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The circular argument behind spider and silkworm silk mechanical properties

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ABSTRACT

Comparative studies of silk mechanical properties often highlight spider silk as superior to silkworm silk, but such claims are frequently based on inconsistent methodologies and limited species selection. This study revisits the comparison by emphasising the importance of accurate fibre cross-sectional area measurements, particularly given the irregular geometry of many silkworm silks. By correcting for overestimated cross-sectional areas, which were often assumed to be circular, we show that spider and silkworm silks exhibit comparable mechanical properties. The highest-performing natural silk in our dataset is not from a spider but from a bagworm. Additionally, we apply the theoretical framework based on fracture mechanics proposed by Porter, demonstrating that fibre strength scales with Young's modulus and inversely with diameter, in line with Griffith-Irwin fracture theory. This scaling holds for both natural and synthetic fibres, suggesting a universal failure mechanism. Our findings advocate for broader consideration of non-model silks and a more physics-informed approach to understanding silk mechanics.

1. Main text

Silk materials have long been regarded as a holy grail for textile and biomedical industries, captivating scientists for millennia [1]. Produced by many animals, silk has been most studied in silkworms and spiders. With more than 150,000 silk-producing Lepidoptera species and 52,000 known spider species, by necessity research has focused on a few "model" silks: the domesticated silkworm *Bombyx mori* and the major ampullate silk of spiders [2].

Major ampullate silk has often been considered among the best biological materials in terms of mechanical properties. This fascination pushed the community to produce large datasets such as the Silkome database [3] and notable discoveries, including the 2010 study on *Caerostris darwini* [4], whose major ampullate silk showed a toughness modulus over 350 MJ/m^3—the highest reported for a biological material. This result inspired work on its protein sequences and recombinant production.

That study is often cited to claim that spider silk is tougher and mechanically superior to silkworm silk. But is this true? More recently, attention has turned toward exploring novel silk types within Lepidoptera with a view to better appreciate the performance envelope of silks in general [5]. Such efforts may help answer the question; is spider silk inherently "better" than silkworm silk?

When comparing silks, fibre collection and testing methodologies are crucial [6]. Collection speed, testing strain rate, humidity, and temperature can all influence measured properties. However, the greatest impact arises from two factors: (i) whether true or engineering stress–-strain values are used (as thoroughly discussed in Greco *et al.* [6]), and (ii) the method used to calculate the fibre cross-sectional area. Spider silks typically exhibit circular cross-sections, whereas Lepidoptera silks often display irregular geometries [7]. Yet many studies estimate area by assuming circularity, taking the widest diameter—an approach that can overestimate true area by a considerable amount (Fig. 1a-c).

Using data from various studies on Lepidoptera silks and by embedding and sectioning 16 Lepidopteran species, we calculated the ratio between the actual cross-sectional area and the value obtained by assuming a circular cross-section. On average, this ratio is approximately 2, meaning the circular assumption can overestimate the true area by a factor of two (Fig. 1d). However, the difference between true and measured values for the 16 species varied greatly, ranging from a 10.6% decrease for *Bombyx mori* to a 59.5% decrease for *Philosamia cynthia*. Therefore, species- specific correction factors should be

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determined.

Applying this correction we compared the mechanical properties of spider and Lepidoptera silks (Fig. 1e, Supplementary Data Sheet, Supplementary information). After correction, spider silks no longer appear universally superior: average values across both groups are comparable, and the highest-performing natural silk in our dataset comes from bagworms, as shown in Yoshioka *et al.* [8]. Reported silkworm silk values often mix native and degummed samples; the thick sericin layer in non-degummed fibres likely leads to an underestimation of the intrinsic strength of the fibroin core, which gentler degumming could better reveal. The curious observation of pores/nanovoids in silks is likely to lead to further underestimations of the contribution of the fibroin brins to the fibre mechanical properties and is something that requires more attention in the future [9,10]. In addition, the typical irregularities in cross-sectional area or porosity often observed in Lepidoptera silks may also induce undesirable stress concentrations, potentially leading to premature fracture [6].

The persistent narrative of spider silk superiority largely arises from selective comparisons between orb-weaving spiders and domesticated *B. mori*. Domestication focused on easier reeling and reduced sericin, not on mechanical optimization [11]. As a result, *B. mori* silk is something of an evolutionary oddity, with altered fibre properties compared to wild silks [12]. Moreover, degumming protocols can weaken fibres, while wild silkworm silks are often tested without optimization—making comparisons with unprocessed spider silks uneven [13]. Additionally, when comparing spider and Lepidoptera silks, the natural variability of spider silk is rarely acknowledged [14], with most reported values obtained under idealized conditions.

A helpful framework for interpreting silk mechanics comes from Porter et al. [15], who argued that silk's strength is not due to unique molecular features but to reduced fibre dimensions. Building on Griffith's fracture theory and Irwin's revisions, they suggested fibre strength (σ) scales with:

$\sigma \sim \sqrt{\frac{GE}{d}}$where E is Young's modulus, d is fibre diameter, and G is the strain energy release rate.

We tested this prediction using our expanded dataset, plotting strength, Young's modulus, and diameter for spider and Lepidoptera silks, alongside carbon and Kevlar® fibres. The fit ($R^2 = 0.708$) supports the universal fracture mechanism proposed by Porter *et al.*, indicating that both natural and synthetic polymer fibres follow similar scaling.

