



Three-dimensional Voronoi model of a nacre-mimetic composite structure under impulsive loading



Abdallah Ghazlan, Tuan D. Ngo, Phuong Tran *

Department of Infrastructure Engineering, The University of Melbourne, Australia

ARTICLE INFO

Article history:

Received 9 January 2016

Revised 23 May 2016

Accepted 7 June 2016

Available online 7 June 2016

Keywords:

Bio-inspired composite

Nacre

Blast resistance

Voronoi

Biomimetic

Finite element

ABSTRACT

Nacre, the inner layer of mollusk shells holds the key to the development of an effective composite system for protecting structures from extreme loads due to its superior fracture toughness, despite its brittle constituents. It is known that the hard mineral tablets provide structural rigidity, while the soft organic polymer matrix provides the mechanisms to mitigate damages and dissipate energy uniformly across the structure. Nacre's composite structure is arranged to have multiple laminates and three dimensional polygonal tablets bonded with organic adhesives to maximize its load sharing capability. This paper presents a novel 3D Voronoi model of an Aluminum/Vinylester composite structure that closely mimics multilayer nacre's tablet. Vinylester cohesive and adhesive layers are introduced between nacre-mimetic polygonal Aluminum tablets and layers, respectively, to simulate the bonding and delamination process. The performances of nacre-like composite structures under blast loading are evaluated in terms of maximum deformation, damage distributions as well as dissipated energy. The influences of size and shape of the nacre-mimetic tablets, as well as the number of composite laminates on the blast resistance of the composite are also investigated. Results reveal the importance of tablet size and number of laminates as opposed to the insignificant influences of tablet overlapping.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Accidental and deliberate loads on civil and military structures continue to cause severe damage worldwide, along with catastrophic losses of human life [1,2]. Consequently, the demand for lightweight high-performance materials has increased significantly in protective structural engineering. Biological structures, meta-materials, woven fabrics, nano-polymers, composite sandwich panels and many others have recently been investigated by structural research engineers because of their unique mechanical characteristics, which make them suitable under a range of extreme applications, namely blast, ballistics, fire and so on [3–10]. In particular, the two-layer armour system (Fig. 1b) found in mollusk shells [11] is believed to be the most efficient armour system, particularly because it is composed mainly of brittle minerals but boasts a fracture toughness which is several orders of magnitude greater. This biological composite system has been perfected by the animal over millions of years of evolution to protect its soft tissues from loads that may arise from predator bites or extremely

high hydrostatic pressure in the ocean. Better understanding of nacre's load sharing mechanism will lead to the development of a superior composite structure for protective applications.

The armour system found in red abalone shells (and other bivalves and gastropod species) consists of a hard brittle outer calcite layer and a tough nacreous layer at its inner surface [12]. The inner layer (nacre), which is mainly composed of aragonite, a brittle mineral that accounts for 95% of its volume [13,14], exhibits remarkable toughness. Moreover, nacre shows a hierarchical structure over several length scales (macro to nano). On the most elementary level, many have observed that nacre's structure resembles that of a brick wall at the micro-scale [15–21], with polygonal aragonite platelets stacked over several layers and bonded together by a soft organic matrix (Fig. 1c and d). This organic matrix serves as both adhesive and cohesive bonds between nacre's layers and polygonal tablets, respectively. Most studies in the literature, however, focus only on the influences of the adhesive layer rather than the cohesive bonds between nacre's grains. Other features believed to contribute to nacre's remarkable toughness are nano-asperities on the tablet surfaces providing additional sliding friction [22–25]; mineral bridges at the interface as reinforcements between tablets [17,22,26] and waviness on the surfaces of the tablets for strain hardening [11,27]. The aspect ratio

* Corresponding author at: Department of Infrastructure Engineering, The University of Melbourne, Victoria 3010, Australia.

E-mail address: Phuong.tran@unimelb.edu.au (P. Tran).

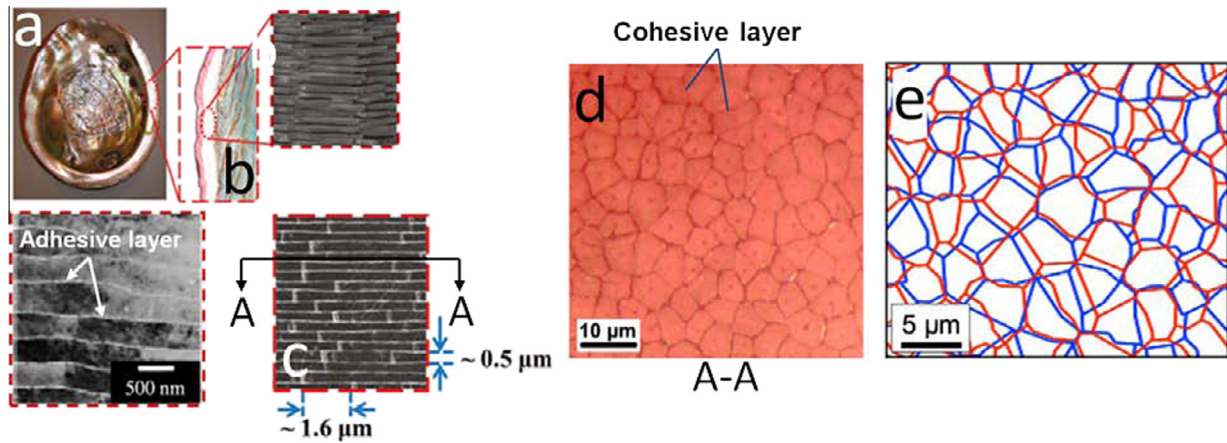


Fig. 1. (a) Red abalone shell; (b) two-layer armour system; (c) brick and mortar microstructure of nacre; (d) Voronoi-shaped polygonal architecture found in each nacreous layer; (e) staggered platelet configuration in nacre (adapted from [6,7]).

of the platelets is also believed to have a certain influence on the strength and stiffness of the nacreous composite [28,29].

