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1 Bioinspired and Biomimetic Design of Multilayered and Multiscale Structures

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1.1 Introduction

In recent years, there has been significant interest in the fields of bioinspired design and biomimetics [1]. Bioinspired design involves the use of scientific and engineering principles in the design of engineering components and structures that are inspired by biological systems. In contrast, biomimetics involves the design of engineering components and structures that copy biological systems. Hence, airfoils and aircraft wings are examples of bioinspired design that are inspired by bird flight but guided by the principles of lift and drag from aerodynamics. In contrast, the early idea of an airplane with flapping wings is an example of biomimetics, which is based on the simple idea of copying nature without thinking carefully about the underlying scientific principles that enable such natural systems to function in the way that they do.

Although archaeological digs reveal numerous examples of relics that were clearly inspired by nature in the remains of ancient civilizations [1,2], the work of Leonardo da Vinci [3] is perhaps one of the earliest recorded studies of flight that was inspired by careful observations of birds. Leonardo da Vinci produced a codex on flight in 1505–1506, which was entitled "Codex on the Flight of Birds" [3]. He was particularly fascinated by the possibility of human mechanical flight, inspired by his observations of birds in flight [3]. Leonardo produced about 500 sketches of flying machines [3]. He also made some observations and identified some concepts that would find their place in the development of airplanes in the twentieth century when the Wright brothers [4] and Alberto Santos-Dumont [5] developed the first aircraft.

More recently, in the twentieth and twenty-first centuries, careful experimental studies of nature have provided the basis for the design and development of future components and systems. These include the pioneering work of Currey [6,7] who initiated some of the early studies of shells that enabled subsequent efforts on bioinspired design and biomimetics in the twentieth and twenty-first centuries. More recently, Chen and coworkers [8], Wegst et al. [9], Beese et al. [10], Rahbar et al. [11], Martini et al. [12], Huang et al. [13], Li et al. [14], Wang et al. [15], Dooley et al. [16], Niu et al. [17],

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Wang et al. [18], Farmer et al. [19], Tan et al. [20], and Du et al. [21] have developed bioinspired design and biomimetic concepts for the design of robust multifunctional structures. These include models for the design of layered structures that could enable the development of robust materials with remarkable mechanical properties.

Similarly, recent advances in our understanding of fluid mechanics and controls have enabled the development of naval structures that are inspired by careful studies of fish locomotion [22], the hydrodynamics of the propulsion of jellyfish [23] and marine mammals [24], experimental studies of fish locomotion by Moored et al. [22] and Melli et al. [25], and models of insect locomotion by Ayali et al. [26]. These are all areas in which recent work has provided new insights for bioinspired design. They are also areas that could find future applications in multifunctional robotics.

Beyond these potential applications, significant progress has been made in the development of bioinspired and biomimetic structures for applications in medicine [27], dentistry [28], batteries [29,30], bionic structures [31,32], micro- and nanostructures [33], and molecular devices [34]. These include the design of bioinspired dental multilayers that are inspired by the structure of natural teeth (Figures 1.1–1.3) with improved crack-growth resistance by virtue of their functionally graded architectures [11,13,17]; the development of soft robotic hands (Figure 1.4) [35]; the development of bionic leaves for solar energy harvesting (Figure 1.5) [31]; and the development of metal-free flow batteries that utilize quinones to move electrons between electrodes, inspired by the electron transfer mediating roles of quinone molecules during metabolism in plants and animals (Figure 1.6) [30].

