Spider webs rely on nonlinear material behavior and architecture

Perhaps no other natural structure better exemplifies a design that optimizes material function than the spider web. However, despite extensive theoretical and experimental investigations of the molecular design and mechanical properties of spider silk, the integrity and performance of the spider web has not yet been fully explained. Recently, M.J. Buehler from the Massachusetts Institute of Technology, N.M. Pugno of Politecnico di Torino, Italy, and their colleagues showed that the superior performance of spider webs can be attributed to a combination of the silk threads' nonlinear stiffening response to strain—which is a result of a unique molecular structure—and their discrete geometrical arrangement in a web, rather than their remarkable strength and toughness as had been previously assumed.

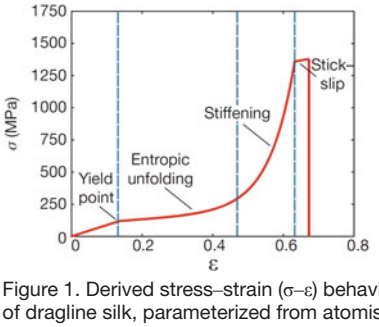

Figure 1. Derived stress–strain (σ–ε) behavior of dragline silk, parameterized from atomistic simulations and validated against experiments. Reproduced with permission from *Nature* **482** (7383) (2012), DOI: 10.1038/nature10739; p. 72. © 2012 Macmillan Publishers Ltd.

As reported in the February 2 issue of *Nature* (DOI: 10.1038/nature10739; p. 72), Buehler and co-researchers used results from atomistic simulations to parameterize the behavior of dragline silk from the species *Nephila clavipes* (see Figure 1). This silk model was used in conjunction with a web model containing spiral (sticky capture silk) and radial (strong dragline silk) threads, which are the primary components commonly found in orb webs. Thread removal (up to 10%) had relatively little impact on the web's response to a load. By comparing the loading of radial versus spiral threads, the researchers found that the force required to break radial threads is about 150% higher than for spiral threads, yet, in both cases, failure and resulting damage were limited and localized about the loaded thread.

In order to determine whether localized failure is due to the silk's materials properties or the web architecture, the researchers constructed and tested two additional web models using idealized engineered fibers exhibiting linear elastic or elastic–perfectly plastic behaviors. Both of these revealed increasingly non-localized damage (see Figure 2). The researchers incorporated their models' materials behaviors into quantized fracture mechanics, which can be used to describe the failure of discrete structures, to prove that the relative size of the damage zones is a function of the materials' stress–strain relationships. They also derived a scaling law that relates the undamaged fraction of the web to a parameter that defines the nonlinear nature of a material's stress–strain relationship. The nonlinear stiffening behavior ensures that a loaded thread becomes the sacrificial element, which can be repaired, while the large majority of the web remains intact.

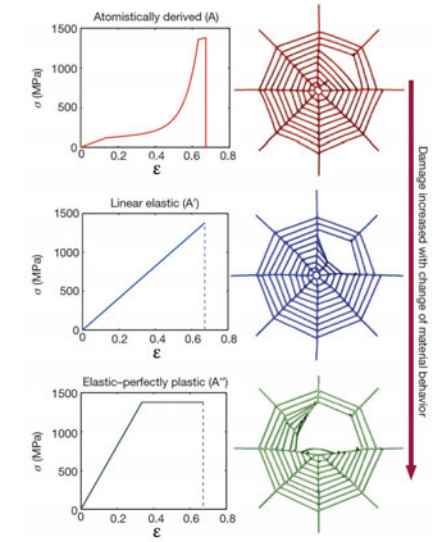

Figure 2. Web response for varied silk behavior under targeted (local) and distributed (global) loading. Reproduced with permission from *Nature* **482** (7383) (2012), DOI: 10.1038/nature10739; p. 72. © 2012 Macmillan Publishers Ltd.

The researchers said that whereas current engineering practices use sacrificial elements to dissipate energy (as in the response to seismic waves, for example), web-design principles should now be considered. They said, "Such an engineering design could ignore the requirements for the magnitude of a potential load and allow local failure to occur, a design stipulation that requires the consideration of both material behavior and structural architecture."

