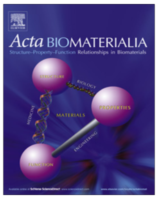
Acta Biomaterialia 9 (2013) 9065–9074

Contents lists available at ScienceDirect

Acta Biomaterialia

journal homepage: www.elsevier.com/locate/actabiomat



Separating the influence of the cortex and foam on the mechanical properties of porcupine quills

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ARTICLE INFO

Article history:
Received 19 March 2013
Received in revised form 27 June 2013
Accepted 1 July 2013
Available online 17 July 2013

Keywords:
Porcupine quills
Buckling
Foam
Cortex
Energy absorption

ABSTRACT

Lightweight thin cylinders filled with a foam have applications as collapsible energy absorbers for crashworthy and flotation applications. The local buckling compressive strength and Young's modulus are dependent on material and geometrical properties. Porcupine quills have a thin cortex filled with closed-cell foam, and are entirely composed of α-keratin. The cortex carries the majority of the compressive load, but the foam is able to accommodate and release some of the deformation of the cortex during buckling. The presence of the foam increases the critical buckling strength, buckling strain and elastic strain energy absorption over that of the cortex. Good agreement is found between experimental results and modeled predictions. A strain distribution map of the foam close to the buckled cortex demonstrates that the deformation of the cells plays an important role in accommodating local buckling of the cortex. The robust connection between the foam and cortex results in superior crushing properties compared to synthetic sandwich structure where the foam normally separates from the shell. The foam/cortex construction of the quill can guide future biomimetic fabrications of light weight buckle-resistant columns.

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1. Introduction

Thin-walled tubes filled with foam have been studied recently for their energy-absorption characteristics and for applications as lightweight structural members [1–3]. Friction, fracture, plastic bending and crushing have been identified as major energy-absorption mechanisms [1]. Configurations such as square, octagonal and circular tubes have been shown to be efficient collapsible energy absorbers [1].

Alexander [4] and Pugsley and Macaulay [5] were the first to examine plastic crushing of circular tubes. Andrews et al. [6] identified that several failure modes can occur for circular tubes subjected to axisymmetric loading, such as concertina (sequential bellows-type folding starting at one end of the tube), diamond (sequential folding accompanying a change in the cross-sectional shape) and mixed concertina–diamond. A tube longer than the critical Euler buckling length will deform in Euler buckling mode, which is a very inefficient energy-absorption mode and needs to be avoided for maximal energy absorption [1].

The onset of buckling under axial compression of metal tubes filled with a metal or polymer foam was found to be greater than that of hollow tubes [1,2]. Additionally, the energy absorbed by a tube filled with foam is greater than that of foam or tube individually [7]. Geometrical parameters (L/D and t/D, where L = length, D = diameter and t = tube wall thickness) and material parameters (yield strength and compressive failure strain) determine the failure mode of a hollow tube [8]. Abramowicz and Wierzbicki [9] compared the theoretical predictions and experimental results of foam-filled columns and developed a unified method of treating large plastic deformations of foam-filled columns, finding that the complex interaction between the sheet metal and foam resulted in an increased energy-absorption capacity of the column. They also established that a foam interior can reduce the length of the buckled regions by up to 50%. Santosa and Wierzbicki [10] examined numerical simulations of crushing of square cross-sectional column, either empty or filled with an aluminum foam or honeycomb. They found up to a 20% increase in the mean crushing load and up to a 30% increase in energy absorption with the foam compared to without it. They also pointed out that having a high adhesion between the filler and the column resulted in enhanced energy absorption. Thus, foam-filled columns optimize the energy-absorption capability over that of a hollow column.

According to Evans et al. [11], the basic requirements for cylindrical shells filled with a porous core are that the core shear stiffness and yield strength need to be adequate to maintain the buckling resistance of the shell. However, an undesirable feature with artificial foam-filled tubes is that under axial compression the foam pulls away from the tube and therefore does not support

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1742-7061/$ - see front matter Published by Elsevier Ltd. on behalf of Acta Materialia Inc.
http://dx.doi.org/10.1016/j.actbio.2013.07.004

any transverse loading (the Poisson's ratio of the foam is then zero) [2]. Consequently, the energy absorption is not maximized.

The porcupine quill is an example of a natural foam-filled tube. Porcupines are classified as Old World (Hystricidae), e.g. African or Indian "crested porcupine", and New World (Erethizontidae). Old World porcupines have longer and thicker quills than New World ones. Quills consist of a dense outer sheath (cortex) and a foam-filled interior (core) and are entirely made of α-keratin. The Hystricidae quills have additional thin, solid, longitudinal stiffeners extending radially from the cortex towards the center of the foam [12–15].

α-Keratin is a composite material of crystalline α-keratin intermediate filaments (IFs, composed of assembled dimers of coiled coils of α-helix molecules) embedded in an amorphous α-keratin matrix. The alignment of the IFs has a significant effect on the mechanical properties. The tensile strength of highly aligned IFs in human hair (~200 MPa) is an order of magnitude greater than that of the more disordered arrangement in fingernails [16]. The volume fraction of IFs in quills is estimated to be 0.37 [17]; however, the organization of the filaments is unknown. Keratin is formed by keratinocyte cells, which are changed both biochemically and morphologically when migrating to the outer layer [18].

