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Mechanical properties and numerical simulation of Sulcata tortoise carapace

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ABSTRACT

Carapace of Sulcata tortoise acts as a natural shield that protects the body from natural predators. The carapace consists of four layers: keratin scutes, dorsal cortex, cancellous interior and ventral cortex. This study aims to investigate the load-bearing mechanisms of the carapace by characterizing the layers, measuring their mechanical properties and relating them to the macroscopic behavior under compression and bending loads. Test results indicate the influence of layers' morphology, especially porosity and structural compositions, on the macroscopic properties of the carapace. The bending samples are simulated using a commercial finite element code as laminate composite structures with homogeneous elastic layers. The models are shown to capture the load-displacement response of the carapace in the elasticity regime under quasi-static loadings.

1. Introduction

Natural protection systems such as hard shell of nacres (Flores-Johnson et al., 2014), bony skin of crocodiles (Sun and Chen, 2013), flexible scute of armadillos (Chen et al., 2011) have been studied to gain insights into their protection mechanisms that can be used in the design of bio-inspired body armors. Among these, turtle carapaces attract numerous interests (Achrai and Wagner, 2013; Rhee et al., 2009) due to their unique forms naturally optimized for threat protection capability. The carapace is a sandwich-like composite, with its thickness derived from layers starting from three to six layers (Balani et al., 2011; Rhee et al., 2009).

Tortoise shell has the same structure as turtles and terrapins. Its bony shell is composed of a dorsal dome-shape carapace and a ventral flat plastron. Both of them are connected by a lateral bridge while leaving holes for its head, legs and tail. Its vertebrae are connected to the carapace so that the tortoise cannot leave its shell. The carapace scutes are arranged into three rows with four tiles on both sides and five tiles in the center. There are also small scutes around the carapaces. The scute patterns can be used to identify tortoises. The plastron scutes are arranged into two symmetric rows as shown in Fig. 1.

Recent studies show many topics of interest in bio-inspired material design from turtle and tortoise carapaces such as strength and hydrodynamics of turtle shells (Stayton, 2011), strength and stiffness of the whole shell (Damiens et al., 2012), response of turtle shell to static and dynamics loads (Zhang et al., 2012), relationship between microstructure and macroscopic properties (Achrai and Wagner, 2013) and effect of rib-suture arrangement (Achrai and Wagner, 2015). Load distribution mechanisms of the sutures between scutes have been reported by Magwene and Socha, 2013.

A carapace of African spurred tortoise (Centrochelys Sulcata) or Sulcata tortoise is selected as the representative structure in this investigation. This tortoise is taxonomically classified as a land-based desert-dwelling reptile; it is the third-largest tortoise in the world with an average length of 80 cm when fully grown and a body weight of more than 100 kg. The size of its carapace provides a sufficient number of samples for test consistency and repeatability. In terms of protective capability, the shape of terrestrial tortoise carapace is known to be stronger than those of aquatic turtles (Stayton, 2011). In Thailand, Sulcata tortoise is one of the exotic pets, and its shell is readily available for study.

This study examines the quasi-static behavior of Sulcata tortoise's carapace under compression and three-point bending tests to gain an insight into the role of its laminate structure on the load bearing mechanism. Elastic moduli of carapace's layers are measured by nanoindentation tests. Results from these experiments shed light into the underlying load bearing mechanisms of the carapace. Both in-plane and out-of-plane effective moduli of the carapace are calculated from the theory of laminate composite with porous layers. The analytical moduli are benchmarked with the experimental results and finite element models of carapace under three-point bending tests.

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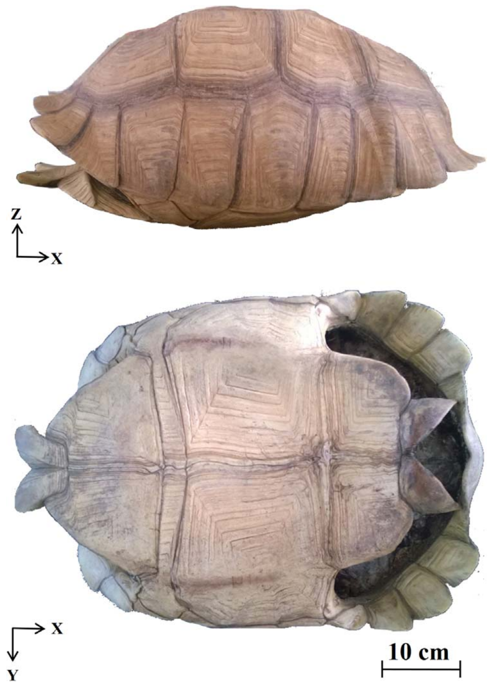

Fig. 1. Top: Side view of tortoise's shell. Bottom: Ventral view showing flat plastron.

