Exploration of tortoise shell structure mechanical characteristics

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Abstract: As one of the oldest creatures on the earth, the tortoises have formed a nearly perfect shell structure after millions of years of evolution. In this paper, Chinese tortoise shell is studied. Firstly, the scanning model of the tortoise shell is established by means of computer tomography (CT) scanning technology and MIMICS software. Secondly, the solid model of three-dimensional structure of the tortoise shell is constructed by using geomagic studio reverse engineering software. Afterwards, the compression numerical simulation of the tortoise shell structure under low strain rate is conducted with the help of finite element software LS-DYNA. Finally, load-bearing characteristics of the tortoise shell structure and dome-shaped structure are compared and analyzed. The results show that compared withthe dome-shaped structure with the same volume, tortoise shell structure has a higher structural rigidity and can withstand higher pressure. Therefore, tortoise shell structure provide some reference to the design of armored vehicles, sheltersand other types of thin shell structures.

Key words: Chinese tortoise shell; computer tomography (CT) scanning; MIMICS software; reverse engineering; structural rigidity

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Most of existent creatures in nature have gone through millions of years of evolution. In order to adapt to the complex surroundings, the structure, morphology and function of them have been comprehensively optimized. Tortoise, one of the oldest living beings on the earth, has formed hard shell to survive. With the continuous development of bionics, how to make use of excellent biological structure to build high-strength, low-cost, low-weight bionic structure has become an important subject.

The tortoise shell structure with remarkable mechanical properties have attracted wide attention of researchers at home and abroad. At present, most of researches mainly focus on the study of tortoise shell's material. For example, the micro-structure of Terrapene carolina box tortoise shell material was observed by Damiens, et al.[1] and quasi-static compression experiment was contructed for three-layer tortoise shell material. The results show that the stress-strain curve of tortoise shell material has a longer platform area and thus this kind of material structure can absorb impact energy and reduce vibration. The composition of tortoise shell material was investigated by Ree H, et al.[2] through scanning electron microscope (SEM). The mechanical test results reveal that the interior closed-cell foam layer plays a significant role in the overall deformation behavior of the tortoise shell. In addition, XU Yong-dong, et al.[3] found that Havesian system is the basic structural unit of compact layer and Volkmann vessel is in the center for transporting nutrients to tortoise shell. The bending test on shell material was made and the results show that the maximum bending strength of tortoise shell material can reach as much as 165.1 MPa.

However, research on mechanical properties of tortoise shell structure is less. The main reason is that shell structure is complicated, therefore traditional computer aided design (CAD) software cannot construct the 3D model of tortoise shell structure.

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With the development of science and technology, triangulation coordinate measuring technology and computed tomography (CT) scanning technology have been widely used in engineering. For example, red-eared slider shell model was reconstructed by ZHANG, et al. [4-5] and the micro-structure and composition of tortoise shell were analyzed by drawing the inspiration of finite element analysis (FEA) results obtained by mechanical, dynamical and modal analysis of the tortoise shell using ABAQUS software. LI, et al. [6] reconstructed Terrapene carolina box outer surface and analyzed the mechanical properties of 2D carapace shell model with the help of triangulation coordinate measuring instrument.

The studies of ZHANG[4-5] and LI[6] have some limitations because they did not consider the influence of stress of ribs on tortoise shell structure. This paper takes the adult Chinese tortoise shell as research object, utilizing CT scanning technology and MIMICS software to built tortoise shell scanning model and using geomagic studio reverse engineering software to construct tortoise shell three-dimensional structure. The compressive properties of tortoise shell structure under low strain rate are studied with the help of finite element software LS-DYNA.

1 Calculation model

1.1 Tortoise shell model

Tortoise shell shows symmetrical structure with the ribs distributed on both sides of the spine, and carapace is composed of five different shields. There is a slight difference between the same species of tortoise shells, but integral structure are similar, which does not affect integral stress analysis of the shell structure.

The composition of tortoise shell structure is shown in Fig. 1.

