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Shear wave filtering in naturally-occurring Bouligand structures

Nicolás Guarín-Zapata [a], Juan Gomez [b], Nick Yaraghi [c], David Kisailus [c,d], Pablo D. Zavattieri [a,*]

[a] Lyles School of Civil Engineering, Purdue University, West Lafayette, IN 47907, USA
[b] Civil Engineering Department, Universidad EAFIT, Medellín 050022, Colombia
[c] Materials Science and Engineering, University of California, Riverside, Riverside, CA 92521, USA
[d] Department of Chemical and Environmental Engineering, University of California, Riverside, Riverside, CA 92521, USA

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ABSTRACT

Wave propagation was investigated in the Bouligand-like structure from within the dactyl club of the stomatopod, a crustacean that is known to smash their heavily shelled preys with high accelerations. We incorporate the layered nature in a unitary material cell through the propagator matrix formalism while the periodic nature of the material is considered via Bloch boundary conditions as applied in the theory of solid state physics. Our results show that these materials exhibit bandgaps at frequencies related to the stress pulse generated by the impact of the dactyl club to its prey, and therefore exhibiting wave filtering in addition to the already known mechanisms of macroscopic isotropic behavior and toughness.

1. Introduction

Many biological organisms are known for their ability to produce hierarchically arranged materials from simple components, resulting in structures that provide mechanical support, protection and mobility. These structures are used to perform a wide variety of functions ranging from structural support and protection to mobility and other basic life functions. All of this is done using only the minimum quantities of a limited selection of constituent materials [1–3], synthesized under mild conditions. The diversity and multifunctionality identified in these materials, combined with their robust mechanical properties [2] make them a rich source of inspiration for the design of new materials. One particular example of a natural material with impressive mechanical properties can be found in the dactyl club of stomatopods [1,4–7]. The *stomatopods* (or mantis shrimps), are an ancient group of marine tropical and subtropical crustaceans that are, on average, 15 cm long but can reach lengths of nearly 40 cm. A distinct feature of stomatopods versus other crustaceans is the presence of a pair of thoracic appendages that are specifically adapted for close-range combat (see Fig. 1a and b). Stomatopods are divided into two groups, depending on the shape of these appendages: those that hunt by impaling their prey with spear-like structures (*spearers*), and those that smash them with a powerful blow from a heavily mineralized club (*smashers*) [5,8–10]. The dactyls of spearers contain spiny appendages with barbed tips that prevent prey from slipping off. On the other hand, dactyls from smashers have a hammer-like structure [11] that can reach, upon impact, accelerations as high as 10400*g* and speeds close to 23 m/s, generating forces up to 1500 N [10]. This hammer-like composite structure can inflict considerable damage after impact against the wide variety of heavily mineralized biological structures present in its preys. In fact, this is reflected in its diet. Smashers, feed on armored animals such as snails, hermit crabs, clams and crabs, which they batter to pieces [11]. Despite these significant forces, the dactyl clubs are fracture-resistant and are able to tolerate thousands of such blows. This astounding capacity to tolerate stress waves generated from the impact of the dactyl club against its preys has prompted questions about the underlying mechanisms responsible for such a high strength to sustain dynamic loads [1,7].

Previous research, conducted by Weaver et al. [7] aimed at identifying the microstructural features of the dactyl club in stomatopods, have recognized its structure as a multiregional biological arrangement made of an external layer, called the impact region, supported by a striated and a periodic zones. These are described in Fig. 1b–e where we show a description of a transversal cross section of the dactyl club together with its microstructural features shown at increasing levels of resolution. In particular Fig. 1c shows a schematic representation of a cross section of the dactyl club where we have labeled the impact, periodic and striated regions as (I), (II) and (III) respectively. The impact and periodic regions are also observed in the optical micrograph of a polished cross section of the dactyl club (Fig. 1d). The layered nature is more evident

* Corresponding author.
E-mail address: zavattie@purdue.edu (P.D. Zavattieri).

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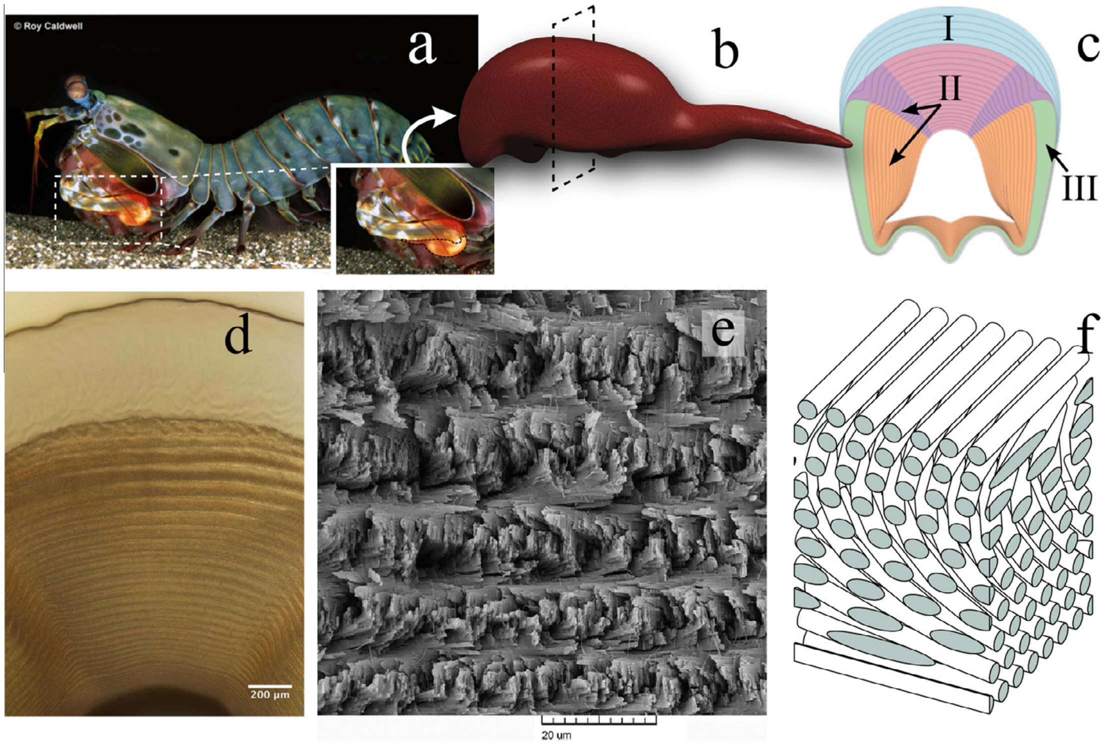

