Research of Circuitous Hole Structure of Mineral-collagen Fibers in Tibia

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Abstract. Through the observation of the microstructure of the longitudinal and transverse sections of the tibia, it is found that the distribution of mineralized collagen fibers is layered. There are many biological micropores in the cross section of the tibia, and the mineralized collagen fibers near the pores bypass the pores in an orderly manner, thereby forming a mineralized collagen fiber circuitous hole structure. According to the observation results, a finite element analysis model of fiber reinforced composites with fiber circuitous hole structure and drilling hole structure is established. The analysis results show that the maximum strain of the drilling hole structure and fiber circuitous hole structure are 6.428e-3 and 3.583e-3, respectively. The maximum strain of the drilling hole structure is about 1.8 times that of the fiber circuitous hole structure under the same load. The results have shown that the fiber circuitous hole structure of tibia has an excellent resistance to deformation, which can effectively improve the toughness of the tibia. The application of the structure to the composite material can effectively improve the strength of the composite material.

1. Introduction

Bone is a representative anisotropic natural biological composite material, which has high strength and toughness and provides reliable support for animal body, and it is also has good dynamic adaptability [1-2]. The investigation of structural-related properties of bones is an interesting topic to researchers and biologists [3-4], who are mainly interested in understanding how the structure of bone affects the mechanical behavior [5-6]. Studies have shown that bone has a complex hierarchical structure, and its excellent mechanical properties are closely related to its microstructure [7-8] and its mineral composition [9].

The structure and mechanical properties of the major bone constituents have been investigated by many research groups for several decades, including seminal works by Currey [10], and Rho et al. [11]. The structural properties of cortical bone are highly hierarchical [12-13]. The study of hierarchical structure of bone is very important work for understanding the mechanism of excellent mechanical properties of bone. The bone is composed of cortical bone and cancellous bone. The cortical bone distributes the outside of various bones and the backbone of long bones, which is thicker at the backbone.
and plays a protective and supportive role, while cancellous bone is distributed inside of cortical bone [14]. At the nanoscale, the main composition of is organic phase, inorganic phase and water. The main element of organic phase is type I collagen, the composition of inorganic phase is hydroxyapatite-like mineral (HA) [15]. The mineralized collagen fibrils are composed of organic phase and inorganic phase, which is oriented in a certain direction to form bone lamella. The thickness of single lamella is 3–7 μm [16]. The cylindrical osteons are non-uniformly distributed in bone, the length of osteon is about 1 mm and the diameter is 200-300 μm, and its axis is almost parallel to the long axis of bone [17-18].

At present, the research of bone mainly focuses on the multi-level structure of bone [15], mechanical properties [6,10] and structural bionics [19], but little research has been reported on the fiber circuitous hole structure. In this paper, the tibia of Chinese yellow cattle was taken as the research object. The micro-nanostructures were observed by scanning electron microscopy. It was found that the collagen fibers in the matrix have layered structure characteristics. The collagen fibers continuously bypass the holes without interruption and forming a hollow cylinder. Furthermore, the finite element analysis model of the composite material plate with fiber circuitous hole structure and drilling hole structure is established, and the influence of the two pore structure models on the strength of the composite sheet is compared and analyzed, which shows the superiority of fiber circuitous hole structure in the tibia.

2. Microstructure observation of tibia

There are obvious differences in the mechanical properties and microstructure of the tibia depending on its type, growth environment and age. In this study, the tibia (bone age: 24 months) of Chinese yellow cattle was selected as the research object. The preparation method and steps of the scanning electron microscope (SEM) sample as follows: (1) The muscle tissue is removed from the bovine tibia, and the surface of the tibia is washed using 95% alcohol. Then the tibia is cut along its longitudinal and transverse. The samples with a length and a width of about 5 mm are obtained; (2) The obtained sample is dehydrated with alcohol and dried; (3) Special conductive adhesive is used to fix the sample on a special aluminum tray, and a layer of gold and palladium coating is sprayed on the surface using ion sputtering KYKY-203; (4) Scanning electron microscope TESCAN VEGA II is used to perform experimental observations. Magnification is from 20× to 11000×.

