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Research Paper

Bending mechanics of the red-eared slider turtle carapace

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ABSTRACT

The turtle shell is a natural shield that possesses complex hierarchical structure, giving rise to superior mechanical properties. The keratin-covered boney top (dorsal) part of the shell, termed carapace, is composed of rigid sandwich-like ribs made of a central foam-like interior flanked by two external cortices. The ribs are attached to one another in a 3-D interdigitated manner at soft unmineralized collagenous sutures. This unique structural combination promotes sophisticated mechanical response upon predator attacks.

In the present study mechanical bending tests were performed to examine the static behavior of the red-eared slider turtle carapace, in different orientations and from various locations, as well as from whole-rib and sub-layer regions. In addition, the suture properties were evaluated as well and compared with those of the rib. A simplified classical analysis was used here to rationalize the experimental results of the whole rib viewed as a laminated composite.

The measured strength (~300 MPa) and bending modulus (~7–8.5 GPa) of the rib were found to be of the same order of magnitude as the strength and modulus of the cortices. The theoretical prediction of the ribs' moduli, predicted in terms of the individual sub-layers moduli, agreed well with the experimental results. The suture regions were found to be more compliant and weaker than the ribs, but comparatively tough, likely due to the interlocking design of the boney zigzag elements.

1. Introduction

The turtle shell is a hierarchical composite designed to protect the animal from sharp trauma such as those caused by predator attacks. This keratin-covered boney exoskeleton consists of two parts: the carapace (dorsal part) and the plastron (ventral part), which are connected by bone tissues situated between the front and hind limbs. The carapace is composed of ribs, which originate laterally from the spine and are engulfed by dermal bone (Gilbert et al., 2001), leading to a sandwich-like structure (Fig. 1). Each of the rib elements possesses two exterior (dorsal and ventral) cortices that enclose a cancellous interior (Fig. 1). The sandwich arrangement enables reduction of weight, which results into high specific mechanical properties (Ashby, 1983; Gibson, 2005). Additionally, the rigid ribs are attached to one another at soft

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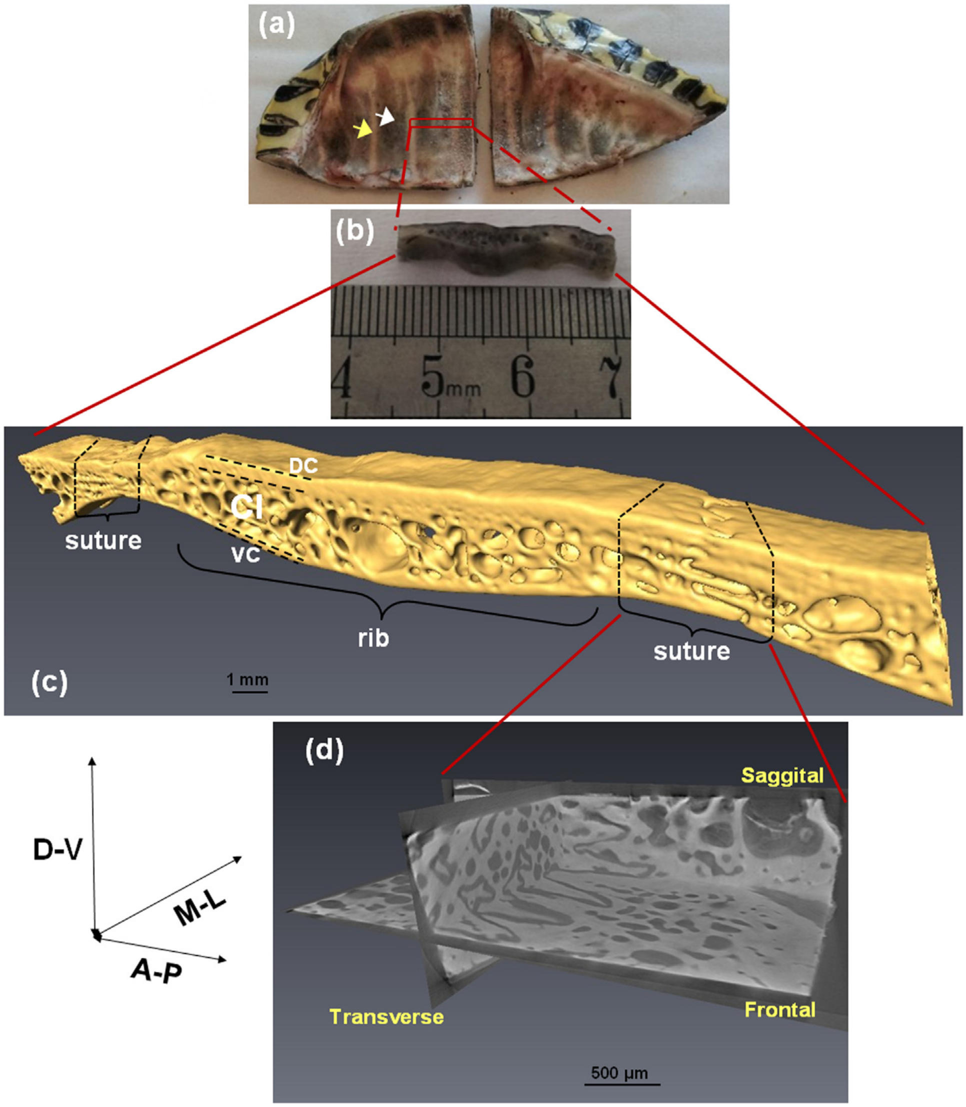

Fig. 1 – (Adapted from Achrai and Wagner, 2013) (a) Ventral view of a carapace cut. The white and yellow arrows mark an individual rib and suture, respectively. (b) A section of the rib enclosed by sutures at the edges. (c) A tomographic reconstruction of (b), showing the sandwich arrangement of the rib. The sub-layers forming the rib are indicated as the dorsal cortex (DC), ventral cortex (VC) and the cancellous interior (CI). (d) Ortho-slice view of the suture region (i.e., the perisuture). The unmineralized suture is indicated by the dark curly path. Images (c) and (d) are oriented in the same anatomical position. The anatomical planes (frontal, saggital and transverse) are marked with the anatomical orientations: anterior–posterior (A–P), medial–lateral (M–L) and dorsal–ventral (D–V). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

unmineralized collagenous sutures in a 3-D zigzag manner (Fig. 1), to enable slight displacements caused by minor loads during respiration and locomotion (Krauss et al., 2009). Higher loads such as during impact are resisted through suture interlocking.

In recent years, material scientists have focused on the structure and performance of natural armors (such as fish scales, Bruet et al., 2008; Yang et al., 2013, crab exoskeleton, Chen et al., 2008, and the armadillo carapace, Chen et al., 2011; Rhee et al., 2011), to try and improve the design of synthetic shields. In particular, efforts have been made to characterize the structural-mechanical properties of the turtle carapace. Rhee et al. (2009) examined the compressive and flexural behavior of the carapace rib while considering its mesoscopic layered structure. Using a combination of nanoindentation and finite element simulations, Balani et al. (2011) extracted the effective Young's modulus of the rib. Later on Damiens et al. (2012) similarly examined the compressive performance by experimental means and finite element simulations. Magwene and Socha (2012) assessed the compressive behavior of the whole carapace and the flexural behavior of the suture and rib regions, but did not consider the layered architecture. Recently, Achrai and Wagner (2013) examined the hierarchical structure of the carapace rib and suture – from the microscopic arrangements of the mineralized collagen fibrils within the sub-layers to the macro-structure – and measured the local modulus anisotropy by nanoindentation.