Bio-structure on the rachis outer surface of a bird feather

Y P Zhao¹,², J J Ji¹,² and J S Zhao¹
¹Department of Mechanical Engineering, Tsinghua University, Beijing 100084, P. R. China
E-mail: zhaoyp16@mails.tsinghua.edu.cn/jingshanzhao@mail.tsinghua.edu.cn

Abstract. From the perspective of biomechanics, this paper studies the outer surface of the rachis. The bio-structure was determined by microscopy. Finite element analysis was conducted on this bio-structure. The results show that, in the feather, the bio-structure of the outer surface of the rachis consists of the basic unit structure of the hexagonal shape of the edge protrusion and a small number of pentagons. The results of the finite element analysis for the basic geometry structure and flange were the edges of which the main bearing stress sites. The practical reference value was for the determination one of safety-structures.

1. Introduction
In the process of studying dinosaur fossils, palaeontologists discovered feather fossils attached to the body of dinosaurs [1-10]. The relationship between dinosaurs and birds has been uncovered. Biologists have identified the structural composition and composition of feathers using a range of biological methods [11-18]. The biological structure of feathers has been revealed elsewhere and Yingjie Guo, leading a research group at Jilin University, obtained the Young’s modulus of feather fibre material and the effect of melanin on feather wear resistance through experiments [19]. Palaeontologists represented by Xing Xu sought and provided the morphological evolutionary features of dinosaurs and their feather fossils. A feather growth model was thus elucidated [20-21]. Quanlu Ren [22] and others at Jilin University posited a theory of biological biomimetic non-smooth wear resistance [23]. There are bubbles inside the feather rachis able to form structures of biomimetic materials [24] and microstructural theory developed thereafter [25].

Here, from the perspective of biomechanics, the microstructures of the rachis was studied. For its structure, mechanical finite element simulation analysis was carried out. Therefore, the following conclusions were obtained: there are a large number of uneven hexagonal structures and a small number of pentagonal structures on the surface of the rachis. These flanges protect the bottom surface of the rachis and this explains the natural phenomenon whereby bird feathers.

2. Materials and methods
2.1. Microscope of the outer surface of the rachis.
The rachis portion of the feather was sampled, it was mounted on the sample platform of the digital microscope (VHX-6000 model, magnification 20-2000 times) for examination of the outer surface of the rachis. First, the pigeon feather was dipped in 75% alcohol, and dried naturally: to facilitate the observation of the surface of the rachis, a blade was used to remove the feathers on the left and right sides, taking care not to scratch the surface of the rachis while cleaning. The outer surface of the rachis, was showed by a pigeon feather (Figure 1a), a section of length 10 mm was taken 80 mm from the root of the feather (in the middle of the feather rachis, as shown in Figure 1b), and observed under a digital microscope (‘KEYENCE’ brand, VHX-6000 model, magnification 20-2000 times), as seen in Figure 1c(magnification:20x) and Figure 1d(magnification:500×). The surface of the rachis presents a pentagon or hexagonal distribution with unevenness and unequal sides. It was observed from the resulting micrograph that the outer surface of the feather rachis had pentagonal and the basic geometry structures and flanges.
2.2. Microscope of the outer surface of the barbs.
The rachis middle portion of the feather was sampled and fixed to the sample. Observed the outer surface of the barbs under the digital microscope.

![Image](image1)

**Figure 1.** Feather and the outer of feather shaft (a) A pigeon feather (b) The feather rachis (c) A section of length 10 mm taken 80 mm from the root of the feather (d) The outer surface of the feather rachis has a bio-structure.

3. Results and discussion
Using the microscope analysis system, a graphic photograph of the surface of the feather rachis was prepared to allow detection of the height difference between paired points on the outer surface of the feather rachis (Figure 2). Measured heights between two points are 0.03 $\text{um}$-12.74 $\text{um}$. These data also indicated the existence of this structure: the inner concave and a convex portion at the edge portion were present on the outer surface of the feather rachis.

![Image](image2)

**Figure 2.** Measured heights between two points on the feather shaft (500x): series of samples numbered [1] to [40].

![Image](image3)

**Figure 3.** 3-d mesh plot of the outer surface of the rachis (a) top view (b) stereo 3-d mesh plot (these flanges were indicated by the yellow area in the figure, and the basic geometry structures on the bottom surface were indicated by the green area).

Using MATLAB™ software, the outer surface of the rachis and its 3-d inner structure could be obtained (50-250 pixel resolution, Figure 3(a, b)). A few pentagons and the majority of the hexagonal structures could be found [26, Figure 4(a-h)], as well as the basic geometry structure and flange were present on the outer surface of the feather rachis. The stress model of the feather rachis was based on
this structure. The area enclosed by the yellow line. The mapping results show that the lengths of the sides constituting the pentagon or the hexagon are not equal. The distribution of such unequal pentagons or hexagons is due to the uneven absorption of nutrients in the growing protein, or the uneven surface of the outer surface of the rachis having been subject to uneven stress over its life, resulting in distortion of the surface of the rachis. To simplify the research problem, we ignored such distortion. The aim was to compare the stress effects of these structures, so the ideal three-dimensional model structure was an equilateral the basic geometry structure.

