SPIDER SILK

Webs measure up

The complete elastic response of a spider's orb web has been quantified by non-invasive light scattering, revealing important insights into the architecture, natural material use and mechanical properties of the web. This knowledge advances our understanding of the prey-catching process and the role of supercontraction therein.

Zhao Qin and Markus J. Buehler

Developing advanced materials based on principles learnt from natural ones, like silk, can be an alternative to the laborious trial-and-error approach conventionally used. Even though silk's superb mechanical properties have been known for decades, only recent work has shown that multiple length scales (from nanometre to metre) in its complex architecture contribute to the performance of orb webs, cob webs, sheet webs, funnel webs and other structures like cocoons[1–6]. Orb webs, in particular, are exceptional structures from a mechanical and an aesthetic point of view, and, are constructed from hierarchically organized simple proteins (Fig. 1). To achieve certain properties, mechanisms interact synergistically across many length scales. For example, the molecular arrangement of beta-sheet crystals combined with a semi-amorphous protein phase at the nanometre scale enables the characteristic nonlinear stiffening response of spider silk — becoming more rigid as the material is stretched — which, in turn, ensures an orb web's consistent load capacity in spite of the presence of defects[5,7].

Although the geometry of different types of web has been measured using optical methods[1–6], most material property assessments are limited to individual silk fibres, and rarely consider the properties of silk materials in their natural arrangement. This *in situ* measurement is important, however, because a spider web consists of at least five different types of silk[8] with different functions, including radial and spiral threads, the junctions between individual threads in a web, and the web's anchorage to the environment[9]. The lack of a complete assessment of the mechanical properties is, in part, a consequence of the fibres' small diameter, and because conventional tests are typically limited to tensile force applied in the fibre direction.

Now, writing in *Nature Materials*, Yarger and colleagues report an intriguing analysis using non-invasive, non-destructive Brillouin light scattering to obtain stiffness tensors, from which the material's elastic responses to forces with any direction and magnitude can be computed[10]. Brillouin light scattering uses laser-light refraction to measure the propagation velocity of elastic waves in a material, and hence, enables the calculation of stiffness. Yarger and colleagues spatially map the stiffness tensor of part of an orb web (Fig. 1) without deforming or disrupting it, and also provide the stiffness changes that happen with supercontraction, which occurs when dry silk fibres are exposed to moisture[11]. Although it is already known that exposure to moisture causes molecular-level changes in silk[11], the mechanical implications need to be probed in the context of the web architecture, connecting the scales.

Yarger and colleagues map the stiffness of the dragline, viscid silks and silk junctions that belong to the same orb web and provide quantitative information about the altered elasticity of the silk threads before and after exposure to moisture. The identification of the web's stiffness tensor helps to answer several questions, in particular, about the mechanical response of silk materials and how they play together in a web. Using these data, it is possible to predict the mechanical response of an orb web under gravity loading as a result of morning dew, including the effects on web stiffness and vibration signal transfer[12] (Fig. 2). Signal transfer is important because spiders have poor eyesight and rely on vibration signals to orient themselves and identify prey. The presence of water droplets leads to deformation of the web exerted by gravity forces (Fig. 2), but also leads to supercontraction, which increases the stiffness of the threads by more than 40%. Using the measured data, and by comparing hypothetical webs built from dry silk and wet silk — both exposed to the same gravity loading — it can be seen that the greater stiffness of wet silk reduces the deformation of the web (the largest deflection in the direction of gravity is reduced by almost 17%) (Fig. 2c). This analysis suggests that a web built overnight in dry conditions might benefit from morning dew as it stiffens. Furthermore, comparing the characteristic and duration of vibration signal transfers from the web peripheral edge (a likely location of captured prey) with the web centre (Fig. 1) before and after exposure to moisture, shows that signals have a higher vibrational frequency after exposure. Moreover, the signal transfer time is shortened by more than 22% under moist conditions, whereas the vibration amplitude in the centre remains on a similar level. Hence, the presence of moisture not only leads to a more rigid web, but may also make the spider more easily aware of the location of prey.

Further experimental and modelling work is necessary, but these examples illustrate an application of this investigation that shows how spiders may take advantage of a molecular mechanism (supercontraction) that improves the responsive nature of the web at the macroscale, for catching prey. Also, it demonstrates how the material can be important in understanding the ecology of spiders[12], which opens avenues for investigations at the interface of biology and materials science.

Although the spatial resolution of Brillouin light scattering is limited by the laser spot size of about 1 μm (which is larger than the thinnest silk fibres of several hundreds of nanometres), it can precisely map the mechanical properties of a sufficiently large portion of the web to grasp its global mechanical behaviour. Other aspects are interesting and open avenues for future work. For example, the study correlates the stiffness of silk with the relative crystallinity of the proteins that make up the fibres, where greater crystallinity leads to higher stiffness[13]. It would be interesting to investigate the link between the amino acid sequence and the molecular structure of silk to the mechanical properties of webs and other macroscale architectures, like cocoons or funnel webs. Understanding these relationships provides tremendous potential for fabricating new 'designer biomaterials'. One of the advantages of silk is that it is biocompatible and can be used to engineer materials that direct cells to respond in particular ways, such that defined tissues can be grown. Further studies could also be carried out to better understand the structural composition of silk fibres, for example, exploring their fibrillar structure, or assessing the mechanical properties of coating proteins that are applied to fibres