Fig. 1. Hierarchical structure of the dactyl club of the stomatopod. (a) Image of the smashing peacock mantis shrimp (*Odontodactylus Scyllarus*). (b) Model of the dactyl club. (c) Schematic of a transverse section of the dactyl club highlighting the (I) Impact region (light blue) (II) Periodic region (pink, purple, orange) and (III) Striated region (green). (d) Optical micrograph of a polished transverse section of the impact and periodic region. (e) SEM micrograph of a fractured surface of the periodic region highlighting the helicoidal microstructure. (f) Model of the Bouligand microstructure.

in the periodic region. A closer examination reveals that this periodicity is related to its helicoidal arrangement (also known as Bouligand structure) of unidirectional chitin fibrils surrounded by amorphous mineral [7]. This structure is observed in the scanning electron microscope (SEM) image shown in Fig. 1e and in the idealized model (see Fig. 1f) where we introduce fibers mimicking such a helicoidal arrangement. It should be noted that each line in Fig. 1d corresponds to a complete 180° rotation of the fibers in Fig. 1e. While it is not clear from Fig. 1d, the impact region also exhibits a similar arrangement of fibers.

The nearly periodic nature of the microstructure in the dactyl club seems to suggest that the interaction between the microstructure and propagating stress waves can lead to phenomena that are common in phononic crystals and metamaterials, such as bandgaps and dispersion of waves [12–14]. As such, the macroscopic behavior can be modified by manipulating the geometry of the microstructure leading to a material capable of guiding waves in a specific way [12–16]. The field of phononic-crystals has some aspects in common with biological materials, in that the properties of the different phases and its architecture (topology/geometry) control the overall macroscopic response. As such, the aim of this paper is to explore the microstructural properties of the periodic and impact regions of the dactyl club in stomatopods from the perspective of spatial periodicity and wave propagation properties in order to identify whether bandgaps and dispersion of waves could be one of the contributing mechanisms responsible for its remarkable impact tolerance capability.

Phononic crystals are materials with a periodic repetition of a unit cell, which results in the periodicity of its mechanical properties (i.e., elastic moduli and density). The wave propagation in this case corresponds to an elastic disturbance [16,17]. One of the main properties of a phononic crystal is the possibility of exhibiting band gaps (i.e., frequency ranges where waves are forbidden to propagate [16,18]). The name, *phononic crystals*, has been coined from the field of photonic crystals in optics, and both, phononic and photonic crystals can be studied using concepts extracted from the theory of solid-state physics. In particular, the use of Bloch's theorem [18,19] allows us to determine the material band gaps after studying a single unitary material cell. The differences between electronic, photonic, and phononic crystals reside in the equations that are being solved: Schrödinger equation, Maxwell equation or Navier–Cauchy equations, for *electronic*, *photonic* and *phononic* crystals, respectively [16,19,20]. In all cases, the media have properties exhibiting space periodicity. There are a wide variety of applications in the field of elastodynamics [16]. Hladky-Hennion and Decarpigny presented a study applying a finite element method (FEM) to periodic materials used as coatings to avoid detection of submarines by ultrasound waves [21]. Ruzzene et al. modeled honeycombs and re-entrant honeycombs (hexagons with inverted angles) to find the directionality of the material (that can be used as an acoustic filter) [22]. Wang et al. developed a material with tunable band gaps, controlling local instabilities in the microstructure [15].

The existence of helically stacked plies (or Bouligand structures) have already been noticed and investigated in terms of their microstructural features in a variety of other animals, such as fish scales [23], exoskeletons of beetles [24], crabs [25] and lobsters [26–29]. For instance, Sachs and co-workers presented experimental measurements for lobster's cuticle using digital image correlation, obtaining the behavior for the elastic and plastic regimes [27–29]. Nikolov and co-workers have studied the hierarchical composition of the cuticle in the exoskeleton of the American lobster [30–32] and showed that the level of anisotropy in the elastic properties of the cuticle is very high at the nano-scale. However, such anisotropy decreases monotonically moving to the higher scale and exhibiting almost isotropic elastic properties at the millimeter scale. A similar result was reported in the exocuticles of beetles by Sun and Bhushan, who characterized the structure and

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