![Figure 4. A few pentagons and the majority of the hexagonal structures in feathers. (Quoted from O. F. Chernova, Doklady Biol. Sci. 405, (2005) 437 – 442)[26].](image)

Results of measured heights between two points on the feather rachis were:

0.23, 2.50, 0.70, 2.19, 0.03, 3.46, 3.66, 1.86, 4.18, 2.01, 10.86, 5.99, 4.06, 5.92, 11.13, 10.79, 2.20, 3.66, 1.11, 3.66, 0.83, 0.87, 12.74, 6.65, 1.14, 5.45, 10.28, 8.19, 7.38, 7.60, 6.55, 9.93, 9.53, 3.97, 4.85, 7.82, 4.43, 8.58, 3.18, 8.12

Sample mean \( \bar{x} = 5.21 \)

The deviations of each measurement were: -4.98, -2.71, -4.51, -3.02, -5.18, -1.75, -1.55, -3.35, -1.03, -3.2, 5.65, 0.78, -1.15, 0.71, 5.92, 5.58, -3.01, -1.55, -4.1, -1.55, -4.38, -4.34, 7.53, 1.44, -4.07, 0.24, 5.07, 2.98, 2.17, 2.39, 1.34, 4.72, 4.32, -1.24, -0.36, 2.61, -0.78, 3.37, -2.03, 2.91

Mean deviation \( \overline{d} = \frac{(4.98 + 2.71 + \ldots + 2.91)}{40} = \frac{113.92}{40} = 2.85\% \)

Relative mean deviation \( \frac{2.85}{5.21} \times 100\% = 54.70\% \)

Standard deviation \( S = 2.85\% \)

The relative standard deviation

The data are processed using MATLAB\textsuperscript{TM} software as follows:

```
1 x0=1:1:40
2 y0=[0.23,2.50,0.70,2.19,0.03,3.46,3.66,1.86,4.18,2.01,10.86,5.99,4.06,5.92,11.13,10.79,2.20,3.66,1.11,3.66,0.83,0.87,12.74,6.65,1.14,5.45,10.28,8.19,7.38,7.60,6.55,9.93,9.53,3.97,4.85,7.82,4.43,8.58,3.18,8.12];
3 n=1:2:3;
4 x=1:1:40;P=polyfit(x,y0,n)
5 y=polyval(P,x);plot(x,y,x0,y0);xlabel('x')
```
Enter the program to get corresponding coefficients P1, P2, P3 and analysis charts (Figure 5 (a, b, c)):

Here, P1, P2, P3 parameters mean that:

When order n=1, the corresponding fitting polynomial was

\[ P_1 = p_0 + p_1 x = 0.1310 + 2.5225x; \]

When order n=2, the corresponding fitting polynomial was

\[ P_2 = p_0 + p_1 x + p_2 x^2 = -0.0060 + 0.3777x + 0.7953x^2; \]

When order n=3, the corresponding fitting polynomial was

\[ P_3 = p_0 + p_1 x + p_2 x^2 + p_3 x^3 = 0.0002 - 0.0170x + 0.5593x^2 + 0.1370x^3. \]

Figure 5. Measured heights between two points on the feather rachis analysis chart (a) Measured heights between two points on the feather rachis analysis chart (n = 1) (b) Measured heights between two points on the feather rachis analysis chart (n = 2) (c) Measured heights between two points on the feather rachis analysis chart (n = 3).
Quadrilateral

Von Mises stress (nodal values)

| N_m2       |
|------------|
| 3.74e+005  |
| 3.43e+005  |
| 3.12e+005  |
| 2.81e+005  |
| 2.51e+005  |
| 2.22e+005  |
| 1.89e+005  |
| 1.58e+005  |
| 1.28e+005  |
| 9.68e-004  |
| 6.64e-004  |

On Boundary

Quadrilateral

Pentagon

Von Mises stress (nodal values)

| N_m2       |
|------------|
| 4.51e+005  |
| 4.1e+005   |
| 3.89e+005  |
| 3.28e+005  |
| 2.87e+005  |
| 2.66e+005  |
| 2.05e+005  |
| 1.64e+005  |
| 1.23e+005  |
| 8.36e-004  |
| 4.06e-004  |

On Boundary

Hexagon

Von Mises stress (nodal values)

| N_m2       |
|------------|
| 3.49e+005  |
| 3.14e+005  |
| 2.83e+005  |
| 2.53e+005  |
| 2.22e+005  |
| 1.91e+005  |
| 1.6e+005   |
| 1.29e+005  |
| 9.85e-004  |
| 6.77e-004  |
| 3.69e-004  |

On Boundary

Heptagon

Von Mises stress (nodal values)

| N_m2       |
|------------|
| 3.48e+005  |
| 3.17e+005  |
| 2.85e+005  |
| 2.54e+005  |
| 2.23e+005  |
| 1.91e+005  |
| 1.6e+005   |
| 1.28e+005  |
| 9.71e-004  |
| 6.58e-004  |
| 3.64e-004  |

