

Structure and mechanical properties of crab exoskeletons

Po-Yu Chen *, Albert Yu-Min Lin, Joanna McKittrick, Marc André Meyers

*Department of Mechanical and Aerospace Engineering and Materials Science and Engineering Program,
University of California, San Diego, La Jolla, CA 92093-0411, USA*

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Abstract

The structure and mechanical properties of the exoskeleton (cuticle) of the sheep crab (*Loxorhynchus grandis*) were investigated. The crab exoskeleton is a natural composite consisting of highly mineralized chitin–protein fibers arranged in a twisted plywood or Bouligand pattern. There is a high density of pore canal tubules in the direction normal to the surface. These tubules have a dual function: to transport ions and nutrition and to stitch the structure together. Tensile tests in the longitudinal and normal to the surface directions were carried out on wet and dry specimens. Samples tested in the longitudinal direction showed a convex shape and no evidence of permanent deformation prior to failure, whereas samples tested in the normal orientation exhibited a concave shape. The results show that the composite is anisotropic in mechanical properties. Microindentation was performed to measure the hardness through the thickness. It was found that the exocuticle (outer layer) is two times harder than the endocuticle (inner layer). Fracture surfaces after testing were observed using scanning electron microscopy; the fracture mechanism is discussed.

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1. Introduction

Arthropods are the largest animal phylum. They include the trilobites, chelicerates, myriapods, hexapods, and crustaceans. All arthropods are covered by an exoskeleton, which is periodically shed as the animal grows. The exoskeleton of arthropods consists mainly of chitin. In the case of crustaceans, there is a high degree of mineralization, typically calcium carbonate, which gives mechanical rigidity.

The arthropod exoskeleton is multifunctional: it supports the body, resists mechanical loads, and provides environmental protection and resistance to desiccation [1–5]. The outermost region is the epicuticle, a thin, waxy layer which is the main waterproofing barrier. Beneath the epicuticle is the procuticle, the main structural part, which is primarily designed to resist mechanical loads. The procuticle

is further divided into two parts, the exocuticle (outer) and the endocuticle (inner), which have similar composition and structure. The endocuticle makes up around 90 vol.% of the exoskeleton. The exocuticle is stacked more densely than the endocuticle. The spacing between layers varies from species to species. Generally, the layer spacing in the endocuticle is about three times larger than that in the exocuticle [6]. Fig. 1a is a SEM micrograph showing the epicuticle, exocuticle, and endocuticle.

A striking feature of arthropod exoskeletons is their well-defined hierarchical organization, which reveals different structural levels, as shown in Fig. 1b. At the molecular level, there are long-chain polysaccharide chitins that form fibrils, 3 nm in diameter and 300 nm in length. The fibrils are wrapped with proteins and assemble into fibers of about 60 nm in diameter. These fibers further assemble into bundles. The bundles then arrange themselves parallel to each other and form horizontal planes. These planes are stacked in a helicoid fashion, creating a twisted plywood structure. A stack of layers that have completed a 180°

* Corresponding author. Tel.: +1 858 531 4571.
E-mail address: pochen@ucsd.edu (P.-Y. Chen).