The underlying concepts associated with these examples will be examined in this chapter along with their implications for bioinspired design and biomimetics. For simplicity, the chapter is divided into four sections. Following the introduction (Section 1.1), the bioinspired design of layered structures will be examined in

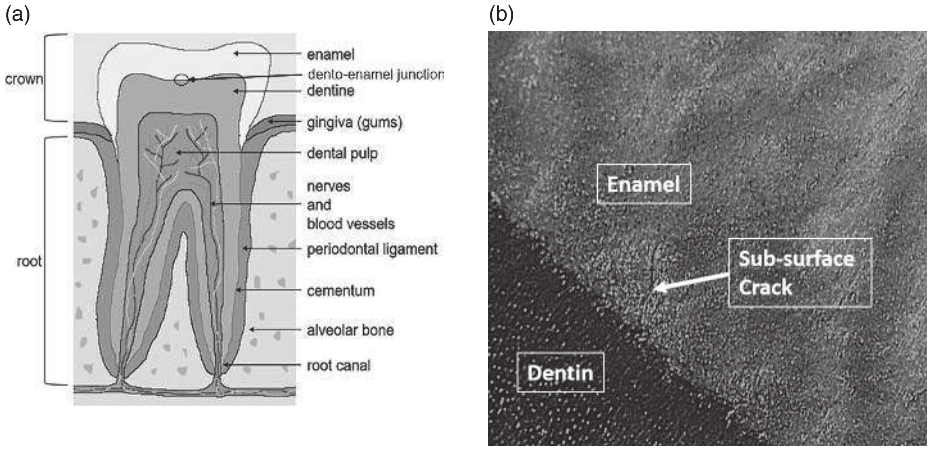

Figure 1.1 Structure of human tooth: (a) schematic and (b) enamel damage (shown by the white arrow) at the dento-enamel junction. (Courtesy of Ivory Kilpatrick, Princeton University.)

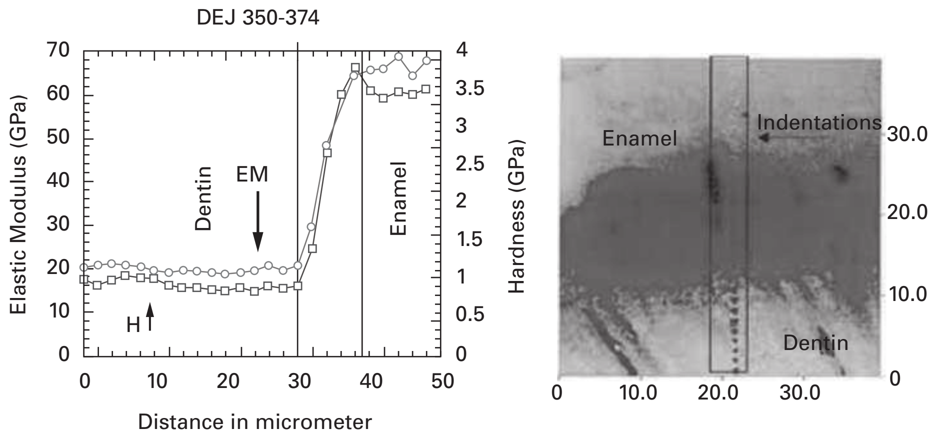

Figure 1.2 Variations in the Young's moduli across the dento-enamel junction. (Reprinted from Marshall et al. [36] with permission from John Wiley and Sons, Inc.)

Section 1.2. This will be followed by a review of the bioinspired design of multifunctional materials in Section 1.3. These include tissue-engineered materials, bionic materials, and materials for energy harvesting. We then conclude with a summary of insights for the bioinspired design and the biomimetic design of materials in Section 1.4.

1.2 Bioinspired Design of Layered Structures

Several materials in nature have layered hierarchical structures that can provide insights into the management of stresses in layered composite materials. These include bamboo [20,37], the dento-enamel junction [13,17,20,21], and turtle/tortoise shells [38,39], in which layered structures have evolved to reduce or manage the stresses that might lead to fracture during exposure to loading under different conditions. Hence, these materials will be explored in this section as potential sources of bioinspiration for the design of robust layered structures.

1.2.1 Bamboo

The layered hierarchical structure of bamboo (Figure 1.7) has evolved due to the wind loading of its cantilevered structure [20,37]. This induces the lowest stress at the tip of the bamboo, intermediate stress in the middle, and the highest stress at the bottom [20]. Consequently, the volume fraction of cellulose and hemicellulose fibers in the lignin matrix has evolved to be highest in the regions with the highest stress, intermediate in the regions with intermediate stress, and lowest in the regions subjected to the lowest stress (Figure 1.7).