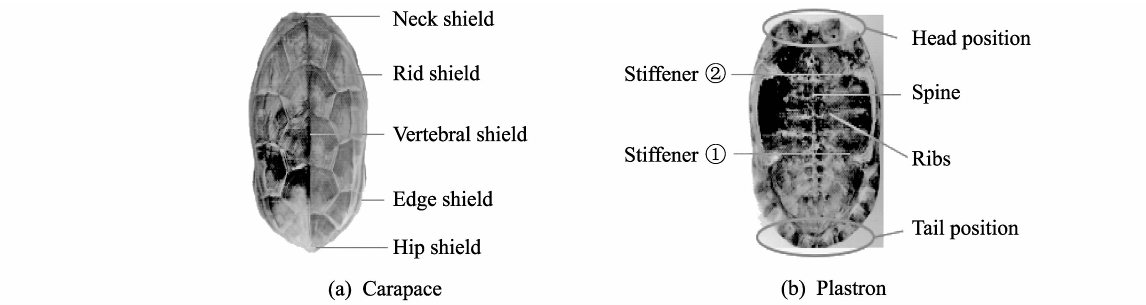

Fig. 1 Composition of tortoise shell structure

In this paper, 3D model of the tortoise shell is reconstructed based on CT scanning technology[7], which provides the complete information of tested entity, avoids damage to tortoise shell structure by conventional measurement methods and ensures integrity of the tortoise shell structure.

The reconstruction process of tortoise shell structure is shown in Fig. 2.

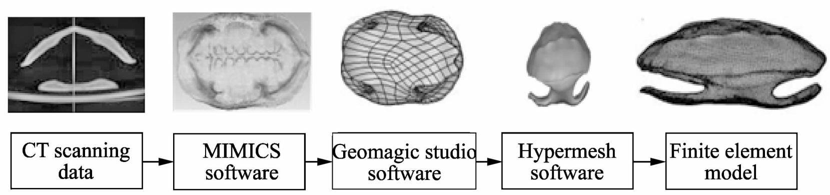

Fig. 2 Tortoise shell structure reconstruction process

Firstly, the section information of tortoise shell is obtained by means of CT scanning technology and then scanning data is output in dicom format. Secondly, quick scanning model is built using MIMICS software[8-9], and the scanning model is output in STL format. Afterwards, STL data is processed using geomagic studio software[10], and NURBS patches[11] can be obtained by the surface reconstruction of geomagic studio with the result output in iges format. Finally, the tortoise shell model's free edges and overlap surface are removed with the help of hypermesh's geometry cleanup function. Thus the tortoise shell 3D model reconstruction is completed. The contrast between reconstruction model and physical model is shown in Fig. 3.

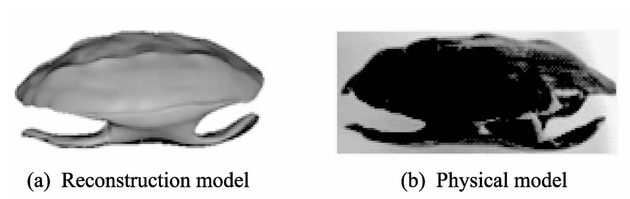

Fig. 3 Contrast between reconstruction model and physical model

It can be seen that the reconstruction model based on CT scanning technology remains the original structure characteristics, and the geometric shapes of key parts under stress such as ribs and stiffeners are obvious, therefore it can satisfy the requirements of research on compressive properties.

1.2 Contrast model

The contrast model of the tortoise shell structure adopts dome-shaped structure. The tortoise shell model and the contrast model have the same size with volume of $V=1\ 020.6\ \text{cm}^3$, span of $S=22.1$ cm, height of $h=10.5$ cm and length of $L=29.5$ cm. With the same volume the thickness of contrast model is calculated to be $t=0.63$ cm. The contrast model is shown in Fig. 4.

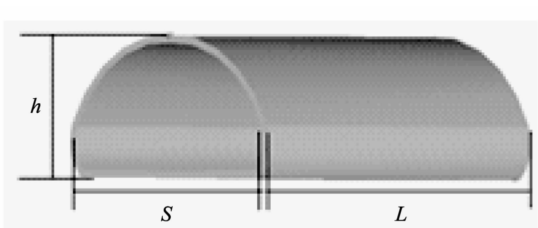

Fig. 4 Contrast model

1.3 Material models

The material models of tortoise shell structure and dome-shaped shell structure all select *MAT_PLASTIC_KINEMATIC. This kind of material model is related to strain rate. The simulation material chooses 45# steel and the material parameters are shown in Table 1[12].

