Measurement of mechanical properties of carp scales based on digital image correlation method

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Abstract. As a kind of high quality natural material, the structure and mechanical properties of fish scale have been widely concerned. At present, there are few researches on fish scales in China, and most of them focus on the composition and nutritional value of fish scales, while there are few researches on their mechanical properties and microstructure. In this paper, based on the digital image correlation method and a set of self-built strain measurement system, the tensile strain of fish scale specimens was measured, and the fish scale specimens after surface speckle treatment were tensile tested and data were collected. The mechanical properties of fish scales in the uniaxial drawing process were studied and analyzed, and the microscopic images showed that the tensile strength of fish scales was related to the number of collagen fiber layers in their inner layers.

1. Introduction
Digital image correlation method is a full-field non-contact measurement method [1]. Through image processing, information such as surface displacement and stress change of the measured object can be obtained. Due to its advantages of low environmental requirements and high measurement accuracy [2], it is widely used in various fields. On the study of fish scales, in 1992, Raschi W et al. conducted a study on shark scales in the study of hydrodynamics [3]. In 2003, Ikoma et al. studied the microstructure, mechanical properties and biomimetic properties of red snapper scales [4]. In 2006, gao juqiong et al. observed the microstructure of carp scale section using microscope and 3d laser scanning, and measured the mechanical properties of the scale section, and found that the carp scale section was a composite lamellar structure [5]. In 2013, Zimmermann Elizabeth A et al. used small-angle X-ray to study the role of the scale structure of giant arapaeus in resisting predation and bite of piranha [6]. In 2014, Wen Yang et al. used small-angle X-ray to study the mechanical properties of arapaima gigas scales, and found that the minerals and collagen fibers of the scales had a significant effect on improving the toughness and tear resistance [7]. In 2015, a. Khayer Dastjerdi et al. studied the ability and principle of improving the scale toughness of collagen fiber [8]. In 2016, Sandra Murcia, Guihua Li et al. performed uniaxial stretching and tearing tests on scale specimens to assess the mechanical behavior of carp scales after exposure to polar solvents [9]. It can be seen that fish biomaterials have been developed to a certain extent and have a good prospect of research and application.

In this paper, the deformation characteristics of carp scales in the uniaxial drawing process were observed, and the changes in the force during the drawing process were measured. The measured experimental results were analyzed in combination with the microstructure of fish scales.

2. Measuring device and experiment

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2.1 Construction of strain measurement system

Tensile test is one of the basic methods for testing the mechanical properties of materials. It is usually carried out in a vertical electronic tensile testing machine. In this experiment, the measuring device used is composed of Hvc-wwx micro-controlled horizontal electronic tension machine and Q-400 image acquisition system.

The measuring device adjusts the CCD lens perpendicular to the tensile surface so that it can film the entire tensile process of the specimen. When the horizontal tension machine is used for tensile measurement, the image acquisition system is synchronized until the specimen is pulled apart.

2.2 Basic principles of DIC

The basic principle of DIC is to use a camera to collect the speckle pattern before and after deformation, and calculate the displacement field and strain field of the object by measuring the displacement change of the surface pixel before and after loading the speckle pattern. Usually, the image collected before deformation is called the reference image, and the image after deformation is called the target image. In the reference image, take the point \( P(x_0, y_0) \) to be measured as the center, select reference sub-area of size \((2M + 1) \times (2M + 1)\), \( f(x_0, y_0) \) is the gray value of the point, Through the correlation search, the target sub-area with the best correlation with the reference sub-area is matched in the target image. The target sub-area is centered on \( P'(x'_0, y'_0) \) and the size is \((2M + 1) \times (2M + 1)\). This method can be used repeatedly to calculate the full-field displacement of the image.
2.3 experimental materials and process
The raw material is carp from the market, the mass is 3-4kg, the length is 45-60cm, and the skin remains intact, without obvious damage or tear. A sufficient number of scales with complete shape were obtained from the head, abdomen and tail respectively.

![Complete the carp and Fish scale specimen](image)

Figure 4 Experimental materials and fish scale specimen

First, one end of the specimen is clamped in the fixed chuck, then the moving chuck is moved to a suitable position, and the other end of the specimen is clamped to perform the tensile test. During the measurement, the camera was calibrated in advance, and then the tension machine and Q-400 system were started synchronously. A small amount of load was preloaded on the fish scale specimen, and the whole deformation process was filmed, until the specimen was stopped after breaking and the recording program was stopped.

3. Experimental data and analysis

3.1 results of fish scale stretching experiment
The comparison of tensile stress-strain curves of each part of fish scale is as follows:

![Comparison of stress-strain curves of fish scales in different parts](image)

Figure 5 Comparison of stress-strain curves of fish scales in different parts
The representative stress-strain curves of uniaxial tension from different parts of the fish scale specimen on the back are shown in Figure 5 and the curves of experimental results in other parts are similar to those in the figure. As can be seen from the figure, all curves exhibit a relatively linear behavior at the beginning, and the slope in the middle part of the curve gradually decreases with the increase of the stress corresponding to the stretching of the material. After reaching a peak, the stress curve decreases in a cliff-like manner. At this point, the specimen has broken through the maximum stress and structural fracture occurs, and the tensile process is over. As can be seen from figure 5 the scales on the head of carp have the highest strength and tearing strain among the scales on the back. The central scale was the first to tear, and both strength and strain were minimal. The elastic modulus of three parts was obtained by tangent method, among which the elastic modulus of E\text{head} and the elastic modulus of E\text{tail} in the middle was E\text{middle}. The tensile strength of head scales was significantly higher than that of middle and tail scales. Among abdominal scales, head scales were the highest in both modulus of elasticity and strength, followed by middle scales, and tail scales were the lowest. The tearing strain of the middle and tail scales is close to that of the head scales.