Hence, the functionally graded structure of bamboo provides us with insights for the design of composites in which variations in the fiber volume fractions can be used to manage or support stresses. One can, therefore, envisage composites in which the fiber volume fractions are varied to manage or reduce the effective stresses under a range of

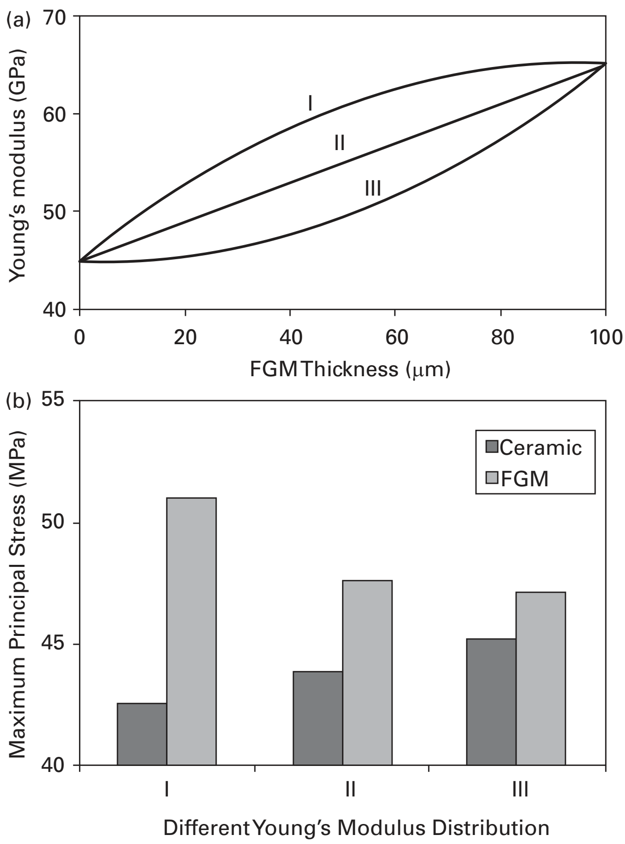

Figure 1.3 The effects of different distributions of Young's moduli of the functionally graded material (FGM) layer on the top ceramic layer in a bioinspired ceramic/FGM/composite dental multilayer structure: (a) the distribution of Young's moduli in the FGM layer and (b) the maximum tensile stresses on the top ceramic and FGM layers corresponding to the different Young's moduli distributions. (Reprinted from Huang et al. [13], copyright 2007, with permission from Elsevier.)

wide loading conditions. Askarinejad et al. [37] and Tan et al. [20] have also shown that the hierarchical and layered structure of bamboo can promote significant improvements in the resistance-curve behavior of Moso culm bamboo in the crack-arrestor orientation that gives rise to significant toughening by crack bridging (Figure 1.8).

1.2.2 Dental Multilayers

In the case of the functionally graded structure of dental multilayers (Figure 1.2), analytical and finite element models of contact-induced deformation [13] have revealed that the approximate linear gradients in Young's moduli across the dento-enamel junction (Figure 1.2) result in lower principal stresses (Figure 1.9) in the top ceramic layers. These serve as a model for natural teeth (Figures 1.1 and 1.2). However, in the

