Influence of gradient structure of yak horn on its biological properties

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Abstract. According to the analysis results of yak horn structure, a horn three-dimensional horn model is established. Based on the horn model, finite element analysis is used to analyse the relationship between structural parameters of horn and the stiffness and specific stiffness. The macrostructure distribution of horn is conical, with a small tip and a large bottom along its axis, and the steepness of the yaw horn is 42. The horn models with different steepness are calculated and results show that as the steepness increases, the angle between the direction of the stiffness $K_1$ and the tangential direction of the little end approaches 15°. Moreover, all the stiffness parameters will increase when the steepness is increased. Within a certain range, the specific stiffness increases significantly with the increase of the steepness of the structure. However, when the steepness is increased to 40, the specific stiffness increase tends to be gentle, and at the steepness of 50, the specific stiffness is maximum. The results indicate that the gradient structure of horn is the result of long-term natural selection, which can provide useful guidance for the design optimization of bionic structures.

1. Introduction

The macroscopic structure of cattle horn is irregular curved cones. The shape and structure parameters are different [1], and the horns own excellent mechanical property [1-2]. Based on the study of the mechanical behavior of horn, it can enhance human understanding to their structure and function [3]. In recent years, the excellent mechanical properties of bovid horns have attracted more and more attention from the academic community.

Farke [4] studied a goat horn, the results shown that the goat's horn has good energy absorption and shock absorption. Lee et al. [5] carried out drop weight test on several biological materials and tested their impact resistance, the results show that the mechanical properties of the sheep horn are the most prominent. Uanl et al. [6] investigated the interrelationships between electrical, mechanical and hydration properties of cortical bone. Tombolato et al. [7] investigated the relationship of water ratio and mechanical behaviour, the mechanical properties will strengthen with the increasing of water content. Surakamhang et al. [8] investigated the structure and mechanical properties of water buffalo horns, and the strength and hardness of buffalo horn are gotten. Li et al. [9] investigated the effects of
humidity on the mechanical properties of the horn shell and the variation of the mechanical properties along the length of the horn by uniaxial stretching and microindentation. Yu et al. [10] used reverse engineering technology to extract the curvature curve of the horn, and designed an automobile anti-collision beam with the characteristics of horn arc, the specific energy absorption of the bionic anti-collision beam is 2.6 times higher than that of the conventional anti-collision beam.

From the research status of the horns can be known, the investigations of horn are mainly about the mechanical tests and structure analysis, but there are few investigates on the relationship between macroscopic structure and biological properties. Therefore, this work aims to study the relationship between macroscopic structure and biological property. The relationship of the macroscopic structure characteristics and its stiffness orientation or specific stiffness are investigated using finite element method. Then, according to the analysis and calculation results, the mechanism with excellent mechanical property of horn was investigated, which is benefit to design optimization of the bionic structure.

2. Materials and methods

2.1. Yak horn macrostructure

The main biological function of horn is that the cow protects itself [9]. The impact load is about 7.6 kN when the cows attack each other [11]. Thus, the horn is a biomaterial with excellent mechanical properties in nature. The property of horn is different due to their species, growth environment and age. In order to study the effects of the macroscopic gradient structure on its biological characteristic, in this paper, the research content is yak horn (Fig. 1). First, the horn is saw along its longitudinal symmetry plane. Secondly, the wall thickness distribution is analysed along its longitudinal section. Then, a horn model is established and calculated using finite element method. Finally, the analysis results are contrasted with the measured results, and based on the measurement and calculation results to investigated the relationship between macroscopic structure characteristics and excellent mechanical characteristics of horn.

2.2. Establishment of horn structure model

Two symmetrical yak horns are obtained along its longitudinal symmetry plane, as shown in Fig. 2. The horn model is established, and the structure parameters is same with the yaw horn (Fig. 3). The radius of arc dotted line is 210mm (Fig. 2), its curvature is $1/R$ and the angle $\theta$ is $0^\circ$~$75^\circ$. A local coordinate of the model is also established. Although the wall thickness is not uniform, the variation is less than that of the horn, so according to the measure result the wall thickness is 5mm. The internal cavity radius is $r_0(\theta)$ ($r_0$ is varied with $\theta$). Thus, horn model is described as arc structure with an angle of 75. And horn structure is like with the fang of spider [12], so it is write to: $r_0 (\theta)= (\theta/75)x a + a_0$, where $a_0$ is the structure of tip ($\theta=0^\circ$) and $a$ is steepness/structural gradient of horn model. When two

![Figure 1. The shape of yak horn](image-url)
cows to collide with each other, the load is mainly from frontal collision. So, the influence of \( x \) and \( y \) components are analysed (Fig. 2).

By adjusting size of the \( a \), the effects of the steepness on the stiffness of the curved conical structure is investigated. After that the measurement results and calculated results are contrasted, and to analyse the advantage of horn.

In addition to investigate the influence of specific stiffness parameters (stiffness-per-volume) of horn on steepness of arc model when it is subjected to a frontal load, which in turn affects its structural strength. By adjusting the steepness of conical structure, the models with different specific stiffness is investigated using finite element method, and measure results of horn and calculation values are contrasted.

3. Results and discussion

The bottom surface of the horn model is constrained and an external concentrated load is loaded on the tip of the model. The load will produce a strain field, and the tip of the model will move relative to its initial position. Based on the coordinate system in Fig. 2, the stiffness of yak horn is defined as three orthogonal directions, that is, \( K_1 \), \( K_2 \) and \( K_3 \). Where \( K_1 \) and \( K_2 \) are in the \( x-y \) plane, but their directions are not same with the \( x \) and \( y \) axes. The direction of \( K_3 \) is the out-of-plane direction and perpendicular to the plane. Since we mainly analyse the mechanical properties of horn under a certain direction, its loading direction is in the \( x-y \) plane. In addition, since there is no external force in \( z \)-axis direction, and the cross section of the model is assumed to be circular (central symmetry), there is no displacement in the \( z \) direction. From \( F = KU \), it can be known that \( K_3 = 0 \). The mechanical properties of the horn are analysed by the following two approaches: finite element method and beam theory, and the shear stress is neglected.

