Materials Science and Engineering C 53 (2015) 128–133

Contents lists available at ScienceDirect

Materials Science and Engineering C

journal homepage: www.elsevier.com/locate/msec

The red-eared slider turtle carapace under fatigue loading: The effect of rib–suture arrangement

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ARTICLE INFO

Article history:
Received 6 February 2015
Received in revised form 26 March 2015
Accepted 21 April 2015
Available online 22 April 2015

Keywords:
Turtle carapace
Biological composite
Fatigue
Flexible suture
Mechanical characterization

ABSTRACT

Biological structures consisting of strong boney elements interconnected by compliant but tough collagenous sutures are abundantly found in skulls and shells of, among others, armadillos, alligators, turtles and more. In the turtle shell, a unique arrangement of alternating rigid (rib) and flexible (suture) elements gives rise to superior mechanical performance when subjected to low and high strain-rate loadings. However, the resistance to repeated load cycling – fatigue – of the turtle shell has yet to be examined. Such repeated loading could approximately simulate the consecutive high-stress bending loads exerted during (a predator) biting or clawing.

In the present study flexural high-stress cyclic loads were applied to rib and suture specimens, taken from the top dorsal part of the red-eared slider turtle shell, termed carapace. Subsequently, to obtain a more complete and integrated fatigue behavior of the carapace, specimens containing a complex alternating rib–suture–rib–suture–rib configuration were tested as well.

Although the sutures were found to be the least resistant to repeated loads, a synergistic effect was observed for the complex specimens, displaying improved fatigue durability compared to the individual (suture or even rib) constituents. This study may assist in the design of future high-stress fatigue-resistant materials incorporating complex assemblies of rigid and flexible elements.

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1. Introduction

Biological composite shields have increasingly been investigated in recent years [1–4]. What motivates such studies is the need for a comprehensive structure–mechanics link that would hopefully assist in future designs of man-made analogues [5–7]. One of these natural armors consists of stiff and strong boney segments, interconnected by compliant and tough unmineralized collagenous sutures [8]. This sort of complex structural motif is found in numerous skulls [9–11] and in several shells such as those of armadillos [12] and turtles [13]. They serve a number of mechanical purposes: in the human skull for instance, interdigitating sutures divide the flat-bone into three sub-regions and help relieve (relatively low) cyclic and static (compressive and tensile) stresses exerted during mastication and skull growth, respectively [14]. In the shell of the armadillo, the collagenous sutures connect abutting surfaces of the boney tiles and undergo tension [12] to enable flexible maneuvering (such as curling up into a ball upon predator attack).

The carapace (the top dorsal part of the shell) of the red-eared slider turtle (*Trachemys scripta elegans*) presents a unique macroscopic configuration of alternating stripes of rigid boney ribs attached to each other by compliant collagenous sutures (Fig. 1). At the micro-level, the ribs possess a flat-bone sandwich structure of a cancellous core enclosed by a disordered (woven-bone like) dorsal and a (parallel-fibered) plywood-like ventral cortices (Fig. 1c, [15]). The ribs are connected to one another by soft unmineralized collagenous fibers spanning the 3D zigzag interlocking sutures (Fig. 1, [13,15]).

The detailed hierarchical structure and the quasi-static mechanical properties of the rib and suture regions of the turtle carapace have been extensively studied, using local microscopic characterization [15–17], bending and compression tests [18,19], and finite element simulations [16,17,20]. Recently, the low-velocity impact response of the carapace was examined as well [21]. The sutures were found to play important roles under both low and high strain-rate loading conditions: under flexural quasi-static physiological low loads, the interlocking morphology was shown to enable relatively large deformations of the shell for respiration, locomotion and metabolic function of the reptile [13], whereas upon impact loads the absorbed impact energy was shown to increase by a factor of three, compared to suture-free regions. This is accomplished presumably through untangling of the boney zigzag elements and rupture of the tough unmineralized collagen fibers that span the sutures [21].

Although many studies have investigated the static mechanical properties of boney materials [22–24], few have focused on their dynamic mechanical response [25–27] and even less on their cyclic loading performance [28–30]. With regard to the turtle carapace, in spite of numerous biomechanical studies, characterization of its response to flexural cyclic loads, and in particular, upon high-stress