Table 1 Material parameters of 45# steel

Parameters	ρ (kg/m^3)	E (GPa)	σ_s (MPa)	ν	SRC	SRP
Value	7.85×10^3	207	350	0.3	40	6

The simulation models of tortoise shell structure and dome-shaped shell structure adopt half of the body and the symmetry plane imposes symmetry constraint. LS-DYNA software is used for numerical simulation and loading method is shown in Fig. 5.

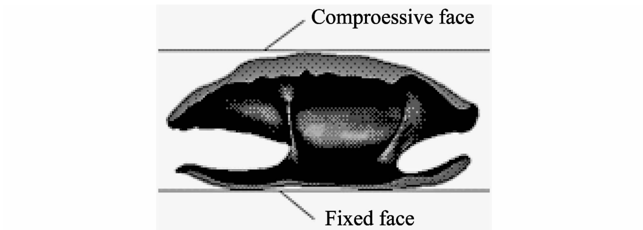

Fig. 5 Loading method

The compressive face moves at a constant rate of 3.0 m/s and accordingly the maximum displacement of compressive face is 0.3 cm. From the perspective of strain rate, the maximum strain rate of the tortoise shell structure is $66.7\ \text{s}^{-1}$, which belongs to low strain rate.

2 Simulation

2.1 Analysis of load-bearing characteristics

The deformation-force curve of the compressive face is shown in Fig. 6.

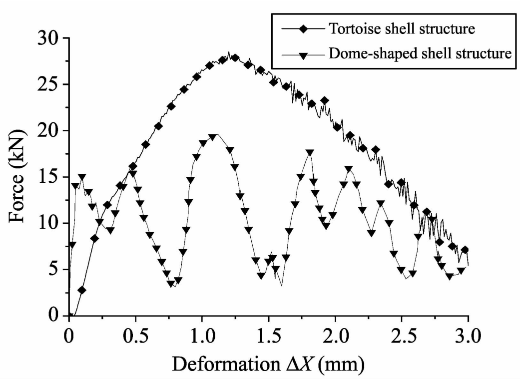

Fig. 6 Deformation-force curve of compressive face

By analysis of counterforce of tortoise shell structure and dome-shape shell structure to the compressive face, the load-bearing characteristics of two kinds of structures are presented intuitively.

The comparison results show that the counterforce of tortoise shell structure to the compressive face is bigger than that of dome-shape shell to the compressive face, which reveals that tortoise shell structure has stronger load-bearing capacity. The bone plates, stiffeners and ribs jointly lead to good load-bearing characteristics of the tortoise shell structure. This article analyzes load-bearing characteristics of the tortoise shell structure during compression process based on equivalent von-mises stress distribution and total displacement.

2.2 Von-mises stress contours of tortoise shell

The von-mises stress contours of tortoise shell structure vary with amount of compression ΔX, as shown in Fig. 7. On the initial stage of the compression, the compressive face contacts with the highest part of the tortoise shell structure and a large contact stress occurs; With the increase of the amount of compression, the first stress concentration area (in addition to the stress concentration area in contact with the compressive face) on the tortoise shell structure appears on stiffener ①; When the amount of compression is $\Delta X = 1.37$ mm, stress concentration phenomenon appears on stiffener ②; With the increase of amount of compression ΔX, the range of stress concentration area on these two stiffeners continues to expand, and the stress values also increase; When the amount of compression is $\Delta X = 3.00$ mm, the high stress area of tortoise shell structure is mainly concentrated in four parts: contact are a Ⅰ with compressive face of tortoise shell structure, position Ⅱ of stiffener ①, position Ⅲ of stiffener ② and connection area Ⅳ of stiffener ① with the carapace. The stress concentration area Ⅰ is the largest and the stress value is higher, while stress concentration area Ⅱ is the smallest and stress value is low.

