Materials Science and Engineering C 70 (2017) 772–776

Contents lists available at ScienceDirect

Materials Science and Engineering C

journal homepage: www.elsevier.com/locate/msec

Modeling of a biological material nacre: Waviness stiffness model

N.S. Al-Maskari *, D.A. McAdams, J.N. Reddy

Department of Mechanical Engineering, Texas A&M University, TX 77843-3123, USA

ARTICLE INFO

Article history:
Received 20 November 2015
Received in revised form 15 August 2016
Accepted 26 September 2016
Available online 28 September 2016

Keywords:
Nacre
Waviness model
Biomimetic
Bioinspired
Staggered biological composite

ABSTRACT

Nacre is a tough yet stiff natural composite composed of microscopic mineral polygonal tablets bonded by a tough biopolymer. The high stiffness of nacre is known to be due to its high mineral content. However, the remarkable toughness of nacre is explained by its ability to deform past a yield point and develop large inelastic strain over a large volume around defects and cracks. The high strain is mainly due to sliding and waviness of the tablets. Mimicking nacre's remarkable properties, to date, is still a challenge due in part to fabrication challenges as well as a lack of models that can predict its properties or properties of a bulk material given specific constituent materials and material structure. Previous attempts to create analytical models for nacre include tablet sliding but don't account for the waviness of the tablets. In this work, a mathematical model is proposed to account for the waviness of the tablet. Using this model, a better prediction of the elastic modulus is obtained that agrees with experimental values found in the literature. In addition, the waviness angle can be predicted which is within the recommended range. Having a good representative model aids in designing a bio-mimicked nacre.

1. Introduction

Natural or biological materials are made from weak constituents that are combined and structured in such a way that results in outstanding mechanical properties [1]. Engineering materials are usually either stiff such as some metals or tough such as ceramics but biological materials can be both stiff and tough such as bone and mollusk shells (nacre) as can be seen in Fig. 1. This comparison is qualitative not quantitative.

Mollusk shells have a two-layer system used by seashells to protect themselves from predators. The outer layer of the shell is made of large prismatic calcite grains while the inner layer is made of nacre as shown in Fig. 2a and b. Nacre, which is known as mother of pearl, is a tough yet stiff natural composite composed of microscopic mineral polygonal tablets bonded by a tough biopolymer. The mineral is calcium carbonate $CaCO_3$ which is 95% of the material while the rest is an organic matrix made from proteins and polysaccharides. The tablets are stacked to form a 3D brick wall structure referred to as a brick and mortar structure. This brick and mortar structure is shown in Fig. 2c and d. It is noted that the tablets' surface is not flat. There is some wedge geometry or waviness that generates interlocking which spreads energy and increases the toughness of nacre. The waviness functions somewhat as a dovetail joint. This dovetail geometry is shown in Fig. 3a and b. The angle is very small to allow sliding and progressive pullout of the tablets [3,4].

Unlike traditional engineered materials, nacre has a combined stiffness, strength, and toughness that is three orders of magnitude higher than its main constituent, namely, the tablet. In comparison with other biological materials; nacre has less complex architecture and its structure is optimized for only mechanical properties since it does not perform sensing, temperature regulating, or other functions. For these reasons, nacre has inspired the desire to understand its mechanical performance, model its deformation behavior, and develop synthetic materials inspired from it [4,6–11]. Bio-mimicking nacre has resulted in materials that have toughness much larger than their constituent materials or materials that exhibit similar deformation mechanisms [1]. In terms of application, nacre has inspired plenty of research to mimic its structure and toughen ceramic materials that could be useful in areas such as material science, biomaterials development and nanotechnology. Nacre-like materials and coatings have been developed for biomedical applications such as developing better implant materials that are usually made of brittle ceramic materials. Using nacre-like materials may enhance the strength and toughness properties of implant materials [12,13].

The remarkable performance of nacre and other hard biological materials, such as teeth, collagen fiber, spider silk, and cellulous fiber, is due to its staggered brick-wall structure that provides an attractive combination of stiffness, strength, and toughness. The well-known shear lag model is widely used to model the behavior of nacre. The shear lag model concerns the transfer of tensile stresses from the matrix to the tablet via the interfacial shear stress [14–16]. One of the earliest models was demonstrated by Kotha, Li, and Guzelsu [15], who proposed a micro-mechanical model for the elastic deformations of nacre that calculates the elastic modulus. Zhang et al. [17] investigated the mechanical properties (i.e. elastic modulus, strength, and failure strain) of a staggered structure with different tablet distributions. In their work,

---

* Corresponding author.
E-mail address: nasraalmaskari@hotmail.com (N.S. Al-Maskari).

http://dx.doi.org/10.1016/j.msec.2016.09.061
0928-4931/

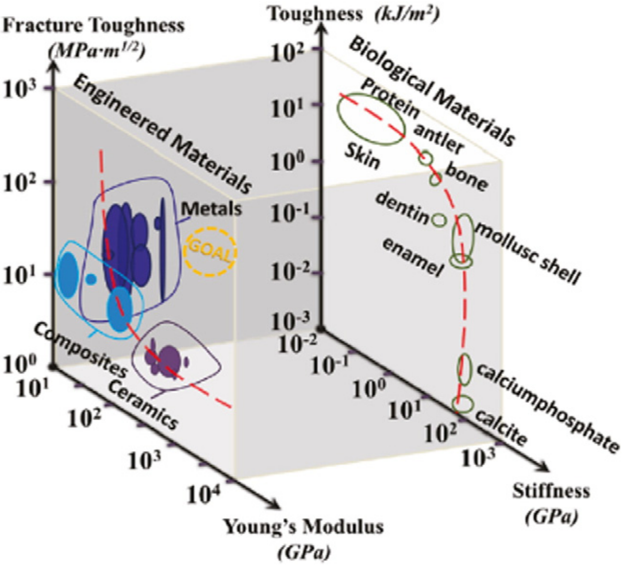

Fig. 1. Comparing stiffness and fracture toughness of engineering materials with biological materials [2].

