The Structure and Mechanical Property of Turtle Shell

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Summary The turtle shell is an amazing structure optimized through the long-term evolution by nature. This paper reports the experimental study and numerical analysis on the mechanical property and the microstructure of the shell of Trachemys scripta (Red-ear turtle) living in South China. The inside surface of the shell, especially the bottom plate, is covered with a biofiber-reinforced thin film with a thickness of ~28 microns. This layer of thin film material gives the highest strength in the turtle shell, reaching ~100MPa. Especially, the reinforced biofibers first go down from the four rib surfaces and then spread into the inside surface of the bottom plate. It is found that such a distribution of the biofibers follows the stress direction on the inside surface of the bottom plate to resist the evolution of shell cracking.

Keywords：Turtle shell, microstructure, mechanical property

1 Introduction

Turtle is among the oldest animals that still exist in the world, which is believed to have evolved since 220 millions years ago [1]. The turtle shell, as the protective armor, plays an important role in helping the animal survive and evolve. The delicacy and optimal design of the turtle shell yields not only strong defense ability, but also an anchoring site for the muscles and the major mineral reservoir of the body [2]. The vaulting shell of the turtle not only provides the animal with the optimal load-bearing capacity, but also results in the maximum space for the animal storing and protecting its internal organs [3]. Rhee et al. [4] found that the turtle shell consists mainly of three layers of materials, namely, the interior and exterior layers consisting of cortical bone, and the middle layer consisting of cancellous bone. Although the turtle shell is quite stiff at the surface, the shell can still yield a small amount of deformation during the turtle movement so as to help it keep the efficiency of both respiration and locomotion. This is because the shell consists of many small plates connected with the soft sutures that give rise to a small elastic deformation of the shell under a small load but become considerably stiff under a large load. Krauss et al.[5] have given a detailed description of the microstructure and mechanical property of the sutures of turtle shell. Until now, most of the reported studies on turtle shell are focused on the genetic, molecular and cellular aspects of its embryonic development. However, little is known on the detailed mechanical property of the turtle shell at different levels and positions. The present study is therefore focused on the mirostructure and mechanical property of the turtle shell.

2 Observation of Microstructure

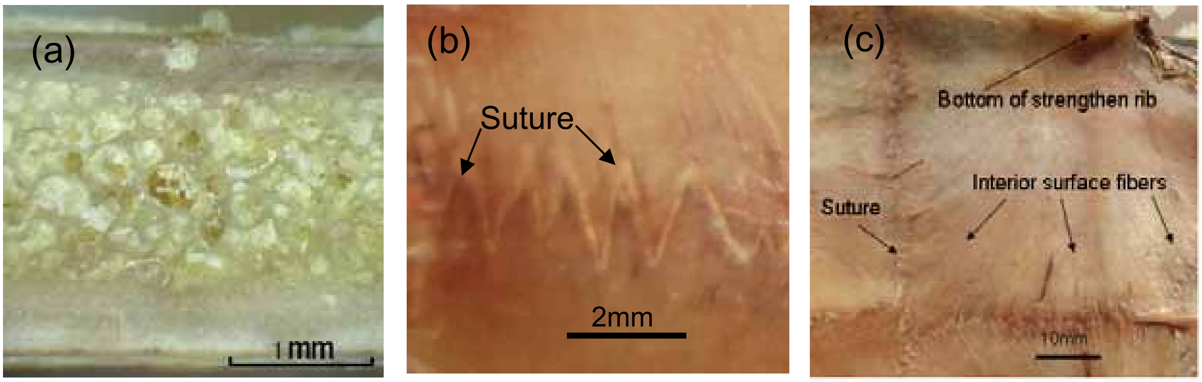

Fig.1 Microstructure of the turtle shell of Trachemys scripta: (a) photo image of the cross section of the bottom shell; (b) photo image of the suture at interior surface showing the suture structure; (c) inside surface image of the bottom plate.

The turtle shell studied here was Trachemys scripta (Red-ear turtle) living in South China. Its microstructure is shown in Fig. 1, which is almost the same as Terrapene carolina carapace studied by Rhee et al. [4]. On each side of the shell, there are two strengthening ribs covered with biofibers extending to the bottom plate surface. They give rise to the highest strength in the turtle shell. The mass densities of the shell at the interior, exterior and middle layers are respectively 1.52, 1.47 and 1.03 g/cm^3.

3 Measurement of Mechanical Property

To measure the mechanical property at different levels and positions, the turtle shell (length ~220mm, width ~145mm) was arranged between two parallel steel surfaces and was pressed with a materials testing system using a compression speed of 2mm/min. The compression failure load for this shell is around 3330N corresponding to the maximum displacement (top board center) of 10.8mm. During the compression experiment, it was found that the rear part of the top board gave the maximum compression displacement, while the front part of the top board almost did not produce the normal displacement. Therefore, the rear part of the top board started to fail first. At the beginning of the failure process, some cracking sounds could be heard from the rear part, and finally a few visible cracks occurred.

The tensile modulus and strength of the turtle shell materials at different locations are given in Tables 1 and 2. The strength and modulus at the strengthening rib are obviously larger than those at other locations. The initial modulus is defined as the modulus at the small strain less than 0.001 and the final modulus is defined as the ratio of the fracture stress and the fracture strain. The later is similar to the average tensile modulus. As mentioned above, the inside surface of the shell, especially the bottom plate, is covered with a biofiber-reinforced thin film with a thickness of ~28 microns. This special composite film yields the highest strength reaching over 100MPa, about 2.5 times the strength of the interior layer material.

Table 1 The tensile modulus and strength of the turtle shell materials

location	Interior	Exterior	Middle	Rib Interior	Rib Middle
Initial Modulus（MPa）	985	530	315	1190	700
Final Modulus (MPa)	500	256	230	511	382
Tensile Strength（MPa）	40	28	19	51.8	34.5

4 Discussions and Conclusions

The turtle shell is an amazing structure optimized through the long-term evolution by nature. Both its material and structure realize a cooperative optimization design to yield an optimal load-bearing capacity. This paper reports the tensile mechanical properties at different levels and locations, and the microstructure of Trachemys scripta (Red-ear turtle) living in South China.

The shell can be divided into three layers according to their strength: interior layer, exterior layer and middle layer. Their average tensile moduli are respectively 500MPa, 256MPa and 230MPa, and their tensile strengths are respectively 40MPa, 28MPa and 19MPa. The inside surface of the shell, especially the bottom plate, is covered with a biofiber-reinforced thin film with a thickness of ~28 microns. This layer of thin film material gives the highest strength in the turtle shell, reaching 98MPa. The turtle shell as a whole will be subjected to bending load so that the inside surface is under tension while the outmost surface is under compression. Thus, the inside surface of the shell is covered with the biofiber-reinforced composite film with a strength of about 100 MPa. Especially, the reinforced biofibers first go down from the rib surface and then spread into the inside surface of the bottom plate. It is found that such a distribution of the biofibers follows the stress direction on the inside surface of the bottom plate to resist the evolution of cracking. An integrated analytical, computational and experimental effort is being made to further explore this interesting issue.

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