2. Material and methods

2.1. Sample preparation and structural characterization

A body of Sulcata tortoise was donated within 24 hours after its natural death by a veterinarian. The organs and tissues were professionally removed from the shell by a local taxidermist. The shell was cleaned by formalin and water and left to dry by sunlight at a temperature ranging from 25 to 33 °C for 84 hours. Fig. 1 shows the dried Sulcata shell. The head-to-tail length of the shell was 60 cm and the end-to-end width was 42 cm. The height from the bottom of the shell to the top of the dome was 25 cm. After the preparation process, the dried shell was kept in room temperature for sample fabrication. Coupons for test samples were cut from the side of the carapace by drill tools (Bosch GBM 10 RE) and jig saw (Bosch GST 65E). Microstructures of the carapace samples taken from OLYMPUS STM7 optical microscope at 5x magnification are shown in Fig. 2.

The through thickness structure of the carapace consists of four layers: keratin scutes, dorsal cortex, cancellous interior and ventral cortex. Keratin scutes form the outermost layer composed of naturally fibrous keratin protein. The keratin is commonly found in animals with various forms such as nail, horn and hoof (McKittrick et al., 2012). According to Fig. 2, there are three rows of the keratin scutes from head to tail on this tortoise's carapace with 5 tiles in the middle and 4 tiles on both sides. Keratin scutes provide both flexibility and elasticity to the shell and also function as structural reinforcement. Another characteristic of keratin scutes is that the number of scute rings can be used to assess the age of desert tortoises. When tortoises grow up, the new layers of their hard shells or scutes are piled up from underside (Germano, 1988). Under the keratin scutes is the bone-like shell with three distinct layers. Dorsal cortex and ventral cortex are dense layers whereas cancellous interior is a closed-cell porous layer. The three layers form a load-bearing sandwich panel with a porous core. The bony shell is composed of small plates connected by a tissue called suture interface (Achrai and Wagner, 2013). The suture interface is the interlocking interface at the junction between hard materials such as nacre, bone or skull. The geometry and mechanical behaviors of suture become research topics in the bio-inspired designs (Boyce et al., 2013; Garzón-Alvarado et al., 2016; Yao et al., 2012). Note that the suture interfaces of the bony shell are not necessarily aligned with the connecting edges of the keratin scutes.

2.2. Three-point bending test

Three-point bending tests were performed to obtain macroscopic flexural strength and macroscopic flexural modulus. The middle section of the tortoise carapace is the maximum load bearing section. However, the vertebra fused within this section of the carapace limits the preparation of straight bending samples with consistent properties. In addition, samples may have different curvatures depending on the cutting location due to the dome shape of a tortoise shell. To minimize the effects of curvature on test results, the bending samples were prepared from the regions along the sides of the carapace. See Fig. 2 for the sample locations. The bending samples were bars with averaged dimensions (length × width × depth) of $120 \times 19 \times 6$ mm^3 and $80 \times 19 \times 6$ mm^3 for long span (L) and short span (S) tests, respectively. The geometries of the bars were recorded as 3D surface models for finite element simulations using a portable coordinate measuring machine (CMM).

The three-point bending tests were conducted by an Instron 5567 universal testing machine. The span between the two supports was 85 mm and 60 mm for long and short span samples, respectively. The loading point was placed in the middle of the span facing the ventral surface. The moving anvil loaded the samples at a rate of 1 mm per minute.

2.3. Compression test

Carapace samples were pressed along through-thickness and in-plane direction of the shell as shown in Fig. 3 to investigate the effects of structural anisotropy. The compression samples were cubes with the length ranging from 5.3 to 8.4 mm: these sizes were controlled by the thickness and curvature of the carapace. The samples were pressed at a speed of 1 mm per minute until failure or reaching an emergency stop when the clearance between the compression platens reached 2 mm. The force-displacement data were recorded and converted to effective stress and strain response of the carapace.

Note that top and bottom surfaces of the through-thickness samples were lightly polished to achieve flatness and parallelism required for the uniaxial compression tests. After the polishing process, the samples were inspected for the presence of all four layers. Removals of materials undoubtedly influence the mechanical response of the samples. However, the test results to be shown later indicate a consistent macroscopic modulus along the through-thickness direction because the core layers remain intact.

2.4. Nanoindentation test

The hardness and elastic moduli of the four through thickness layers were examined on the virgin bar samples by IBIS Nanoindentation system with Berkovich diamond indenter. The Young's modulus and Poisson's ratio of the indenter are 1000 GPa and 0.07, respectively. The area function calibration of the indenter tip was performed on fused silica with an elastic modulus of 72.5 GPa and a Poisson's ratio of 0.17 (Fischer-cripps, 2005). The through thickness surface was polished using 1000 grit silicon carbide sandpaper. Load-displacement data of the nanoindentation tests with an elastic-plastic loading followed by an elastic unloading were converted to hardness and elastic modulus using Oliver and Pharr method (Oliver and Pharr, 1992).

3. Experimental results and discussions

3.1. Results of three-point bending test

Stress-strain curves of the carapace under three-point bending tests