On Boundary

Octagon

Von Mises stress (nodal values)

| N_m2       |
|------------|
| 2.85e+005  |
| 2.61e+005  |
| 2.37e+005  |
| 2.12e+005  |
| 1.88e+005  |
| 1.64e+005  |
| 1.38e+005  |
| 1.15e+005  |
| 9.07e-004  |
| 6.64e-004  |
| 4.23e-004  |

On Boundary

Heptagon

Von Mises stress (nodal values)

| N_m2       |
|------------|
| 2.26e+005  |
| 2.52e+005  |
| 2.28e+005  |
| 2.06e+005  |
| 1.79e+005  |
| 1.53e+005  |
| 1.31e+005  |
| 1.07e+005  |
| 8.3e+004   |
| 5.89e-004  |
| 3.48e-004  |

On Boundary

Decagon

Von Mises stress (nodal values)

| N_m2       |
|------------|
| 2.06e+005  |
| 2.43e+005  |
| 2.19e+005  |
| 1.96e+005  |
| 1.72e+005  |
| 1.49e+005  |
| 1.26e+005  |
| 1.02e+005  |
| 7.89e-004  |
| 5.55e-004  |
| 3.21e-004  |

On Boundary

Nine-shaped

Von Mises stress (nodal values)

| N_m2       |
|------------|
| 5.35e+005  |
| 4.89e+005  |
| 4.43e+005  |
| 3.98e+005  |
| 3.52e+005  |
| 3.06e+005  |
| 2.6e+005   |
| 2.15e+005  |
| 1.69e+005  |
| 1.23e+005  |
| 7.73e-004  |

On Boundary
Figure 6. Finite element analysis of structure on the basic geometry structure and flange.

The test results showed that the height difference between the two points on the outer surface of the feather rachis was between 0.03 to 12.74 µm. From the analysis charts (above), the height between the two points on the outer surface of the feather rachis could be seen. The difference curves (red mark) and the fitting curves (n = 1, in blue; n = 2, in pink; n = 3, in green) were not horizontal, which indicated that the outer surface of the feather rachis contains concave and convex features. The test results show that the outer surface of the feather rachis contains the basic geometry structure and flange.

The finite element analysis results were: 18-sided \( \sigma_{\text{min}} = 2.82 \times 10^4 \text{ N/m}^2 \) < Triangle \( \sigma_{\text{min}} = 7.75 \times 10^2 \text{ N/m}^2 \); 16-sided \( \sigma_{\text{max}} = 2.27 \times 10^5 \text{ N/m}^2 \) < Triangle \( \sigma_{\text{max}} = 5.35 \times 10^5 \text{ N/m}^2 \). The colour legend in the finite element analysis graph represented the magnitude of the stress in different locations. Here, the (Figure 6). From the results of the finite element further obtained, by running the CATIA V5 finite element simulation analysis software, it can be seen that the maximum and the minimum stresses on the basic geometry structure and flange (see right bar legend) maximum stresses and the minimum stresses were equations [27]:

\[
\sigma_{\text{max}} = \frac{M_{\text{max}}}{I} \quad \text{and} \quad \sigma_{\text{min}} = \frac{M_{\text{min}}}{I}
\]

Among the basic geometry structure and flange, the stress concentrated in the region of the flange was the largest, but the stress of the basic geometry structure in the bottom plane was the smallest. Therefore, under the action of external force and airflow, they were practically unaffected, and the amount of deformation of the basic geometry structures in the bottom surfaces were the smallest. The flange area protected the bottom plane of the outer surface of the rachis, for the measurement and analysis method of the height difference value between the two at different positions. Moreover, such a similar structures existed on the outer surface of the feather barbs.

Results of the finite element analysis in the maximum-minimum stresses on the basic geometry structure and flange were as shown in Figure 6 value shown in bar legend. In terms of structured materials, to increase the wear resistance and impact resistance of the material surface such as hexagons of the basic geometry structure and flanges, a three-layer structure as shown in Figure 7(a, b, c, d, e) could be designed. The total thickness was \( a+t+b \), the intermediate material was a substrate of thickness \( t \), and the surface layer had thicknesses \( a \) and \( b \) respectively on the left and right-hand sides of the substrate. The model simulated the bionic feather rachis outer surface structures with the basic geometry structures and flanges, the role of this structures were to "sacrifice the edges and protect the real surface", and the edges increased the surfaces wore resistance and impacted resistance thereof.
Therefore, the surfaces were designed as the basic geometry structures and flanges, thus matching the resistance and the outer surface profile of the deck to increase surfaces resistance to high pressure.

4. Conclusion
The bio-structure of the outer surface of the rachis is composed of the basic geometry structure and flange. The results of finite element analysis showed that the basic geometry structure and flange, under the same load. The flanges are the main bearing stress sites. Meantime, the basic geometry structure of the outer surface of the rachis, a region with the smallest stress load was formed. With such a structure, under high load, first, the edge of the protrusion was broken, however, the real surface structure was unaffected which helped to protect the outer surface of the rachis and improved the load bearing capacity thereof. The results have practical reference value for the determination of the safety of such structures.

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Disclosure interests
The authors declare no conflict of interests to disclosure.

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