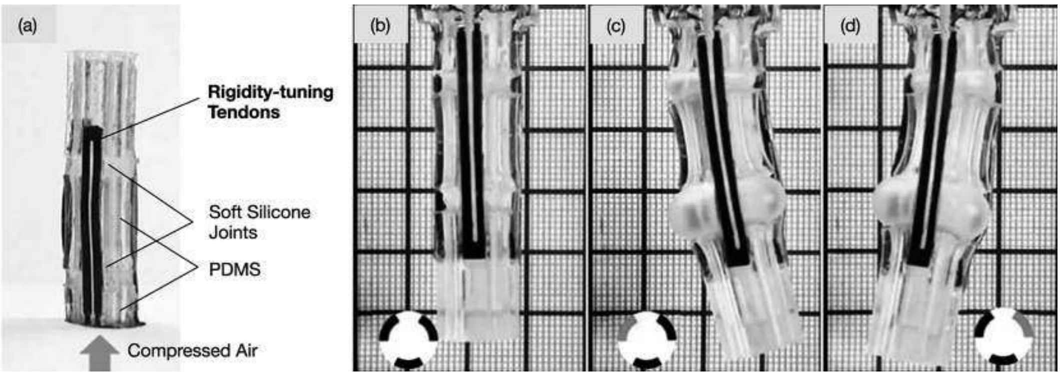

Figure 1.4 Bioinspired soft robotic gloves. (Reprinted from Shan et al. [35] © IOP Publishing. Reproduced with permission. All rights reserved.)

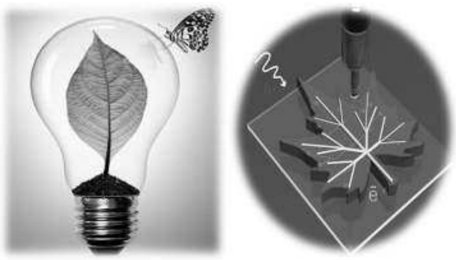

Figure 1.5 Bionic leaves for solar energy harvesting. (Adapted from Mannoor [32].)

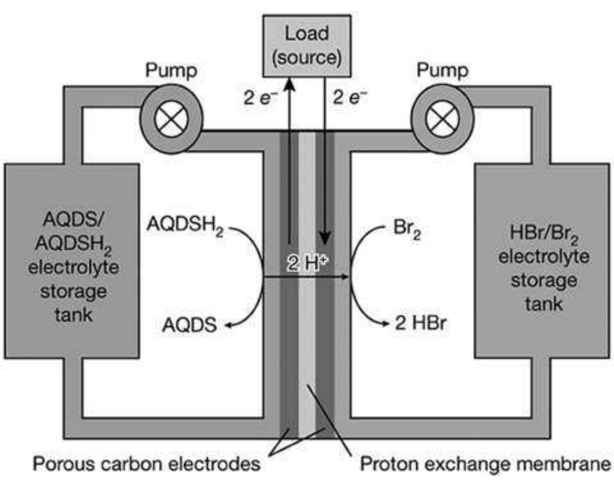

Figure 1.6 Schematic of a bioinspired flow battery utilizing 9,10-anthraquinone-2,7-disulphonic acid (AQDS), a rhubarb-like quinone compound, as an electrode. (Reprinted with permission from Springer Nature from Huskinson et al. [30].)

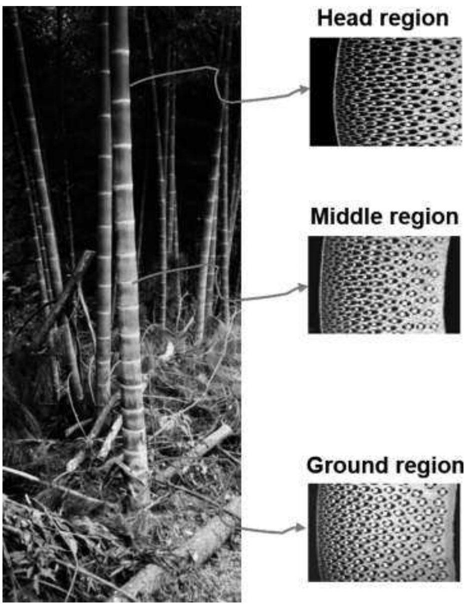

Figure 1.7 Layered functionally graded structure of Moso culm bamboo. (Adapted from Ghavami et al. [40].)

