ELASTOCAPILLARY WINDLASS : FROM SPIDER WEBS TO SMART ACTUATORS

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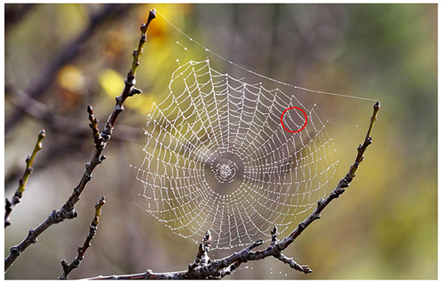
Abstract

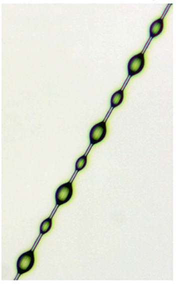
Spiders' webs and gossamer threads are often paraded as paradigms for lightweight structures and outstanding polymers. Probably the most intriguing of all spider silks is the araneid capture thread, covered with tiny glycoprotein glue droplets. Even if compressed, this thread remains surprisingly taut, a property shared with pure liquid films, allowing both thread and web to be in a constant state of tension. Vollrath and Edmonds proposed that the glue droplets would act as small windlasses and be responsible for the tension, but other explanations have also been suggested, involving for example the macromolecular properties of the flagelliform silk core filaments. Here we show that the nanolitre glue droplets of the capture thread indeed induce buckling and coiling of the core filaments: microscopic in-vivo observations reveal that the slack fibre is spooled into and within the droplets. We model windlass activation as a structural phase transition, and show that fibre spooling essentially results from the interplay between elasticity and capillarity. This is demonstrated by reproducing artificially the mechanism on a synthetic polyurethane thread/silicone oil droplet system. Fibre size is the key in natural and artificial setups which both require micrometer-sized fibres to function. The spools and coils inside the drops are further shown to directly affect the mechanical response of the thread, evidencing the central role played by geometry in spider silk mechanics. Beside shedding light on araneid capture thread functionality, we argue that the properties of this biological system provide novel insight for bioinspired smart and extremely extensible actuators.

Biological Material

Cribellate spiders coat their circumferential threads with a water-based glue to capture insects, by cushioning their impact on the web and ensnaring them tightly

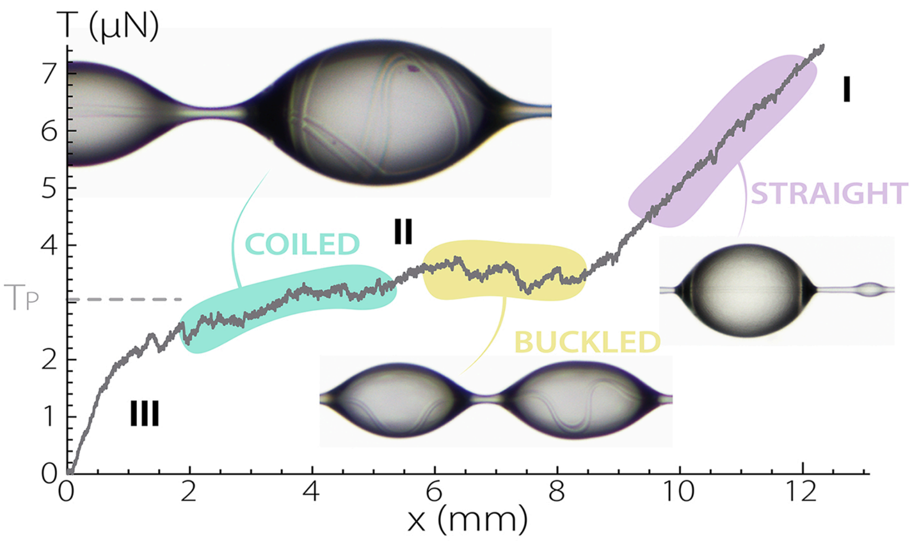
Nephila Madagascariensis





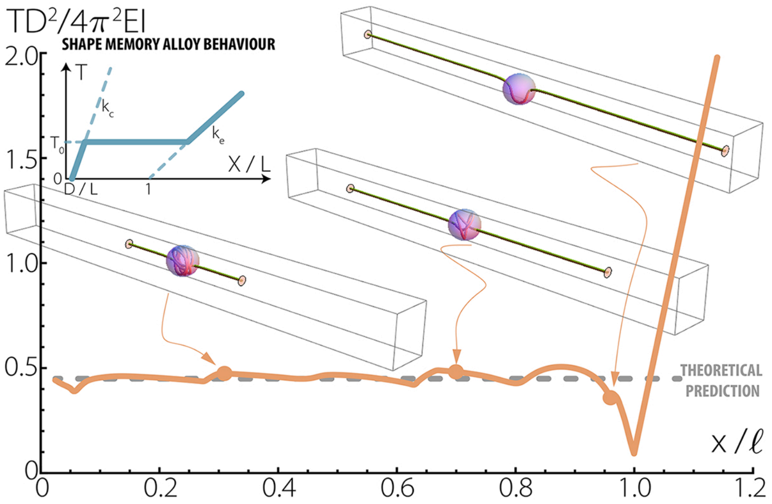
Circumferential spider silk from Nephila Madagascariensis

