reality, support is achieved by the combination of rigid elements called bones that are interconnected with and attached to muscles through tensile elements called ligaments and tendons. The whole animal is surrounded by the pliant composite skin, and the contact surfaces of bone are lined with another pliant composite, cartilage.

Bone, the rigid composite material that forms the major structural elements in the vertebrate skeleton, is a composite of collagen fibers infiltrated by mineral crystals of calcium phosphate, but there is a broad diversity of rigid composite materials in biology. The fiber-forming polysaccharide chitin is the reinforcing fiber in the rigid composite that forms arthropod cuticle, and cellulose is the ubiquitous fiber-forming
polymer in the plant world, where it forms the reinforcing fiber in plant cell walls. In addition to tensile elements like tendons and ligaments and rigid elements made from bone, the horse employs a broad range of plant materials for multiple functions, two of which are illustrated here. First, note that the animal is covered with a robust, stretchy skin, a plant composite made from collagen fibers, the rubberlike protein elastin, and a variety of highly hydrated “matrix” molecules that fill the spaces between these two structural fiber systems. In addition, the contact surfaces where bones meet are lined with another plant composite, cartilage, which is formed from a three-dimensional mesh of collagen fibers embedded in a proteoglycan gel. Cartilage forms a soft, energy-absorbing surface that transfers compressive forces between bones without allowing the rigid bony surfaces to impact each other. The cartilage also plays an important role in lubricating the sliding of joint surfaces during limb rotation.

5. THE QUALITY OF MECHANICAL DESIGN IN ANIMALS. One notion that is very strong amongst biologists is that organisms have evolved to exhibit outstanding design, perhaps even optimal design. One important goal of the next chapter will be to consider this proposition and evaluate the quality of design in structural biomaterials. In carrying out this evaluation we will need to make quantitative estimates of design quality, and to do this we need to be able to quantify functional attributes of biomaterials and material systems. These functional attributes are called properties and are usually mechanical properties like the stiffness or the strength of a structural material. Engineering theory provides us with a number of properties that we can use to quantify the design quality of biomaterials. The next chapter introduces you to some important engineering properties. In addition, however, we will need to develop other measures based on these properties that will allow us to assess the quality of design in a system. That is, the properties alone are usually not sufficient to quantify design quality.

First, there are many properties that can be defined and measured, but all are not equally important in determining the quality of a design in achieving its function. Thus, it is essential that the functional goals be understood so that appropriate properties are measured. In addition, however, good properties alone do not necessarily provide the answer to the question of design quality because in the construction of a complex machine, like a bird or an airplane, there are many compromises required between complex and often conflicting requirements. As a consequence, it is frequently very useful to analyze design quality in terms of cost-benefit ratios, in which a benefit may be some measurable mechanical output (i.e., an important mechanical property), and a cost may be some important consequence of this output (i.e., a measurable biological, metabolic, or energetic input required to achieve the output).

As you will see, there are many types of cost-benefit ratios, but because the energetic consequences of skeletal design and locomotor performance are so crucially important in biomechanics, we will use efficiency as one of the cost-benefit ratios. Efficiency, however, is used much too frequently to describe all aspects of design. We will use efficiency only to define the quality of an energy-exchange mechanism, and efficiency will always be defined as the ratio of energy recovered from an energy-transformation process divided by the energy input to that system. Other measures of design quality may have a similar appearance, as a ratio of some system output (e.g., stiffness, strength, speed, etc.) divided by a system input (e.g., weight, cost of synthesis, metabolic cost, etc.), but
you must resist calling these ratios efficiencies. Their units will vary depending on the nature of the inputs and outputs (note that efficiency has no units; it is the ratio of two energies), and we will call these *effectiveness ratios*. As you proceed through this book you will discover quite a number of ratios that can be used to quantify different aspects of the quality of mechanical design in skeletal systems.