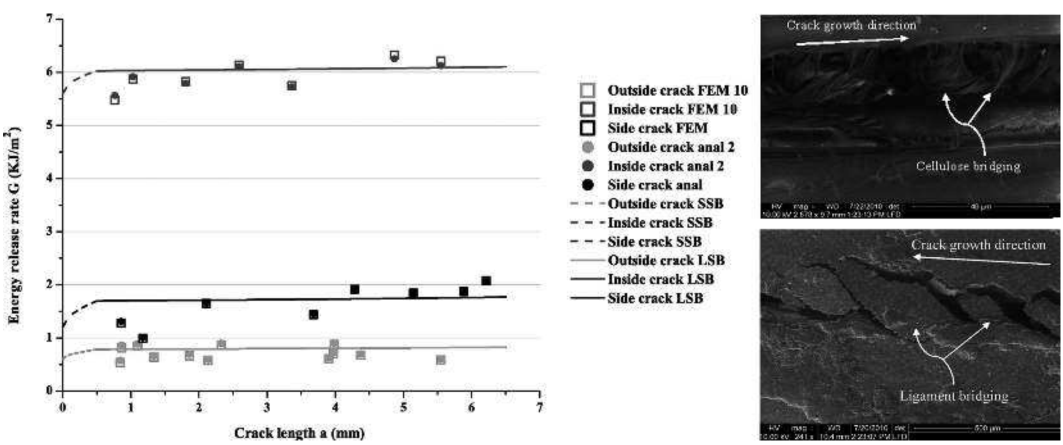

Figure 1.8 Resistance-curve behavior of bamboo along different crack growth planes. (Reprinted from Tan et al. [20], copyright 2011, with permission from Elsevier.)

case of typical ungraded interfaces in dental ceramic crowns, the sharp changes in Young's moduli (from one layer to the other) result in high-stress concentrations that give rise to high principal stresses in the top ceramic layers (Figure 1.9) [13]. These stresses are much reduced when almost linear or sigmoidal functionally graded nanocomposites are used to mimic the variations in Young's moduli associated with natural teeth (Figure 1.9).