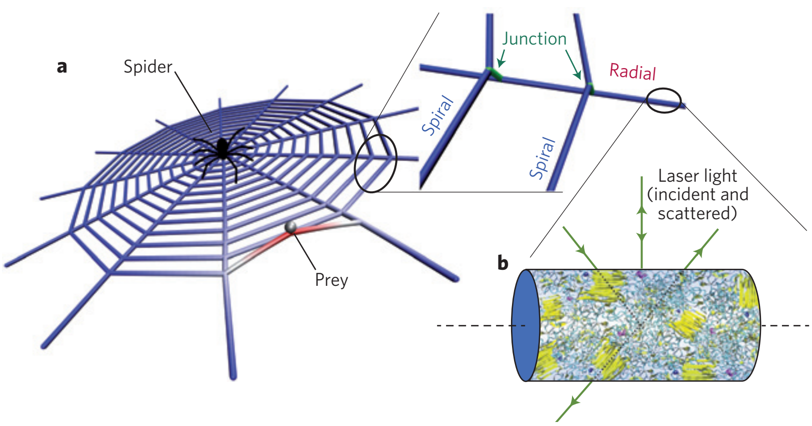

Figure 1 | A schematic diagram of a *Nephila clavipes* spider web model and its experimental investigation using Brillouin light scattering. **a**, The snapshot of the web model is taken as the peripheral spiral thread is hit by prey (grey sphere). A section of the web has been magnified to show the different types of silk used to construct a web. **b**, A schematic view of the molecular structure of silk, showing a nanocomposite of crystalline (yellow) and semi-amorphous (multicoloured) domains, which includes a diagrammatic representation of the Brillouin light scattering approach used to calculate the stiffness tensor of silk. The results are used in a simple web model[5], where the stiffnesses of the radial, spiral and junction threads reflect the measurements by Yarger and colleagues.

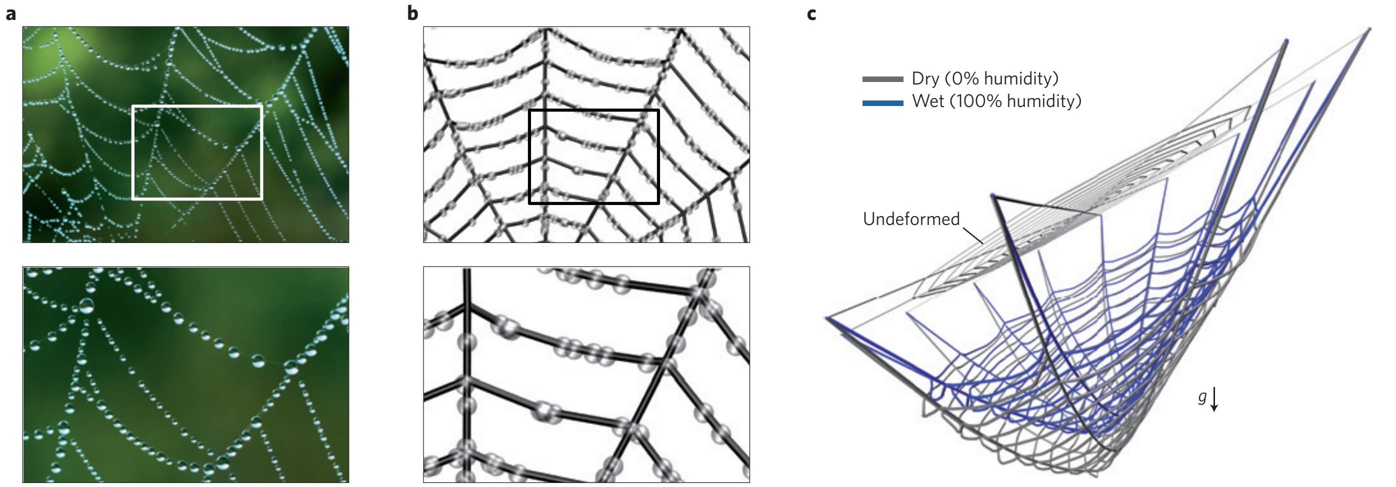

Figure 2 | The deformation of a spider web under gravity loading as a result of water droplets in morning dew. **a**, Photographs of an orb web with water droplets resulting from morning dew. Bottom: close-up of droplets and web deformation. **b**, A model of a deformed web because of gravity loading imposed by water droplets. Bottom: close-up of droplets and web deformation. **c**, Comparison of web deformation because of gravity (*g*) loading in dry and wet conditions (droplets not shown for clarity). Two sets of axial stiffnesses of the dragline silk, viscid silk and the junctions between them, in the dry state (dark grey, at 0% humidity) and moist state (blue, fully supercontracted at 100% humidity) as measured by Yarger and colleagues are used in the model. The light grey shows the web in its initial, undeformed state. In the moist state, web deformation because of water droplets is smaller and signals travel faster. Hence, supercontraction not only leads to a stiffer web, but also increases the sensitivity for the presence of prey. Panel **a** reproduced with permission from © Shutterstock/Alexander M. Omelko.

to control their surface properties such as stickiness[2,4].

Important challenges remain with respect to the nonlinear material properties of silk fibres — the stiffness changes under different stages of deformation — which are known to be important for understanding web mechanics under loading in windy conditions and at larger deformation[5], but have not yet been investigated. The various types of web found in nature provide many exciting opportunities to improve the design of structures, signalling strategies, armours and biomaterials. ❐

Zhao Qin and Markus J. Buehler are in the Laboratory of Atomistic and Molecular Mechanics in the Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA.
e-mail: mbuehler@MIT.EDU

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