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http://dx.doi.org/10.1016/j.msec.2015.04.040
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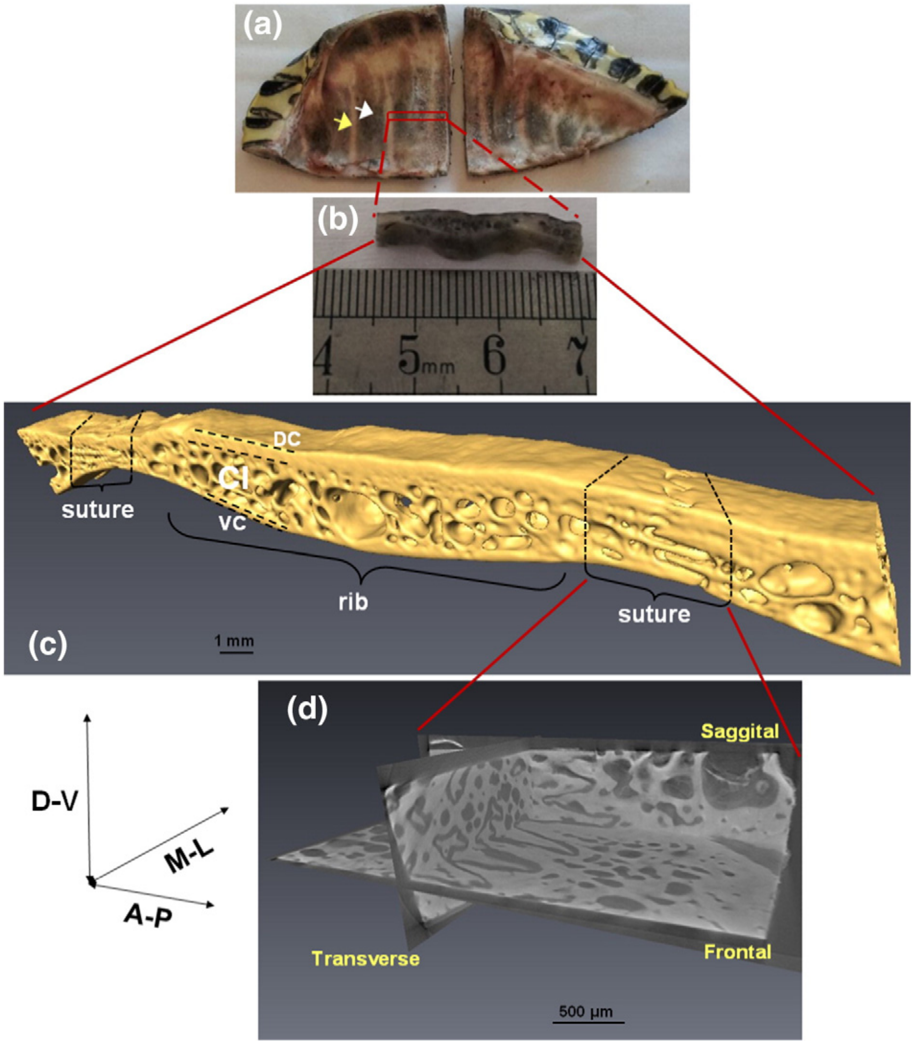

Fig. 1. (a) Ventral (inside-out) view of a carapace cut. The white and yellow arrows mark an individual rib and suture, respectively. (b) Section of the rib enclosed by sutures at the edges. (c) Tomographic reconstruction of (b), showing the sandwich arrangement of the rib. The sub-layers forming the 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, sagittal and transverse) are marked with the anatomical orientations: anterior–posterior (A–P), medial–lateral (M–L) and dorsal–ventral (D–V).
Adapted from [15]

loading is still lacking. This is, however, of great interest, since at times of predator attacks, the carapace may undergo repeated high-stress bending loads during biting or clawing.

In the present study the flexural high-stress cyclic loading responses of the rib and suture sub-regions of the red-eared slider turtle carapace were evaluated. Subsequently, to obtain a more complete and integrated description of the fatigue behavior of the carapace, specimens containing a complex alternating rib–suture–rib–suture–rib configuration were tested and their fatigue performance discussed.

2. Material and methods

2.1. Sample preparation

Several red-eared slider turtles (*Trachemys scripta elegans*) were obtained from the Israel Nature and Parks Authority. Considered as an invasive species in Israel, this animal is being eradicated by environmental agencies. 15–22 cm long carapaces were harvested from the turtles and frozen at −20 °C. Each carapace was subsequently thawed and cleaned from soft tissues (scutes were not removed). Miniature rectangular beam specimens were cut with an inner hole diamond coated low speed saw (Buehler Isomet), under constant water irrigation. All specimens were cut from the carapace center with regard to the anterior–posterior (A–P) and the medial–lateral (M–L) axes, while the specimen long axis is parallel to the A–P axis. Three types – rib, suture and complex – were considered (note that in all of them, the specimen depth was of the order of 2–3 mm for all carapaces):

Rib — the specimens were cut to a final size of ~(15–20) × 3 × ~(2–3) mm^3 (Fig. 2a, b).

Suture — the specimens, ~(15–20) × 3 × ~(2–3) mm^3 in size, contained the suture in their center, flanked by neighboring ribs (Fig. 2a, c). In this configuration, the anvil of the moving actuator applied load at the suture region, while the neighboring ribs rest on the supporting anvils.

Complex — the specimens, ~(35–50) × 3 × ~(2–3) mm^3 in size, contained a rib–suture–rib–suture–rib sequence (Fig. 2a, d). In this configuration, the anvil of the moving actuator applied load at the middle of the central rib, while the neighboring ribs (which are attached to the central rib through the zigzag sutures) rest on the supporting anvils.

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