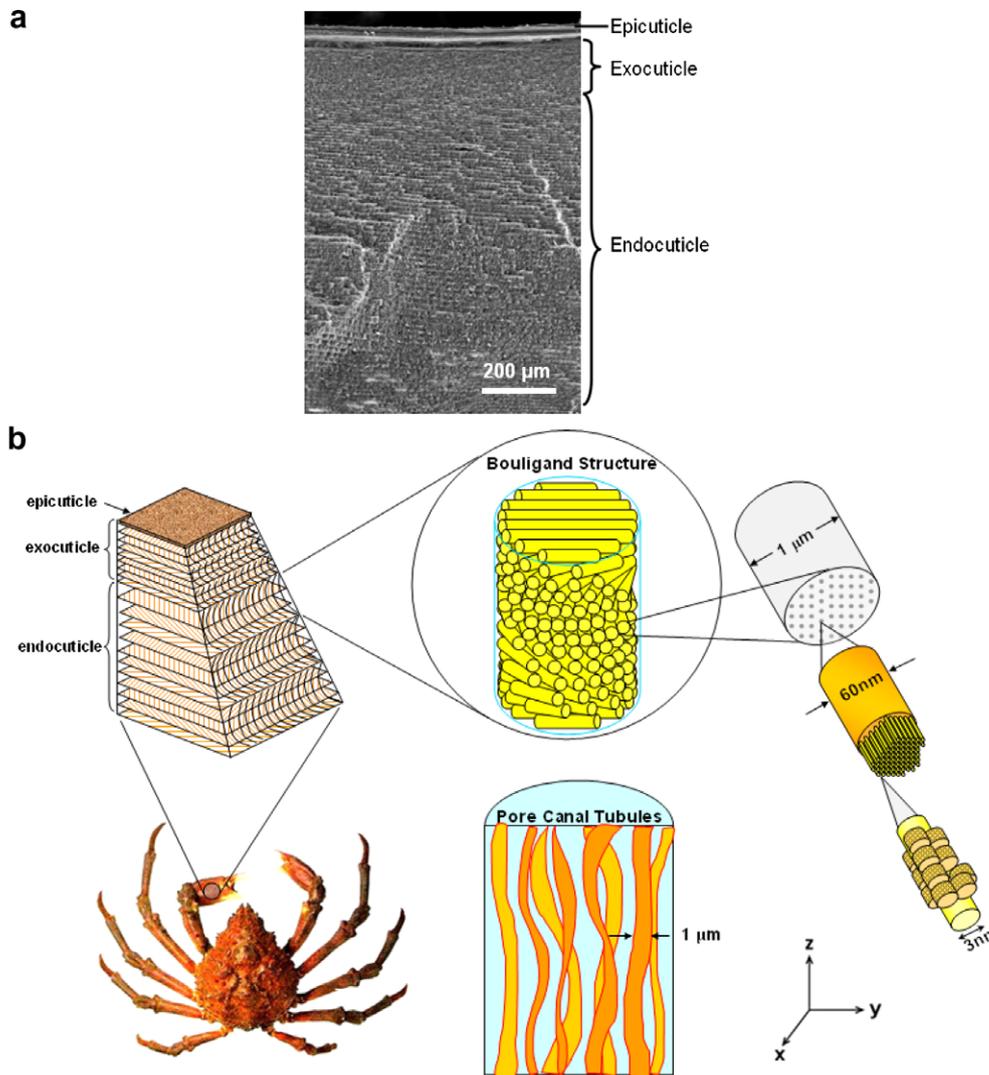


Fig. 1. (a) SEM micrograph of a cross-sectional fracture surface showing three different layers in the exoskeleton: epicuticle, exocuticle, and endocuticle. (b) Hierarchical structure of the exoskeleton of sheep crab, *Loxorhynchus grandis*. Chitin fibrils (~ 3 nm in diameter) wrapped with proteins form a fiber of ~ 60 nm in diameter. Fibers further assemble into bundles, which form horizontal planes (x - y plane) superposed in a helicoid stacking, creating a twisted plywood structure (180° rotation). In the z -direction there are ribbon-like tubules, $1 \mu\text{m}$ wide and $0.2 \mu\text{m}$ thick, running through the pore canals.

rotation is referred to as a Bouligand structure. These structures repeat to form the exocuticle and endocuticle [7–11]. The same Bouligand structure is also characteristic of collagen networks in compact bone, cellulose fibers in plant cell walls and other fibrous materials [12]. In crab exoskeletons, the minerals are in the form of calcite or amorphous calcium carbonate, deposited within the chitin–protein matrix [11,13–16].

In the direction normal to the surface (the z -direction), as shown in Fig. 1b, there are well-developed, high-density pore canals containing long, flexible tubules penetrating through the exoskeleton. These tubules play an important role in the transport of ions and nutrition during the formation of the new exoskeleton after the animals molt [17].

The mechanical properties of crustacean exoskeletons (mud crab, *Scylla serrata* and prawn, *Penaeus mondon*) were first investigated by Hepburn et al. [18] and Joffe

et al. [19]. Melnick et al. [20] studied the hardness and toughness of exoskeleton of the Florida stone crab, *Menippe mercenaria*, which exhibits a dark color (ranging from amber to black) on the chelae (tips of the claw) and walking legs. The dark material was much harder and tougher than the light-colored material from the same crab chela. The most comprehensive study is the one by Raabe and co-workers on the American lobster, *Homarus americanus* [6,21–25].

However, the mechanical properties in the direction normal to the surface have not yet been investigated. In this study, the mechanical properties of the sheep crab exoskeleton in the longitudinal direction (the y -direction) and the z -direction were measured. The exoskeleton is highly anisotropic, both in structure and mechanical properties. The motivation for this study is to understand the relationship between structure and mechanical properties in different

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