Other investigations on nacre's microstructural features (volume fractions, tablet aspect ratio, overlap length etc.) have been conducted in an attempt to link them with its mechanical properties. Dutta et al. [30] claimed that nacre chooses its overlap length to minimize crack driving forces at the interface, thereby delaying crack initiation. Kotha et al. [31] concluded that composites with high toughness can be manufactured from platelets with low aspect ratios through a shear-lag modelling approach. Gao et al. [24] employed Griffith's fracture criterion to show that mineral platelets become insensitive to flaws at small length scales. Barthelat et al. [32] found that nacre does not achieve steady state crack propagation due to toughness amplification from tablet pullout and subsequent process zone toughening mechanisms. Other investigations have also found that nacre has tremendous ability to arrest crack propagation due to intrinsic and extrinsic toughening mechanisms that operate in front of and behind a developing crack tip, respectively [33]. Flores-Johnson et al. [34] claimed that the performance of nacre-like plates under blast loading is explained by the hierarchical structure, which facilitates globalized energy absorption by interlayered interlocking and delamination.

In summary, the geometric parameters such as tablet aspect ratio, interfacial waviness, overlap length and interlayer interactions of platelets have been found to influence nacre's toughness. The aforementioned investigations have focused mainly on the localized load sharing mechanisms of nacre activated by tablet sliding under uniaxial tension or pure bending. This raises the question of whether the same mechanisms are activated under transverse loadings such as hydrostatic pressure or blast impulse. There are, however, very limited studies in the literature focusing on this topic both numerically and experimentally. This paper develops a novel nacre-mimetic composite model for simulating the Voronoi-shaped tablets, multilayer structures, grain cohesion and interfacial bonding to address: (1) The influences of the multilayered hierarchical structure of the nacre-mimetic composite on its resistance to impulsive loadings; (2) The impact of laminate staggering on the toughness of the composite; and (3) The size and shape effect of the platelets on fracture resistance. Specifically, the crack propagation patterns in the adhesive/cohesive layers and the energy dissipated via fracture, delamination and plastic deformation will be captured and analyzed. The model consists of a Voronoi-like platelet arrangement resembling red abalone nacre and the nacre-like laminates are bonded together with different overlapping configurations. The composite platelets are modelled

with amour-graded Aluminum AA5083-H116, which are adhered together by a Vinylester matrix. A rate-dependent material model is used to simulate the transient responses and plastic deformation of the Aluminum tablets under impulsive loading.

2. Voronoi model mimicking nacre's tablet structure

2.1. Assembling the nacre mimicking geometry

Barthelat et al. [11] observed that the arrangement of the tablets in each layer of nacre is similar to that of a Voronoi diagram, through optical images of a red abalone specimen (Fig. 1d). Based on these optical images, they have generated a model consisting of two layers of nacre's tablet structure for finite element analysis. This procedure offers limited control over the geometry and arrangement of the tablets in each layer, making it challenging to develop nacre-mimetic composite systems. Each nacre laminate is characterized by the random distribution of mineral tablets and bonded to other nacreous layers. There is limited study on how these nacreous tablet structures are chosen, as well as the influence of the shape and size parameters of the mineral tablets on the load sharing capability of nacre. In this work, a novel technique for developing a model that closely mimics the geometry of nacre is described. This technique could be effectively used to fabricate nacre-mimetic composites using 3D additive manufacturing such as 3D-printing technology.

Voronoi diagrams are well-known in computational geometry. Briefly, a Voronoi diagram comprises of sites (or points, illustrated in Fig. 2a), where every point inside the polygon enclosing the site is closest to that site. Mathematically, this can be represented by the following equation:

$$R_k = \{x \in X | d(x, P_k) \leq d(x, P_j) \forall j \neq k\}$$

where R_k is the set of all points in the Voronoi diagram X such that the distance $d(x, P_k)$ between each point x and a site P_k is less than or equal to the distance $d(x, P_j)$ between that point and any other site P_j . Note that the distance function can be arbitrary but the Euclidean distance is normally used to give a more uniform distribution of the Voronoi regions, which happens to be closer to the tablet profiles found in nacre.

The simplest possible configuration for a Voronoi diagram is shown in Fig. 2a, where the sites are arranged in a grid to form square Voronoi regions of length β . The sites could be shifted diagonally to generate an overlapping gap (α) between two adjacent layers (Fig. 2b). A Voronoi diagram generated from the newly

Download English Version:

<https://daneshyari.com/en/article/6705234>

Download Persian Version:

<https://daneshyari.com/article/6705234>

[Daneshyari.com](https://daneshyari.com)