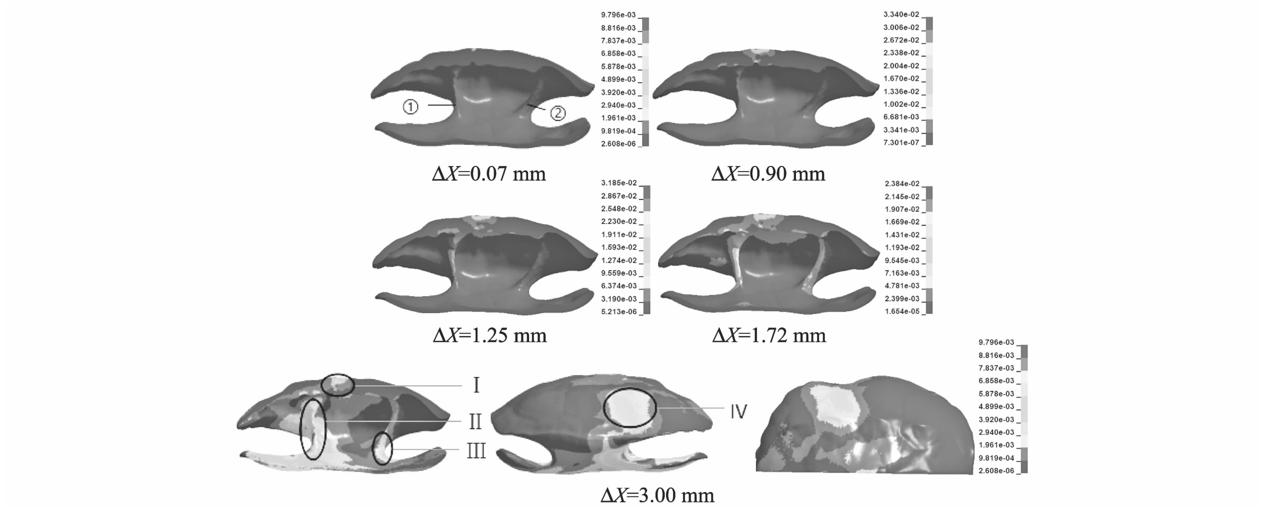

Fig. 7 Von-mises stress contours of tortoise shell

The stiffeners are the main parts to connect carapace with plastron and the stress between carapace and plastron is transfered mainly by stiffeners, therefore the stiffeners bear higher stress; The connect area of stiffener ① with carapace produces high stress zone Ⅳ, but there is no stress concentration phenomenon in the joint area of carapace and stiffener ②, which results from shapes of the stiffeners and connection method between carapace and stiffener. Stiffener ② and ribs are directly connected, which increases junction area of stiffener and carapace and reduces stress.

When amount of compression is $\Delta X = 3.00$ mm, the von-mises stress contours of tortoise shell structure and dome-shaped shell structure are shown in Fig. 8. In the process of compression, the stress of dome-shaped shell structure is distributed as strips and more uniformly, and the stress value of ribs is higher than that of the transition area between ribs. The main reason is that the ribs in the inner surface of the tortoise shell structure have obvious bluge. In addition, under the external load, ribs have similar function with stiffener. Ribs are the main load-bearing structure, therefore, ribs have great influence on the stress distribution of the tortoise shell structure.

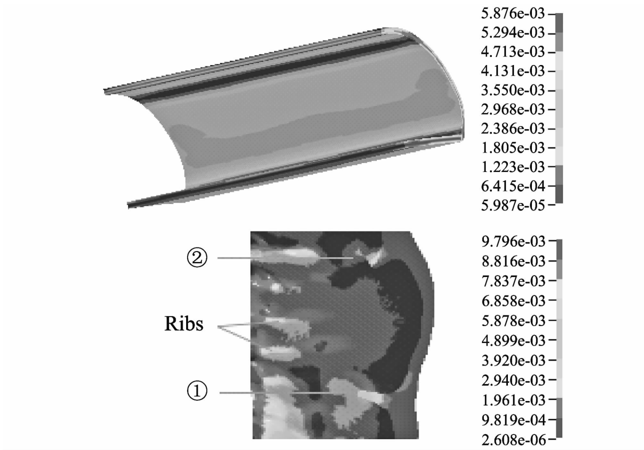

Fig. 8 Von-mises stress contours

From von-mises stress distribution figures above it can be found that most element stress values is low, there is no large concentration points during stress transfer. This kind of stress distribution can avoid the material from partial invalidity because of the appearance of stress concentration points. The stress value at zone Ⅰ is higher than zone Ⅱ as a result of long-term natural evolution of the tortoise. Stiffener ① is far from head, heart and other vital organs of the tortoise, this form of stress distribution makes the high stress zone away from the critical organs such as tortoise head, thus it can protect the safety of tortoise as much as possible.