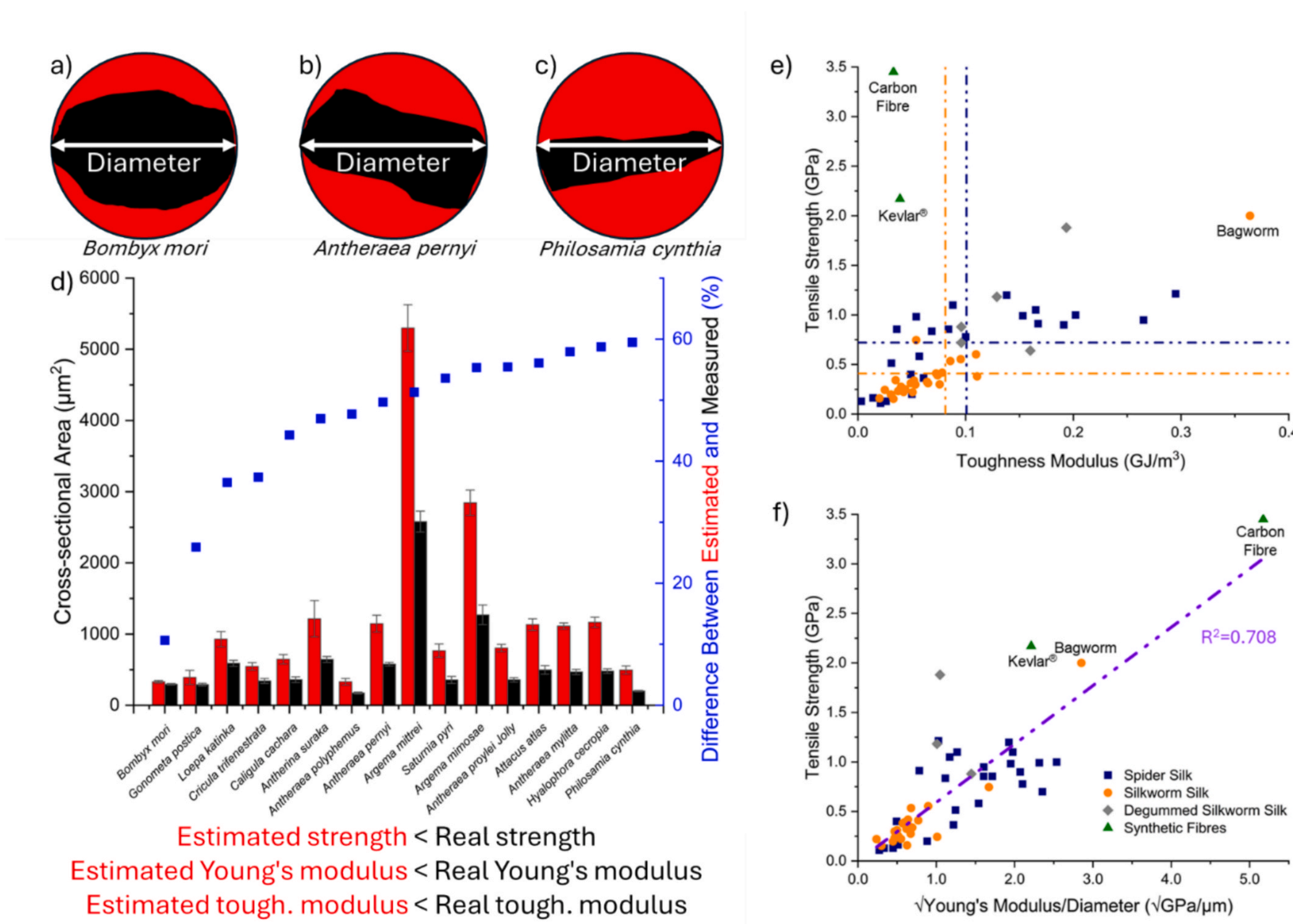

Fig. 1. Comparison of real vs. estimated cross-sectional area between different species of silkworm. Cross-sectional outlines (black) superimposed onto estimated (red) circular diameters as viewed from above and their difference in areas for a) *Bombyx mori,* b) *Antheraea pernyi,* c) *Philosamia cynthia*. Graph d) shows the comparison of estimated cross-sectional area (red) against measured cross-sectional area (black) for 16 species of silkworm. Data are presented as mean ± standard error. The real cross-sectional area is typically much smaller than estimated, thus the real stress on the fibre under tension is much higher, which increases the calculated values of strength, Young's modulus and toughness modulus. e) Ashby plot of spider (blue) vs. silkworm (orange) silk properties. Gray diamonds represent degummed silkworm silk and green triangles represent synthetic fibres (these data were obtained from the literature). Spider silk data are corrected based on Greco *et al.* 2023[6]. Dashed lines represent averages. The averages on silkworms were taken considering only non-degummed fibres. f) Plot inspired by Porter *et al.*[15], in which the strength of the fibre is fitted vs the square root of the ratio between its Young's modulus and diameter. In addition to original data, further mechanical properties were obtained from the literature (see supporting information).

That said, it is important to note that silk fracture mechanisms may differ due to its unique molecular structure.

In conclusion, this study offers two key takeaways. First, spider silk is not universally superior to Lepidoptera silk; meaningful comparisons must specify species and methods. Second, the scaling of fibre strength with Young's modulus and diameter supports a universal fracture mechanism across natural and synthetic fibres.

This work is timely, for it encourages exploration of underrepresented silk types beyond traditional models and promotes a physics-informed view of silk mechanics grounded in polymer science.

CRediT authorship contribution statement

Thomas Braxton: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **Chris Holland:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Gabriele Greco:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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We would like to dedicate this work to the memory of Prof. David Porter.

Appendix A. Supplementary information

Supplementary information to this article can be found online at https://doi.org/10.1016/j.matdes.2025.115224.

Data availability

Additional data is available in the supplementary information. Further data that support the findings of this study are available under CC-BY 4.0 from the ORDA repository DOI 10.15131/shef.data.30009400.

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