The stress-strain curves of abdominal scales and back scales are shown in figure 6:

![Figure 6](image)

**Figure 6** Comparison of stress-strain curves of fish scales at dorsal and abdominal position

As can be seen from figure 6, in both the head and the middle scales, the strength of the dorsal scales is greater than that of the abdomen, and the abdominal scales reach the tearing limit before the dorsal scales. In the tail fish scale, the back fish scale first tore, the strength of the belly fish scale is greater than the back. The slope of the linear part of the front part of the curve is calculated by the tangent line method, and the elastic modulus is obtained. Table 1. shows the average mechanical properties of scales in different parts of carp and scales in different parts of abdomen:

|                      | The back of the scales | Abdominal scales |
|----------------------|------------------------|------------------|
|                      | The head | Middle part | The tail | The head | Middle part | The tail |
| $E_{\text{head}}$ (MPa) | 596.645  | 414.57    | 380.05   | 373.057  | 358.786    | 261.47   |
| $S$(MPa)              | 26.455   | 21.767    | 18.85    | 26.957   | 20.555     | 19.378   |
| $\varepsilon_f$ (m/m) | 0.072    | 0.058     | 0.060    | 0.059    | 0.056      | 0.054    |
| MOT(MPa)              | 0.933    | 0.647     | 0.569    | 0.781    | 0.587      | 0.523    |

It can be seen from table 1 that the over all difference in the mechanical properties of each part of the fish scales. Among the fish scales on the back, the scales on the head have the largest elastic modulus and strength. The modulus and strength of elasticity decrease from the head to the middle and the tail. Similar to the dorsal scales, the maximum modulus and strength of the abdominal scales were obtained from the head scales, followed by the middle and the lowest modulus of the tail scales, which were slightly lower than the middle in terms of strength. The tear limit of the back was significantly higher than that of other parts, and the average tear limit of the middle and tail was close to each other. Toughness modulus, head greater than the middle greater than the tail.
3.2 analysis of microscopic image results

The scales of carp were observed by electron microscope, and the factors that might influence the mechanical properties were analyzed. Carp scales are bilayer structure, mainly composed of calcified mineral outer layer and fibrous collagen inner layer. The outer surface of the scales, that is, the surface of contact with water, presents a braided rough texture, while the inner surface of contact with the fish skin is relatively smooth. In the enlarged view, a series of parallel ridges appear on the outer surface, covering almost all of the outer surface, as shown in figure 7(a):

![Figure 7: External surface and interface microstructure of fish scales](image)

The cross section of the scales clearly shows the two characteristic layers of fish scales, namely the calcified outer layer and the inner layer composed of multi-layered collagen fibers. As can be seen from figure 7, each collagen fiber layer is separated from each other and arranged in parallel with each other.

As shown in the overall experimental results in table 1, the scales obtained from the head, middle and tail showed significant differences in different mechanical properties. The elastic modulus, strength and toughness modulus of the tail were the lowest, while the mechanical characteristics of the head and middle were higher. Figure 8 shows the microscopic cross sections of fish scales in different parts:

![Figure 8: Microscopic image of fish scale cross section](image)

In figure 8, (a) is the section of fish scales at the head, (b) is the middle, and (c) is the tail. The scale is shown in the lower right corner. As can be seen from the cross sections of three different parts, the upper (outer) layer of fish scales composed of hydroxyapatite and calcium carbonate is seriously mineralized, while the inner layer is mainly composed of collagen fiber layer, which is slightly mineralized. The microscopic results showed that the mineralized outer thickness of the fish scale specimen was all less than 100um, and there was no significant difference between the three regions of head, middle and tail. However, the mineralization degree of the inner layer decreased gradually from the outside of the fish scale to the inside of the fish scale, without quantifying the specific mineralization degree of the fish scale. The difference in mechanical properties of the scales studied in this paper can be attributed to the low mineralized number of layers of inner collagen fibers of fish scales, or the mineral-collagen fiber ratio of inner collagen fiber layers.

At higher magnification, the separated collagen fibers can be clearly observed:
As can be seen from figure 9, each collagen fiber layer is composed of strips of collagen bundles. The thicker strands of the main collagen fibers are separated from each other and are interwoven with scattered free filaments. As mentioned above, all specimens were axially stretched by a tension machine until they broke, and the fracture process was observed by an optical microscope. The fracture mechanism observed is mainly the fracture of the outer mineralized layer and the separation of the inner collagen fiber layer from each other. The layers of collagen fibers perpendicular to the transverse loading axis are first separated from each other, then stretched along the loading axis and finally broken. This fracture mechanism is similar to the failure mechanism of fiber-reinforced plastics in engineering.

4. Results and discussion

On the scales; Uniaxial tensile data of statistics and comparison, the scales of elastic modulus of central from head to tail, in turn, reduced, strength and other mechanical properties of the head and the middle is superior to the tail, to the fish guts has certain protective effect, microscopic image display scales lining of collagen fiber layer and the elastic modulus difference.

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