Zhang et al. [17] calculated the critical tablet aspect ratio which distinguishes between tablet and matrix failure with the assumption of a uniform shear stress distribution. Bar-On and Wagner [18,19] proposed an accurate and compact formula for the effective modulus of staggered composite structures built on a generic tablet architecture. Begley and coworkers [20] introduced different failure mechanisms for identical and uniformly distributed tablets lifting the assumption of a uniform shear stress. Wei and coworkers [2] proposed an optimal overlap length of identical and uniformly distributed tablets in elastic and plastic regimes. Dutta et al. [21] developed an analytical model for a staggered structure considering dynamic time dependent loading and computed the optimal overlap length in dynamic regime. Recently, Sakhavand and Shahsavari [22] developed a more generalized model considering non-identical tablets properties. However, all of these models assume that the tablets are flat and do not account for the waviness of the tablets. In this work, a model is developed to account for tablet waviness. Thus, an understanding of the impact of tablet waviness on bulk material properties can be understood, predicted, and designed into a nacre-like engineered material.

2. Modeling of nacre

The high stiffness of nacre is attributed to its high mineral content. Of interest, the specific mechanism creating the high toughness of nacre is less obvious although remarkable. Nacre's toughness is explained by the ability of nacre to deform. As nacre deforms past its yield point, it develops large inelastic strain in large volumes around defects and cracks. The failure strain of nacre exceeds 1%. A 1% failure strain rate is 100 times that of typical engineered ceramics. High strain is mainly due to tablet sliding and waviness [5,14]. The work here builds on the work of Zhu and Barthelat [6] who built a millimeter size wavy poly-methyl-methacrylate (PMMA) sample inspired from the structure of nacre. They developed an analytical model for the synthetic nacre. In their model, they did not account for shear stress between the tablets but instead used coulomb friction. In the present work, the shear stress between the tablets is included. Understanding the relationship between bulk property of materials and micro scale structure and mechanics is an important contribution toward designing bioinspired engineered materials.

3. Waviness stiffness model

The structure of nacre and a representative volume element (RVE) are shown in Fig. 4a, and b. The RVE is symmetric with respect to the horizontal axis and one half of the RVE can be used in order to reduce the computation cost. The reduced RVE is shown in Fig. 4c and the applied stress is shown in Fig. 4d. The tablet has a length L, thickness t, a dovetail angle θ, and a modulus of elasticity E_t. The length where the

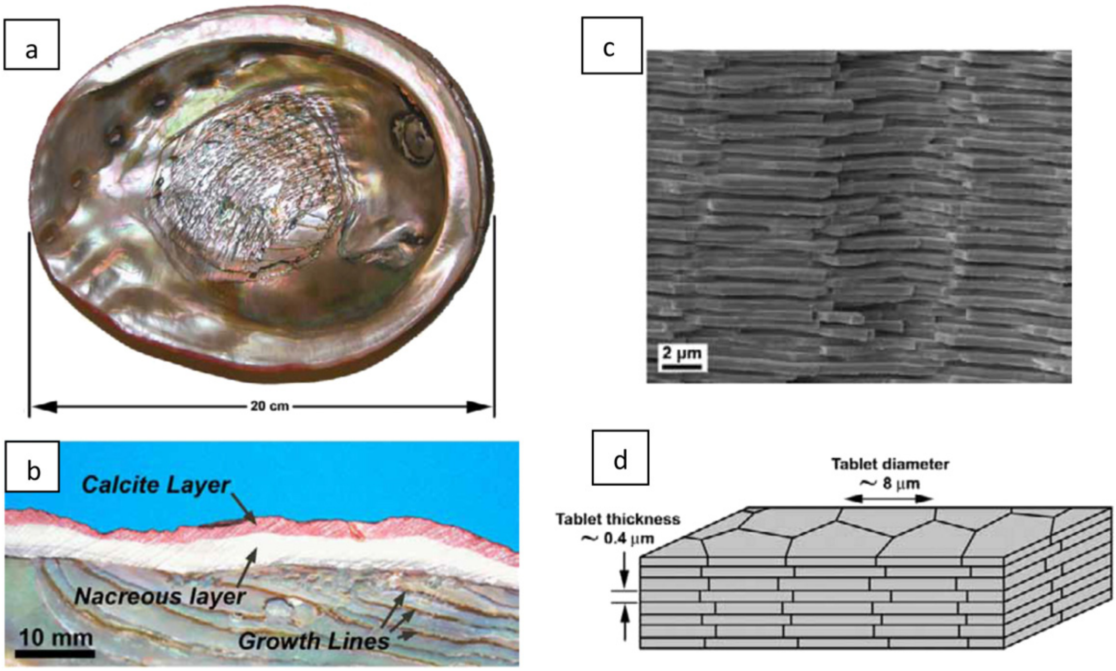

Fig. 2. Hierarchical structure of red abalone shell: a) red abalone shell in centimeters; b) the shell showing the nacreous layer; c) scanning electron micrograph of a fracture surface in nacre showing the brick and mortar structure; d) schematic of the tablet arrangement in nacre [5].