In previous work [15], we reported the structure as well as compressive mechanical properties of these quills and determined that the experimental data (critical buckling strength and Young's modulus) fit well with the models based on geometrical measurements for hollow cylinders filled with a porous interior, developed by Karam and Gibson [13,19].

In this report, the cortex and foam from Hystricidae quills and the cortex of Erethizontidae quills are investigated and compared to whole quill properties. The experimental results are compared to predicted values using models based on geometrical measurements [13,20]. The different functions of the cortex and the foam served in quills under the load as well as the relationship between structures and mechanical properties are discussed.

2. Experimental procedures

Hystrix (Hystricidae) quills (Atlantic Coral Enterprise, Inc., St. Augustine, FL) and an uncured *Erethizon* (Erethizontidae) pelt (Jernigan's Taxidermy, Waco, TX) were purchased, both of unknown age. No special care was given to them and they were examined in the as-received condition.

Fig. 1 shows the detailed procedure for preparation of the cortex and foam samples as well as the final dimensions of the specimens. The quills have a smaller diameter at the ends and a constant diameter in the middle, so all the samples were prepared using the middle part. The *Hystrix* quill samples have an average diameter of ~3.3 mm and a cortex thickness of ~94 μm; thus *Hystrix* quills are large enough to prepare the cortex and foam samples separately. However, the *Erethizon* quill samples have a smaller diameter (~1.3 mm) and a cortex thickness of ~49 μm, and hence foam samples of the *Erethizon* quill could not be prepared. The samples were excised, maintaining the cuts as parallel as possible to each other and perpendicular to the sides of the quill. Preliminary results showed that testing without some sort of reinforcement on the quill or cortex ends led to inconsistent results due to the effects of cracking, splitting or folding at the weak edges of the samples. Therefore, short reinforcements were glued onto the ends of the cortex in order to eliminate the edge effects and provide smoother and proper stress–strain plots.

The foam from *Hystrix* quills was removed from the cortex using a needle, and discarded, and a section of a stiff plastic straw (used as reinforcement) of ~1 mm height was inserted and glued into either end. Straw sections glued inside the cortex eliminate the edge effects better than washers glued outside the hollow cylinders [12]. To prepare the foam sample, the cortex was sliced off using a surgical blade, so that a square prism was formed to reach the dimensions shown in Fig. 1a. Twenty cortex and twenty foam samples were examined.

The same procedure was used to prepare *Erethizon* cortex samples, as shown in Fig. 1b; however, instead of plastic straws, pencil lead sections were glued into the ends of the samples due to the smaller diameter of these quills. Twenty cortex samples were examined.

Samples were stored at room temperature in the air for several weeks before compression tests. All the samples were subjected to compressive deformation using an Instron 3342 (Instron Corp., Norwich, MA) load frame with a strain rate of 0.002 s^{-1}, in air with a relative humidity of ~78%. Most of the samples were tested to final failure (complete crushing). A few of the samples were compressed and removed before the final failure, to examine the deformation process. The stress in the whole quill and the cortex was obtained by dividing the applied load by the whole cross-sectional area of the quill and the area of the cortex (tube), respectively. The Weibull method was used to determine the mean strengths, mean Young's moduli and standard deviations of all samples [21].

The surfaces and cross-sections were observed using a Phillips XL30 environmental scanning electron microscope (Phillips, Portland, OR). Before observation, samples were sputtered with chromium or iridium.

3. Results and discussion

3.1. Characterization of structure

The microstructures of a *Hystrix* quill and an *Erethizon* quill are shown in Fig. 2 [13]. The *Hystrix* quill has stiffeners indicated by the arrows in Fig. 2a and b. The stiffeners extend from the cortex to the center and along the length of the quill. These stiffeners assist in supporting the foam walls. From Fig. 2, it is apparent that there is a gradual change in cell size. The foam cell size inside the *Hystrix* quill increases from the cortex to center. The diameter of cells in the center of the quill is up to 150 μm, while the cells close to the cortex are much smaller, some <30 μm (see Fig. 3a).

The *Erethizon* quills do not have any stiffeners inside the foam. Fig. 2c and d show the morphology of the transverse and longitudinal cross-sections, respectively. In Fig. 2c, the *Erethizon* quill appears somewhat distorted from a circular cross-section since it was compressed by slicing during sample preparation. Similar to the cores in the *Hystrix* quill, the cell size in the center is larger than those closer to the edge; the cell size ranges from 20 μm (close to cortex) to 70 μm (in the center) (see Fig. 3b). It appears that nature creates larger cells in the center to reduce the amount of material and decrease density while maintaining bending resistance. As a cylinder bent, the stress increases linearly from the centroid (zero stress) to the radius (maximum stress). Thus, the center of the cylinder does not experience substantial stress and material can be removed without compromising the bending resistance.

3.2. Mechanical properties

3.2.1. Cortices

Fig. 4a presents typical compression stress–strain curves of the cortices where the maximum stress is taken as the compressive strength (onset of local buckling). The Weibull method [21] was chosen for statistical analysis for calculation of the average Young's modulus and buckling strength, which has been employed successfully in the past to analyze other biological materials [15,22,23]. Weibull analysis can assess the distribution of the properties