Force-strain curve, obtained with capacitance-deflection sensing technology

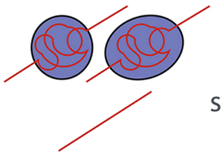


Numerical simulations

Following post-buckling 3D equilibria with a continuation method (AUTO)



A mechanical phase transition



coiled wet phase

$$E_C = \frac{1}{2}k_C\left(x_C - D\right)^2$$

stretched dry phase

$$E_e = \frac{1}{2}k_e\left(x_e - \ell\right)^2 + \epsilon_0\ell$$

energetical cost for phase transformation

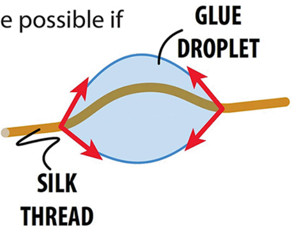
$$\epsilon_0 = 2\pi r\gamma\cos\theta - \frac{1}{2}\pi E r^4/D^2$$

Matching between numerical plateau value and phase transition model prediction

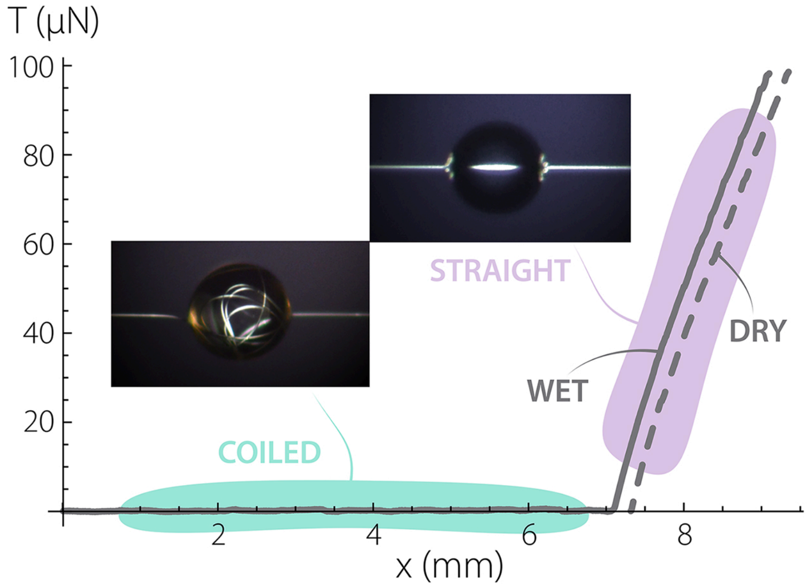
Drop capillary compression > local buckling force possible if

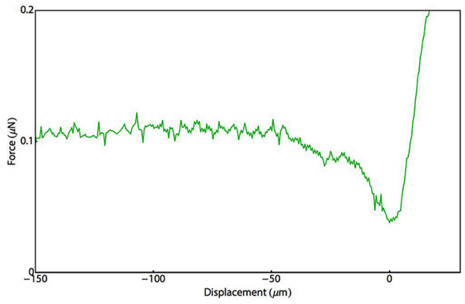
$$r \leq r_{\mathrm{crit}} \approx 2.27 \times \frac{(\gamma\cos\theta)^{5/7}}{(\rho g)^{2/7}\,E^{3/7}}$$

$$\rightarrow \text{nm-}\mu\text{m range}$$



Bio-Inspired Artificial Liquid-Solid Mechanical Hybrid





Bibliography :

[1] Matthias Heil. Minimal liquid bridges in non-axisymmetrically buckled elastic tubes. JFM, 380:309–337, 1998.

[2] Thomas Eisner and Daniel J. Aneshansley. Defense by foot adhesion in a beetle (hemisphaerota cyanea). PNAS, 97(12):6568–6573, 06.

[3] José Bico, Benoit Roman, Loic Moulin, and Arezki Boudaoud. Adhesion: Elastocapillary coalescence in wet hair. Nature, 432(7018):690–690, 2004.

[4] Fritz Vollrath and Donald T. Edmonds. Modulation of the mechanical properties of spider silk by coating with water. Nature, 340(6231):305–307, 07 1989.