The calculation process of stiffness parameters \( K_1 \) and \( K_2 \): Firstly, 14 simulated horn models with steepness of 0~78 are established (Fig. 3) and analysed in Abaqus, and in analysis process the material parameters of Young modulus and passion ratio are 1000MPa and 0.3, respectively. Two groups of nonlinear loads are applied in the \( x-y \) plane, then two groups of forces and displacements are obtained, \((F_{x1}, u_{x1}), (F_{y1}, u_{y1})\) and \((F_{x2}, u_{x2}), (F_{y2}, u_{y2})\). The relationship between force and displacement in different directions is:

\[
\begin{pmatrix}
F_x \\
F_y \\
F_z
\end{pmatrix} =
\begin{pmatrix}
K_{xx} & K_{xy} & K_{xz} \\
K_{yx} & K_{yy} & K_{yz} \\
K_{zx} & K_{zy} & K_{zz}
\end{pmatrix}
\begin{pmatrix}
u_x \\
u_y \\
u_z
\end{pmatrix}
\tag{1}
\]

From \( F_z = 0 \), it can be known that \( K_{xz} = K_{yz} = 0 \), and the stiffness matrix can be obtained by Eq. 1. Then, the eigenvectors and the eigenvalues of the stiffness matrix are calculated, and two eigenvalues are \( K_1 \) and \( K_2 \) respectively. The two eigenvectors represent the direction of \( K_1 \) and \( K_2 \) in the \( x-y \) coordinate system, respectively.
The stiffness \((K_1 \text{ and } K_2)\) directions obtained in the models with different steepness are shown in Fig. 4(a), where \(\phi\) is the angle between the stiffness parameter \(K_1\) and the tip tangential direction (x-axis). When \(a=0\), the analytical model is a thin tube with equal diameter; when \(a=60\), it means that the bottom section diameter is larger than the tip and the wall thickness is equal. From the analysis results can be seen (Fig. 4(a)), when the steepness of the model increases, the angle between the direction of \(K_1\) and the tangential direction of the tip approaches 15°. Since the basic line of the model is a 75° arc, as the steepness increases, the direction of \(K_1\) approaches parallel to the bottom section of the model. Since the direction of \(K_2\) is perpendicular to the \(K_1\), \(K_2\) approaches perpendicular to the bottom cross section of the model.

Fig. 4(b) shows the relationship between \(K_1\) and \(K_2\) with steepness \(a\). From the analysis results can be known that as the increasing of gradient of horn models the stiffness also increased, and the increase amplitude of \(K_1\) is obviously larger than that of \(K_2\) \((K_1>>K_2)\).

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**Figure 4.** Calculation results of stiffness. (a) The stiffness \((K_1 \text{ and } K_2)\) directions in the models with different steepness, (b) the relationship between \(K_1\) and \(K_2\) with steepness \(a\)

From the analysis results of the models with different steepness \(a\) can be seen, the larger the steepness \(a\), the larger the model volume, and the stiffness becomes larger. Excessive steepness can bring better mechanical properties to the structure, but it also brings disadvantages such as material waste and unreasonable structural design. Thus, the specific stiffnesses are mainly investigated: \(K_{b1}, K_{b2}, K_{b3} (K_{bi} = K_i / V)\), where \(V\) represents the volume of the model). From \(K_3=0\), it can be known that \(K_{b3}=0\).

The relationship between specific stiffness and steepness is shown in Fig. 5. From the analysis results in Fig. 5 can be seen that when the steepness is within a certain range, the specific stiffness increases significantly with the increase of the structural steepness \(a\). However, when the steepness \(a\) is increased to 40, the specific stiffness increase tends to be gentle, and at the steepness of 50, the specific stiffness is maximum.

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**Figure 5.** The relationship between specific stiffness and steepness
Comparing the above analysis results with the measurement results of the horn, we can know that the measurement result ($a=42$) of the yak horn is close to the theoretical analysis result of the optimal steepness of 50. The actual structure and analytical model of the yak horn differs at the tip, the actual tip is a solid structure, and the tip of the model is a tubular structure, so the measurement results are different from the calculated results. The macroscopic structural features of horn have excellent specific stiffness and are the result of long-term natural evolution. The above analysis results are benefit for the design optimization of bionic structure.

4. Conclusions
According to the measurement to the macroscopic structure parameters of horn, a yak horn analysis model is established and analysed when the model applied different external load. Furthermore, the load is applied to the tip to analyse the relationship of stiffness, specific stiffness and macroscopic structure parameters of horn. Through measurement analysis and calculation, the following conclusions can be obtained:

(1) The cross-sectional area gradually increases from the tip to the bottom of yak horn, and from the measurement result can be known that its steepness is approximate 42;

(2) Through the finite element analysis and calculation of 14 models with steepness from 0 to 78, the relationship between steepness of horn and stiffness is obtained. The stiffness of the model is increased monotonically, as the increasing of steepness, and the angle between the direction of the stiffness $K_1$ and the tangential direction of the tip of the model approaches 15°;

(3) When the steepness is within a certain range, the specific stiffness increases significantly with the increase of the structural steepness $a$. However, when the steepness is increased to 40, the specific stiffness increase tends to be gentle, and at the steepness of 50, the specific stiffness is maximum.

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