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Research Paper

Failure analysis of porcupine quills under axial compression reveals their mechanical response during buckling

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ABSTRACT

Porcupine quills are natural structures formed by a thin walled conical shell and an inner foam core. Axial compression tests, differential scanning calorimetry (DSC), thermogravimetric analysis (TGA) and Fourier transform infrared spectroscopy (FT-IR) were all used to compare the characteristics and mechanical properties of porcupine quills with and without core. The failure mechanisms that occur during buckling were analyzed by scanning electron microscopy (SEM), and it was found that delamination buckling is mostly responsible for the decrease in the measured buckling stress of the quills with regard to predicted theoretical values. Our analysis also confirmed that the foam core works as an energy dissipater improving the mechanical response of an empty cylindrical shell, retarding the onset of buckling as well as producing a step wise decrease in force after buckling, instead of an instantaneous decrease in force typical for specimens without core. Cell collapse and cell densification in the inner foam core were identified as the key mechanisms that allow for energy absorption during buckling.

1. Introduction

Porcupines are found in two main families (about 29 species of porcupines) distributed throughout most areas in the world. They are classified as Old World porcupines and New World porcupines. Old World porcupines are found in Europe, Africa and Asia. Some examples include the North African crested porcupine *Hystrix cristata* and the African brush-tailed porcupine *Atherurus africanus*. New World porcupines are found in North, Central, and South America. These include the North American porcupine *Erethizon dorsatum* and the prehensile tailed porcupine *Coendou prehensilis*. Both families have muscles at the base of the quills enabling the quills to be raised, thereby making the animal look larger when threatened.

The *Erethizontidae* quills can be as long as 10 cm, while the *Hystricidae* quills are longer, up to 35 cm, and also have a proportionally larger diameter. All porcupine quills consist of a stiff outer sheath (cortex) and compliant porous core (medulla). The *Hystricidae* quills have additional thin solid longitudinal "stiffeners" extending radially from the cortex towards the centre of the core (Vincent and Owers, 1986; Karam and Gibson, 1994; Gibson et al., 1995).

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Quills are entirely composed of keratin. Natural keratins can be found in the outer most layer of the skin of vertebrate animals forming a protective structural covering for the organisms. Keratins are also found as fibres (hair and furs), laminates (nails, hooves, horns) and composites (quills, feathers, beaks) of mammals, birds and reptiles. This fibrous protein, known by its sulphur rich content and unique disulfide crosslinks, consists of filamentous scaffolds embedded in an amorphous matrix. Keratin materials have been categorized into α-type (α-helix) and β-type (β-sheet) based on the dominant secondary structure of the polypeptide chains. Keratin is surprisingly strong due to the S–S crosslinks and the protein's efficiency in atomic arrangement and unit cell packing (Astbury and Street, 1932; Fraser et al., 1986; Fraser and Parry, 2008).

Chou and Overfelt (2011) have studied the tensile deformation and failure of North American porcupine quills and have found that the shell of the porcupine quill is composed of 2–3 concentric layers and the quill shell exhibits a somewhat non-uniform thickness. They tested the fracture strength and the strain at fracture of North American porcupine quill at 100% RH and 65% RH and found that their tensile stiffness and strength increase as the water content decreases. In recent studies (Chou et al., 2012), it has been found that at 65% relative humidity, the mean axial elastic modulus of the shell was found to be over three times greater than the mean circumferential elastic modulus. In addition, increasing the relative humidity from 65% to 100% consistently decreased the measured values of the axial and circumferential modulus and strength and increased the fracture strain.

Vincent and Owers (1986) have measured the elastic modulus of porcupine quills. They reported an elastic modulus of 6.0 GPa for *H. cristata* quills and of 5.6 GPa for *C. prehensilis* quills. The elastic moduli reported for other keratin based structures are in the same order of magnitude as those reported for porcupine quills. For instance, Weiss, Kirchner (2010) measured the elastic modulus of the feathers from peacock's tail, and found a longitudinal elastic modulus of 3.3 GPa and a transverse modulus of 1 GPa.

Porcupine quills are one example of a thin walled conical shell structure found in nature. Other examples include plant stems, feather shafts and hedgehog spines. According to Karam and Gibson (1995a), these natural structures are typically loaded in some combination of compression and bending; failing by buckling. The interest in their study is based on the fact that cylindrical shells and tubular structures are used in several engineering applications. It has been suggested that biomimicking of such natural structures can lead to engineering structures with improved mechanical efficiency (Karam and Gibson, 1994) and to the design of efficient light structures (Van Hinte and Beukers, 1998).

In this study we have focused on porcupine quills from *C. prehensilis*, which is a porcupine from the Amazonian region belonging to the family *Erethizontidae* (New World porcupine). Axial compression tests were used to evaluate the mechanical response of the quills while attenuated total reflectance Fourier transform infrared spectroscopy (FTIR) was used to confirm the structural similarities between the inner foam and outer shell of the quills. The quill fracture morphologies were assessed with scanning electron microscopy (SEM). The main driving idea of the research presented here was to determine how the failure mechanisms that arise during axial compression of the porcupine quills affect their mechanical response and explain the differences between the predicted theoretical values of critical compressive forces and stresses with the actual measured values. Such discrepancies between predicted and experimental values had already been previously reported in the literature and further studies were needed to clarify them (Yang et al., 2013). This study aims to do that.

2. Experimental part

2.1. Materials

Porcupine quills from an Amazonian porcupine, namely, *C. prehensilis* were obtained from the city of Iquitos (Loreto, Peru). They were washed and stored in standard conditions (20 °C and 80% of relative humidity). Their dimensions were in average 1.057±0.076 mm in diameter and 20.094±0.415 mm in length.

2.2. Axial compression tests

An ESM (MARK-10) micro-mechanical testing machine was used. The tests were performed at 10 mm/min. The samples

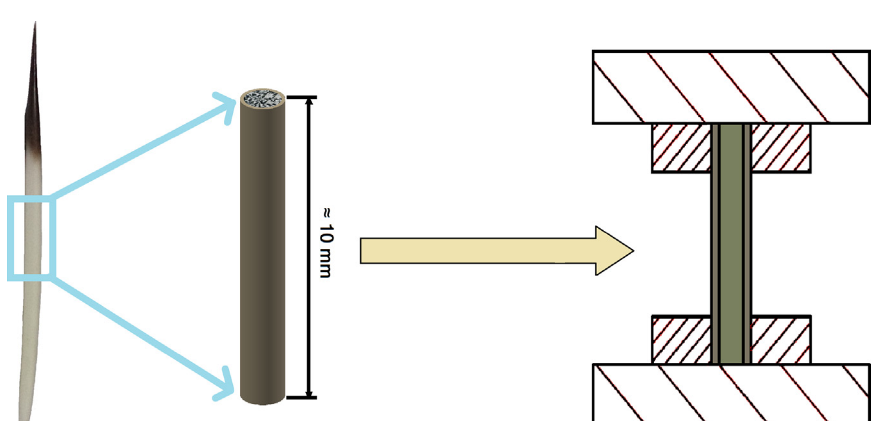

Fig. 1 – Scheme of the experimental rig used for the compression tests of porcupine quills.