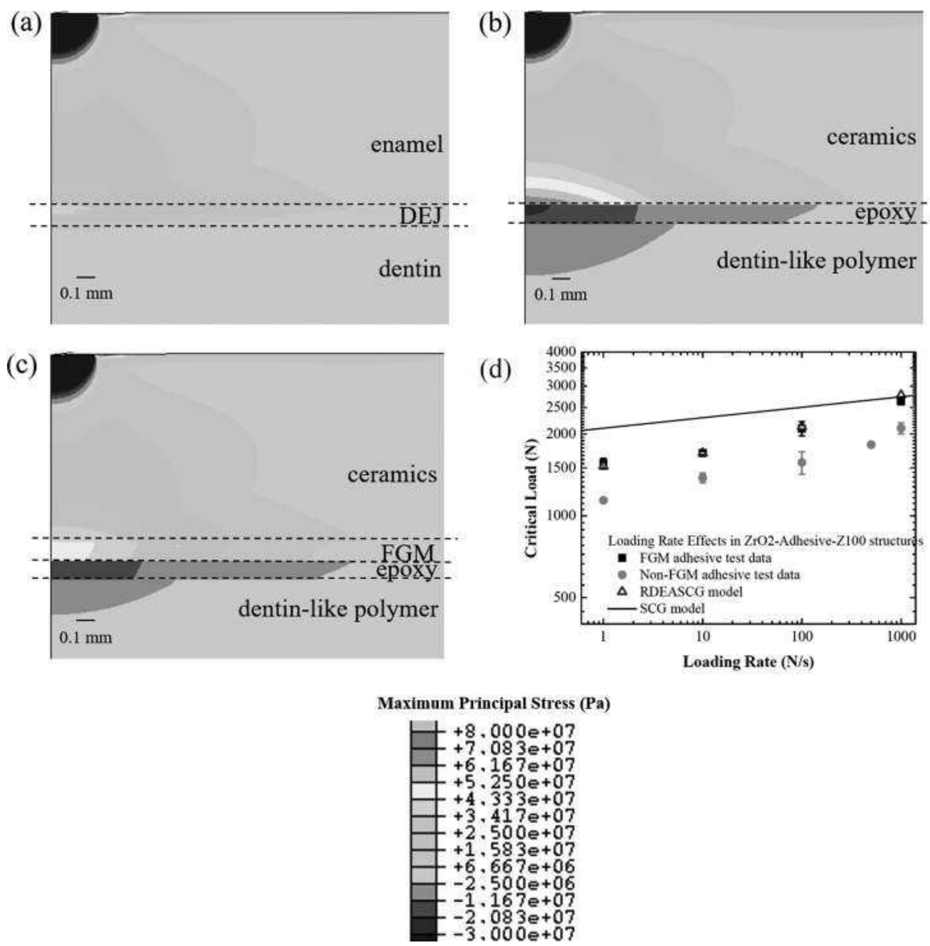

Figure 1.9 Principal stresses in finite element models of: (a) natural tooth, (b) typical crown multilayer, (c) synthetic functionally graded crown structure inspired by the functionally graded structure of natural teeth, and (d) the effect of loading rate on the critical loads of zirconia/FGM/substrate and zrconia/non-FGM/substrate dental multilayers. (Parts (a), (b), and (c) reprinted from Huang et al. [13], copyright 2007, with permission from Elsevier.)

The critical loads for cracking l_R, and the time to rupture t_R, have also been estimated from mechanism-based models. The models incorporate the loading-rate dependent mechanical properties of the individual layers into slow crack-growth fracture mechanics models of cracking in the top ceramic layers. This gives

$$D = \frac{K_{I_C}^N \left({c_o}^{1-\frac{N}{2}} - {c_f}^{1-\frac{N}{2}} \right)}{\left(\frac{N}{2} - 1 \right) \nu_o \beta^N}, \tag{1.1}$$

where

$$\int_0^{t_R} \sigma(t)dt = D \tag{1.2}$$

and D is a parameter dependent on material geometry and properties, and independent of load and time; K_{I_C} is the fracture toughness; c_o is the initial radial crack size in the ceramic subsurface; c_f is the final radial crack size; N is the crack velocity exponent; ν_o is the crack velocity parameter; β is a crack geometry coefficient; t is the time, and $\sigma(t)$ is a time-dependent expression of the stress state at the center of the subsurface of the top ceramic layer.

For monotonic loading at a loading rate of $\dot{P}$, with a predicted time to rupture of t_R, this gives a predicted critical load of

$$P_C = \dot{P} t_R, \tag{1.3}$$

where P_C is the critical load.

Plots of the loading-rate dependence of the critical loads are presented in Figure 1.9d. These show that the trends in the loading-rate dependence of P_C are only consistent with the experimental data when the layer-dependent mechanical properties are incorporated into the models. However, in the absence of this, the predicted pop-in loads are much less than the experimental measurements on the bioinspired functionally graded multilayers. Hence, the bioinspired dental multilayers increase the predicted and measured values of the critical loads that are related to subcritical cracking under lower top layer stresses associated with bioinspired functionally graded structures.

1.2.3 Turtle/Tortoise Shells

In this section, it is interesting to explore the layered structure of the turtle/tortoise shell (Figure 1.10) and how this contributes to the management of contact stresses in shell structures. This has been studied by Damiens et al. [38] and Owoseni et al. [39]. The studies of Owoseni et al. [39] on *Kinixys erosa* tortoise reveal a layered structure that consists of an outer layer of cortical bone, a middle layer of trabecular bone, and an inner layer of cortical bone (Figure 1.10).

Because such a structure can absorb energy due to external contact of the turtle/tortoise shell (Figure 1.10), it can reduce the potential effects of contact stresses that can occur due to contact with potential predators. The layered structure of the shell is, therefore, a likely outcome of evolution to promote the survival of turtles/tortoises. It also has implications for the design of protective helmets for soldiers and on contact sports in which bioinspired porous structures can be designed for protection from impact loads (Figure 1.10b–d).