Observations have shown that the bovine tibia has multi-scale microstructure features. First, nanoscale mineralized collagen fibers form a fiber sheet with a thickness on the nanometer scale [7, 11, 12]. Then these fiber sheets form a fiber layer parallel to the surface. The observation along the axial section of the tibia indicates that the mineralized collagen fibrous layers are distributed in parallel and the thickness of the fibrous layer is non-uniform (Fig. 1a). The mineralized collagen fibers of the tibia are parallel to the surface of the tibia and have a layered structure, which can exert a large bearing capacity of the mineralized collagen fibers. The observations along the transverse section of the tibia indicate that there are many biological micropores in the cross section. The distribution of mineralized collagen fibers near the micropores is observed carefully. It is revealed that the mineralized collagen fibers near the pores bypassed the pores in an orderly manner, thereby forming a fiber circuitous hole structure (Fig. 1b).

Figure 1. Layer structure of collagen fibers (a) and the fiber circuitous hole structure (b)
3. Biomimetic and analysis of fiber circuitous hole structure

3.1 Analysis model establishment

In practical engineering, it is inevitable to encounter the problem of drilling hole of the fiber reinforced composite laminate [8]. Since the composite hole is often machined by drilling, the fiber at the hole is cut. According to SEM observations, there is a fiber circuitous hole structure. In order to compare and analyze the influence of the fiber circuitous hole structure and drilling hole structure on the mechanical properties of the fiber reinforced composite laminate. According to the observation results of scanning electron microscopy, a unidirectional fiber reinforced composite laminate with a fiber circuitous hole structure (Fig. 2a) and a unidirectional fiber reinforced composite laminate with a drilling hole structure (Fig. 2b) analysis model was established.

The two analytical models are square fiber reinforced composite panels with side length $L = 100$ mm and include a hole, the radius of hole is $R = 22.5$ mm. In the finite element model of the fiber circuitous hole structure (Fig. 2a), the fibers are continuously bypassed. In the model of drilling hole structure, the fiber around the hole is cut off. The CAX4R (quadrilateral four-node bilinear isoparametric elements) elements is used in the two analysis models. A tensile load of 10 MPa is applied to both ends. The material parameters are shown in Table 1.

![Figure 2. Bionic fiber reinforced model with fiber circuitous hole structure (a) and drilling hole structure (b)](image)

**Table 1 Material parameters of the fiber and matrix**

|       | Elastic Modulus (Mpa) | Poisson's ratio |
|-------|-----------------------|----------------|
| Matrix| 8000                  | 0.25           |
| Fiber | 44638                 | 0.281          |

4. Analysis of calculation results

The maximum strain distribution of the fiber circuitous hole structure and drilling hole structure is calculated as shown in Fig. 3. It can be seen from Fig. 3 that the maximum strain of the drilling hole structure is $6.428e^{-3}$ and the maximum strain of the fiber circuitous hole structure is $3.583e^{-3}$ under the same load. The maximum strain of the drilling structure is 1.8 times that of the fiber circuitous hole structure. Therefore, the drilling structure may firstly reduce the stability of the entire structure due to large deformation of the internal structure, so the fiber circuitous hole structure has a good resistance to deformation.

Fig. 4 shows the relationship of the $y$-direction average strain of the two holes structures along their radial distance. From the analysis results can be known that the maximum average strain of the fiber circuitous hole structure is $3.013e^{-3}$, the maximum average strain of the drilling hole structure is $3.87e^{-3}$. The maximum average strain of the drilling hole structure is about 28% larger than that of the fiber circuitous hole structure under the same load. The pore structure may firstly reduce the stability of the whole structure due to the large deformation of the internal structure, the analysis results indicates that the fiber circuitous hole structure has a good resistance to deformation.
Figure 3. The strain distribution of unidirectional fiber reinforced composite board with fiber-intermitted hole (a) and the fiber-round hole (b)

Figure 4. The variation of average strain of the drilling hole and the fiber circuitous hole along the radius direction

The above analysis results show that the fiber circuitous hole structure in the tibia is beneficial to avoid the composite material strength obvious reduced due to the hole structure. At the same time, it also shows that the fiber circuitous hole structure of the tibia can effectively improve the toughness of the composite.

5. Conclusions

(1) The mineralized collagen fibers in the tibia are layered in parallel, and the thickness of the fibrous layer is non-uniform. There are many biological micropores in the cross section of the tibia, and the mineralized collagen fibers near the pores bypass the holes in an orderly manner, and forming a mineralized collagen fibers circuitous structure.

(2) Under the same load, the maximum strain of the drilling hole structure is 6.428e-3, the maximum strain of the fiber circuitous hole is 3.583e-3. The maximum strain of the drilling hole structure is about 1.8 times that of the fiber circuitous structure. The fiber circuitous hole structure has very excellent resistance to deformation.

(3) The fiber circuitous hole structure in the tibia can effectively improve the toughness of the tibia, and the structure can be applied to the composite material to effectively improve the strength of the composite material.

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