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Influence of interfacial geometry on the energy absorption capacity and load sharing mechanisms of nacreous composite shells

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ABSTRACT

The excellent mechanical properties of nacreous composites are partly attributed to its staggered microstructure, which is made of multiple layers of mineral tablets bonded through a soft protein matrix. An important parameter that could affect the load sharing mechanism in nacre is the waviness of aragonite tablets. In this work, a continuum model of nacre composite is developed, which takes into account the waviness factor. The tablets are subjected to tensile loading and are initially modeled to have dovetail shapes with varying slopes. The load sharing efficiency of nacre is evaluated through displacements, stresses and strain energy density (SED) of the unit cell. The SEDs of unit cells, tablet and matrix are presented for different overlapping lengths and inclination angles, from which maximum SEDs and optimum overlapping lengths are determined. Parametric studies show that larger inclinations of nacre tablets result in higher energy absorbing capacity. A more general case is also presented, where nacre's platelet is modeled to have sinusoidal waviness of different wavelengths. By varying the wavelength while maintaining the periodicity of the unit cell, stresses, SEDs and displacements are obtained and compared. Analytical results on the optimum waviness of designed unit cells are validated with observed nacreous microstructures.

1. Introduction

Nacre, the inner layer of mollusk shells has attracted the attention of researchers over the past few decades. It comprises 95% aragonite, in brittle ceramic tablets that are joined by an organic matrix [1–4] and arranged in a bricks and mortar type structure [5,6,7–9], as illustrated in Fig. 1. Although nacre is made from relatively weak components, it surprisingly exhibits high levels of strength and toughness [10–12]. Specifically, it exhibits a work of fracture that is 3000 times greater than that of its major brittle constituent, aragonite [5,6,13,14]. This has motivated structural engineers to mimic the mechanisms of nature in order to improve the energy absorption capacity of structures. More specifically, mimicking nacre encourages the possibility of toughening brittle materials to levels never achieved before for a range of engineering applications. A typical example where this is very important is under extreme loads, where the connection of a façade panel can fail and dislodge it from the supporting frame, as demonstrated by experiments conducted in [15]. Learning from nature can reduce the energy that is imparted from extreme loads before it reaches critical structures using composite materials [16,17]. However, we must first understand the mechanisms by which natural composites like nacre develop such high toughness from mainly brittle components.

It is observed in recent work [7] that the organized sliding between the ceramic tablets is a key mechanism responsible for nacre's ability to develop large strains over large volumes around cracks and defects. This key mechanism has also been discussed in other works, including [6,20–24]. When nacre is subjected to tension, the tablets translate against each other with nano-asperities along the interface, creating friction and interlocking [25–27]. There are also mineral bridges in the organic matrix layers to increase their stiffness, strength and toughness by preventing tablet pull-out and deflecting cracks [6,28,29]. These friction and interlocking mechanisms are further amplified by the waviness of the tablet, which eventually leads to hardening in nacre's mechanical responses. This energy absorbing mechanism could extend over the entire volume of nacre, delaying the inevitable localized failures [25]. The waviness of the tablets also plays a key role in developing transverse interlocking forces that guide the path of fractures [30].

Several models and synthetic composites have been developed to mimic the tablet sliding mechanism of nacre [7,19]. Barthelat and Zhu [7] developed a composite to mimic the tablet sliding

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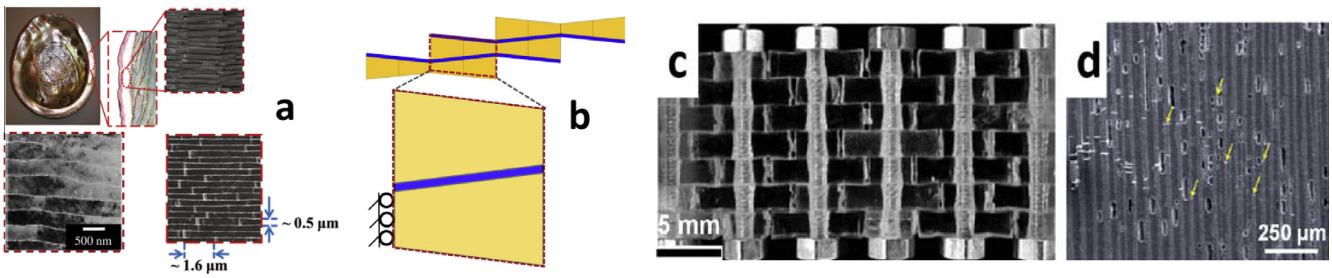

Fig. 1. Bricks and mortar microstructure of nacre (a) [18]; and a schematic model for the nacre's unit cell with a dovetail-shaped structure (b). Nacre-like mimicry composite structures made by (c) staggering PMMA platelets with bolted joints [7] and by (d) fabricating of Al_2O_3/PMMA hybrid materials [19].