2.3 Displacement analysis of tortoise shell structure

The displacement of tortoise shell structure is shown in Fig. 9.

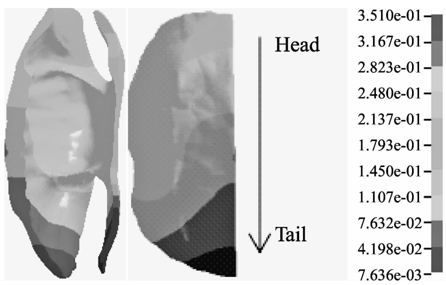

Fig. 9 Displacement of tortoise shell structure

The total amount of displacement of tortoise shell structure increases from head to tail. The biggest displacement is 3.51 mm at the end of tortoise shell near the tail of tortoise; The total displacement of the position of the head is about 1.80 mm, it is only half of the total amount of displacement of the tail. The displacement of inner cavity between stiffener ① and stiffener ② is in the range of 2.03−2.51 mm, the relative displacement is smaller. The inner cavity of the tortoise shell structure is the house of the viscera, under the action of external loads, maintaining the inner cavity volume constant can ensure the tortoise visceral pressure in a stable state, it has great significance to maintain the tortoise's normal physiological activity.

From the view of the stress distribution, compared with the the tortoise shell structure, the stress distribution of contrast structure is more uniform, but the it does not suit for lightweight designing. Although the use of high specific strength and high specific modulus can meet the requirements of armored vehicle, shelters and other shell structure designs, sometimes it is hard to avoid increasing the weight of structure. How to reduce the cost of material and structure weight becomes one of important topic in modern time. The tortoise shell is typical integral structure, the ribs, stiffeners and bone plates are integrated in the natural evolution, it can reduce the stress of excessive centralization phenomenon through smooth transition between various parts. The tortoise shell structure mainly relys on ribs and stiffeners to transfer load, the shields, ribs and stiffeners are fused together to go through force. Integral structure not only is beautiful, but also has higher structure strength than the skeleton strength[13]. It has important reference to design of the shell structure. It can achieve the purpose of saving material and reducing weight through adopting high strength materal at weak place and adopting low density and low cost material at low stress place.

3 Conclusion

The tortoise shell structure has better compression capability than domeshaped structure with the same volume. The joint action of ribs, stiffeners and shields makes tortoise shell structure withstand high pressure. The stiffeners and ribs are the main parts for transfer stress. The bone plates not only plays a role of connecting stiffeners and ribs, but also bears stress. The tortoise shell structure has an important reference to design of thin shell structure because of its excellent load-bearing characteristics and large inner cavity volume in the compression process.

Many factors affect the mechanical properties of the tortoise shell structure, therefore further study on the mechanical properties of shell structure need to be carried out in order to build tortoise shell biomimetic structure and satisfy actual project requirements.

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草龟龟壳结构力学性能初探

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摘　要： 乌龟作为地球上最为古老的生物之一，在上亿年的进化中，形成了趋于完美的龟壳结构。以中华草龟龟壳为研究对象，利用CT扫描技术以及MIMICS软件建立了龟壳扫描模型，通过geomagic studio逆向工程软件完成龟壳三维结构的实体建模。利用LS-DYNA有限元软件对龟壳结构进行了低应变率下的压缩数值仿真，并分析比较了龟壳结构与圆拱形结构的承载特点。结果表明，与相同体积的圆拱形结构相比，龟壳结构有较高的结构刚度，可以承受更高的压力。龟壳结构对装甲车辆、方舱等薄壳类结构设计有一定的借鉴作用。

关键词： 中华草龟；CT扫描；MIMICS软件；逆向工程；结构刚度

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