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# Silk cocoon (*Bombyx mori*): Multi-layer structure and mechanical properties

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ABSTRACT

*Bombyx mori* cocoon is a natural composite made of silk fibre with a distinctive multi-layer structure that provides mechanical protection for its biological functions. Here we investigate the components, structure and mechanical properties of cocoon layers, and quantify the contributions of the multi-layer structure to the mechanical properties of cocoon. A better understanding of the multi-layer mechanism of a natural composite could help the further design of biomimetic multiscale artificial materials.



## 1. Introduction

Although silk is an interesting natural material in its own right due to its attractive range of combinations of strength and toughness [1], silk fibres have evolved for a biological function, often within complex engineering structures such as silkworm cocoons, which have themselves evolved as tough composites to protect developing larva. Interest in silk cocoons in recent years stems from their combination of porous structure, mechanical strength, and potential for control of the gaseous environment inside the cocoon. The early work concentrated on the mechanical properties and permeability of *Bombyx mori* cocoon, an agricultural product that provides commercial silk fibres for the textile industry [2–4]. Our own previous work expanded this research to a wide range of wild species to study the biodiversity of cocoon properties for their very diverse hierarchical structures and optimized properties [5]. We also developed a physical model to understand the structure–property relationships of silk cocoons as nonwoven fibre composites to learn important lessons for the practical purpose of designing new synthetic nonwoven and particulate composites [6,7].

Fig. 1 shows the hierarchy of the morphology of a *Bombyx mori* cocoon, both in the plane of the cocoon wall and through its thickness. *Bombyx mori* cocoon is a natural polymer composite shell made of a single continuous silk strand with a length in the range of 1000–1500 m and conglutinated by sericin. Each fibre is composed of two fibroins coated by a layer of sericin. The cocoon has a three-dimensional (3-D) nonwoven structure with multiple layers. Sericin acts as an adhesive to maintain the random fibre and the multi-layer structure in the whole cocoon.

As a composite cultivated for its commercial function of providing silk fibres for industry, the *Bombyx mori* cocoon has been selected to have strong fibres, ease of unravelling, and attractive optical properties. Compared to the cocoons of "wild" (as opposed to domesticated) silkworm species, the *Bombyx mori* cocoon has a relatively high thickness, low strength but high toughness, and a distinct graded layer structure. While calcium oxalate crystals (cubic or columnar shape, side length from 1–3 μm to 20–30 μm) or leaves strengthen the structures of wild cocoons, the *Bombyx mori* cocoon has a delicate random fibre arrangement, which acts as a simple 3-D nonwoven composite structure [5]. While the fibres and sericin of *Bombyx mori* cocoons have been studied extensively [8,9], the cocoons themselves have been researched in far less detail, and consequently the relationships between their structure and morphology are poorly understood.

Here we present our investigation of *Bombyx mori* cocoons in terms of their multiple layer structure and its relationship with mechanical properties. We believe that a solid understanding of such a highly selected cocoon will provide important lessons for the design of new composite materials with an interesting balance of porosity, strength and toughness.

## 2. Experiments: materials and methods

### 2.1. Materials collection

*Bombyx mori* silkworms were raised in a laboratory (23 ± 2 °C, 60% relative humidity) and fed with mulberry leaves until they

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