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Seagull feather shaft: Correlation between structure and mechanical response

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ABSTRACT

Flight feathers are unique among a variety of keratinous appendages in that they are lightweight, stiff and strong. They are designed to withstand aerodynamic forces, but their morphology and structure have been oversimplified and thus understudied historically. Here we present an investigation of the shaft from seagull primary feathers, elucidate the hierarchical fibrous and porous structure along the shaft length, and correlate the tensile and nanomechanical properties to the fiber orientation. An analysis of the compressive behavior of the rachis based on a square-section model shows a good fit with experimental results, and demonstrates the synergy between the cortex and medulla. Flexural properties of the shaft along the shaft length, analyzed as a sandwich composite, reveal that although all flexural parameters decrease towards the distal shaft, the specific equivalent flexural modulus and strength increase by factors of 2 and 3, respectively. The failure mode in flexure for all specimens is buckling on the compressive surface, whereas the foamy medulla prevents destructive axial cracking and introduces important toughening mechanisms: crack deflection, fiber bridging, and microcracking.

Statement of Significance

Using mechanics principles, we analyze the feather shaft as a composite beam and demonstrate that the flexural strength is extraordinary, considering its weight and tailored along the length. The cross section changes from circular in the proximal base to square/rectangular in the distal end. We also discovered that the composite design, a solid shell enclosing a foam core, produces synergistic strengthening and toughening to the feather at a minimum of weight.

1. Introduction

Among a plethora of biological materials that may serve as a source of bioinspiration, feathers stand out with extraordinary mechanical properties that have evolved for flight: lightweight, stiff and strong, yet able to flex, which are coincidently the goals of many modern structural materials. Flight feathers primarily bend during flight, and have to sustain aerodynamic forces within allowable flexural/torsional strains. The central feather shaft provides major mechanical support, and consists of calamus (below the skin) and rachis (above the skin), shown in Fig. 1. It is composed of a solid keratinous shell, called cortex, enclosing a foamy core named medulla; the cortex contains the dorsal, lateral and ventral regions (specified in Fig. 1a).

The feather shaft exemplifies a naturally designed composite beam facilitating flight; it is of paramount importance to unravel the functionalities by correlating the structure with mechanical properties. It is entirely composed of β-keratin proteins [1–5], which generally show higher stiffness and strength than α-keratin based materials [6]. The shell (cortex) shows an ultra-fine filament-matrix structure at the nanoscale, ~3.5 nm β-keratin filaments [7] formed from β-pleated sheets. It displays a fibrous structure at microscale: axial fibers covered by thin superficial circumferential fibers [8–10] and crossed-fibers observed through selective degradation [11].

There have been plenty of studies [8,12–14] on the tensile response of cortex; however, the specific sampling locations usually were not specified. The broad range of reported Young's moduli of feather keratin from different species has been attributed to the experimental procedures [12]. However, it should be kept in mind that the anisotropy of feather cortex along the whole shaft