resistance mechanism of nacre under in-plane tension, resembling the critical loading scenario in which nacre is required to maintain the integrity of its outer abalone shell under extreme loads from the environment (Fig. 1c). The prototype consisted of arrangements of dovetail-shaped tablets in direct contact with each other, connected via bolts passing through their cores. By raising the tablet inclination angles, an increase in tensile stresses was observed in the tablets. Moreover, [28] highlights the importance of tablet waviness in the progressive hardening behaviors accompanying the tablet sliding mechanism. Wei et al. [18] analytically modeled a unit cell of nacre as bricks (brittle aragonite tablets) and mortar (organic matrix) composite structures. The shear lag model [31], which is usually used for lap-joint modeling, was employed to quantify the shear transfer mechanisms in the organic matrix. By maximizing the strain energy density of the unit cell, the optimal overlapping length of the unit cell is predicted to achieve uniformity of shear transfer in the matrix. Wei et al. [32] has further extended shear lag model by employing a statistical model to account for the variation in failure properties of bio-inspired double-wall carbon nanotube composites. Chen et al. [33] reported a similar solution using a tension-shear-chain model, while Dutta et al. [34] also employed a shear-lag model to investigate the behaviors of nacre's unit cells under dynamic tensile loading. Barthelat et al. [35] developed a finite element model considering the waviness of the tablet with a sinusoidal profile.

Although these abovementioned studies have identified the tablet waviness as a key mechanism for nacre's superior toughness, there are still very limited researches focusing on quantifying the influences of this factor on its load sharing mechanisms. This waviness mechanism is expected to further enhance the effects of mineral bridges and nano-asperities on the energy absorption and failure mitigation capacities of abalone shells. In this work, the waviness of the tablets is firstly modeled by simple dovetail-shaped models with controls on the overlapping length and inclination angles. The dovetail angle and overlapping length parameters could be further optimized to achieve the optimal configuration of a nacre unit cell in withstanding uniaxial loads. Analytical approaches will be employed to investigate the influences of these factors and to provide further insights into the load sharing processes of nacre within the elastic regime. With one of the aims being to maximize the load carrying capacity of the nacre unit cell before failure, the analysis in this work will concentrate on the elastic behavior of tablets and the matrix prior to plastic yielding. More general analytical models of nacre platelets with sinusoidal interfaces will be developed and examined in the last section of this work. From these models, interfacial stresses, displacements and strain energy density will be obtained for discussion and comparisons.

2. Continuum model formulation

The staggered arrangement of nacre tablet structures (Fig. 1) is represented by the periodic dovetail-shaped unit cell containing the upper and lower tablets adhered by the cohesive matrix. Key parameters defining this unit cell model are the width of the tablet b, the overlapping length L, the inclination angle θ, and the matrix thickness t (Fig. 2). The upper tablet is subjected to uniform cross-section loading, while the lower one is fixed on rollers. The continuum model (Fig. 2) is set up similar to the approach presented in [18,34], employing the shear-lag model. However, different from previous work [18,34], the dependence of continuum components (stresses, strains and displacements) on the additional geometrical parameters, such as inclination angle, makes the equilibrium equation system more complex, as described as follows. The cross-sectional areas per unit length of the upper (A_1) and lower (A_2) tablets can be expressed as $(b-2\phi x)$, and $[b-2\phi(L-x)]$, respectively, where $\phi = \tan\theta$ is the tablet slope (Fig. 2). The tablets have a Young's modulus E, and the matrix has a shear modulus G. The stress σ_0 is applied to the upper tablet, transmitted through this tablet axially, and then to the matrix via shear and normal stresses developed at the tablet-matrix interface.

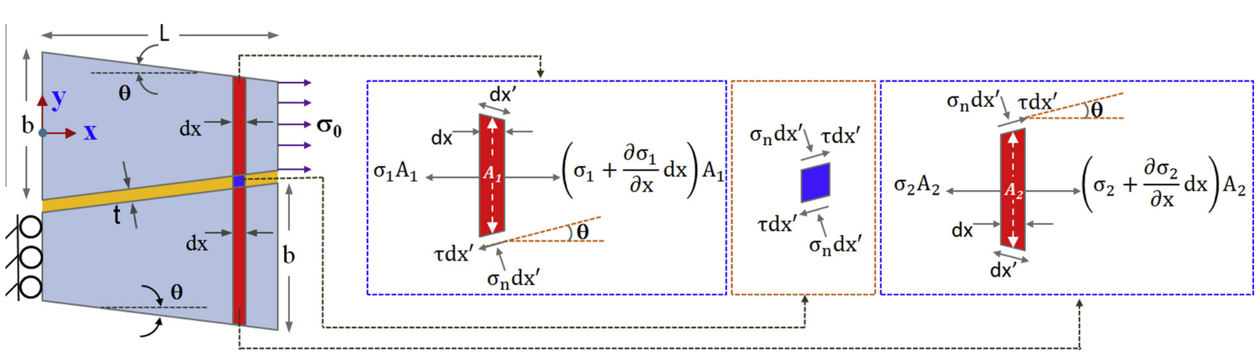

Fig. 2. Free body diagrams for the nacre's unit cell model subjected to tensile loading.