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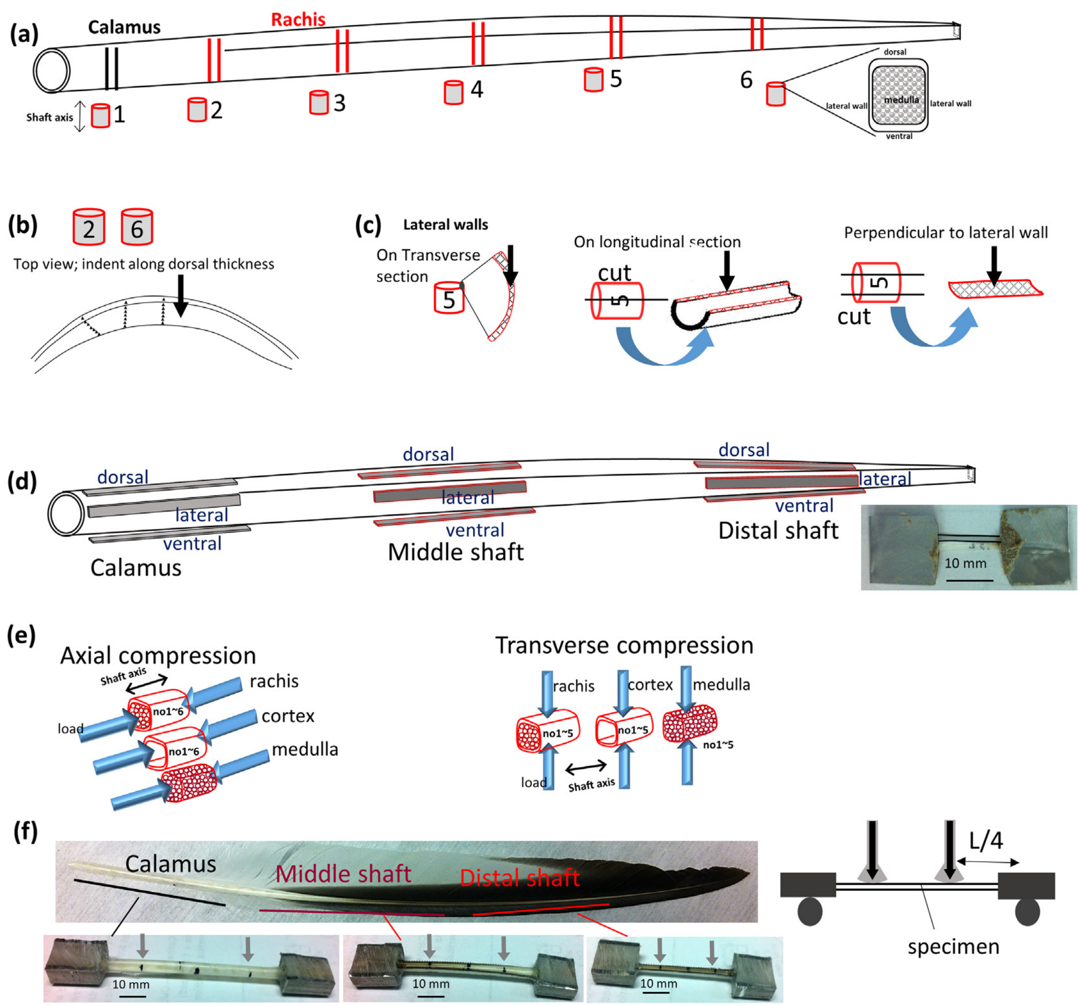

Fig. 1. (a) Specimens for structural observation: the feather shaft consists of calamus (proximal) and rachis, and is cut into cylindrical sections with numbers 1–6 representing positions along the shaft axis from the calamus to the distal end. Dorsal, lateral and ventral regions of cortex on transverse cross section are shown. Nanoindentation (b) on the dorsal region along cortex thickness at positions 2 and 6, and (c) in three loading orientations including on transverse section, longitudinal section and perpendicular to lateral wall at position 5. (d) Tensile tests on thin strips at dorsal, lateral and ventral regions at calamus, middle shaft and distal shaft, with a photo of specimen ready for test. (e) Axial and transverse compression specimens, both include rachis, cortex and medulla. (f) Four-point flexure along the shaft length including calamus, middle shaft and distal shaft; the two ends of each specimen were embedded in epoxy and square tubes, and the loading points are indicated by arrows.

length and among cortical regions at a given location also contribute to the discrepancy.

Widely present in nature, sandwich structures save weight and increase the buckling resistance during compression. Theoretical analyses on foam-filled cylindrical shells have been developed [15–18]. The feather rachis is distinguished from other biological shell-over-foam materials in that it possesses a square cross section. However, studies on the compressive behavior of the feather shaft have been very rare, and only on flightless feathers via simple cylinder models [13,19]. No attempts have been made to incorporate the square cross section into a quantitative analysis of the buckling of feather rachis, which, nevertheless, presents the real scenario for most flight feather rachises. Additionally, our understanding of the function of the foam core (medulla) is quite limited due to the few and somewhat controversial reported studies: medulla removal has no significant effect on buckling stress or tensile strength [1]; medulla removal leads to 16% more flexural deflection [2]; in vivo strain measurement in pigeons suggests buckling to be the most important mode of failure [3]; the peacock's tail feather rachis splits before buckling [4]. A comprehensive and rigorous examination of the compressive behavior of flight feather rachis is therefore needed.

The feather shaft bends both naturally (all feathers) and under aerodynamic forces (flight feathers). A few reports describe the response of the feather rachis in cantilever beam bending [13,20–23], three-point bending [24] and four-point bending [25] at very small deformation (elastic region) and neglect the cellular medulla. Although the medulla does play a role in the feather performance [20,24], its effect and function in bending behavior have not been investigated considering the rachis as a composite.

In an aim to address the above issues, this work provides a thorough and rigorous study of the biomechanics of the seagull feather shaft with quantitative analysis, correlating to the features involving the composite design and the hierarchical structure. Our findings and analysis are intended at stimulating the design of novel synthetic structures that can reproduce the remarkable properties of the feather shaft.

2. Materials and experimental procedures

2.1. Materials

Primary flight feathers from two juvenile California gulls (*Larus californicus*) were collected, after the natural death of the birds,