Steven Trohalaki

Bio Focus

Molecular self-assembly controlled by different pathways

Molecular self-assembly is the process through which molecular building blocks organize themselves into supramolecular structures. Controlling the principles of molecular self-assembly opens the door to new materials with special properties, for example, self-repairing coatings. The properties of these materials are strongly influenced by the way the building blocks are assembled; a small difference in their organization can lead to very different properties. Peter A. Korevaar and colleagues at Eindhoven University of Technology in The Netherlands have succeeded in monitoring and controlling a molecular self-assembly process through different pathways.

As reported in the January 18 advanced online issue of *Nature* (DOI: 10.1038/nature10720), the research team uses a molecular building block whose assembly can be studied with time using circular dichroism: *S*-chiral oligo(p-phenylenevinylene) or SOPV. Molecules of this kind are frequently used in organic electronic devices, in which small differences in the morphology of the material lead to large differences in their properties. At the start of

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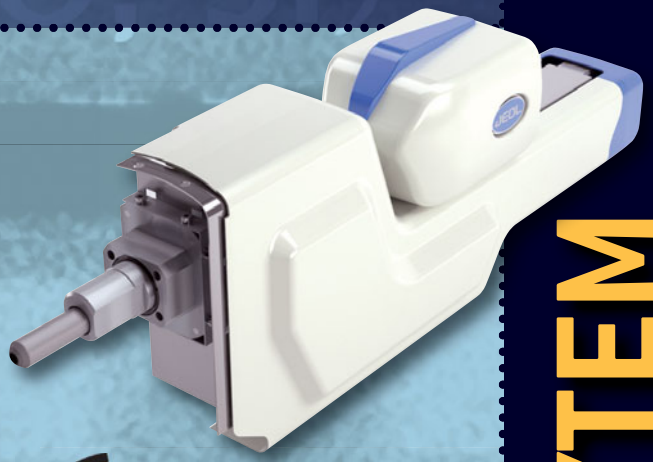

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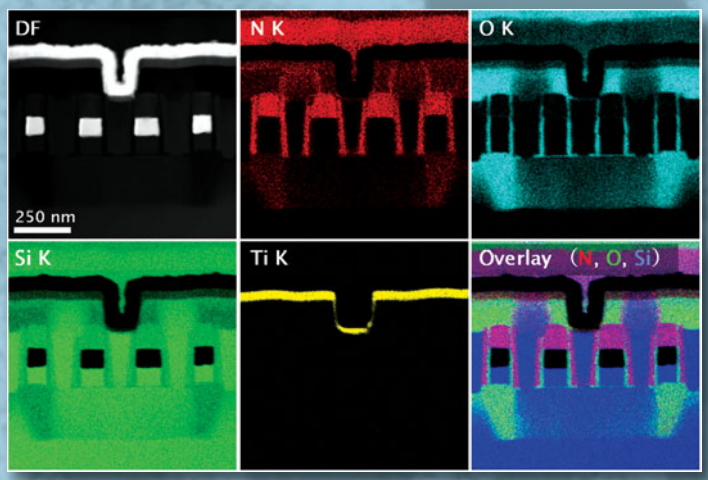

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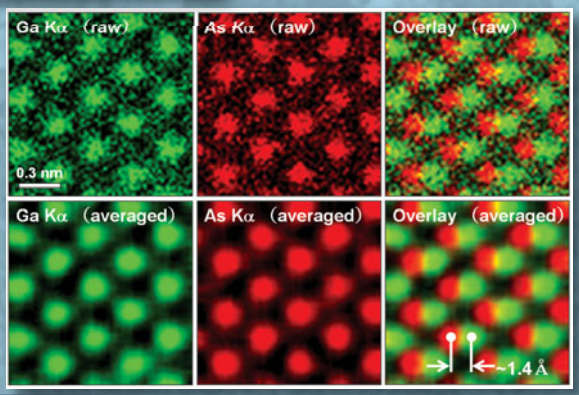

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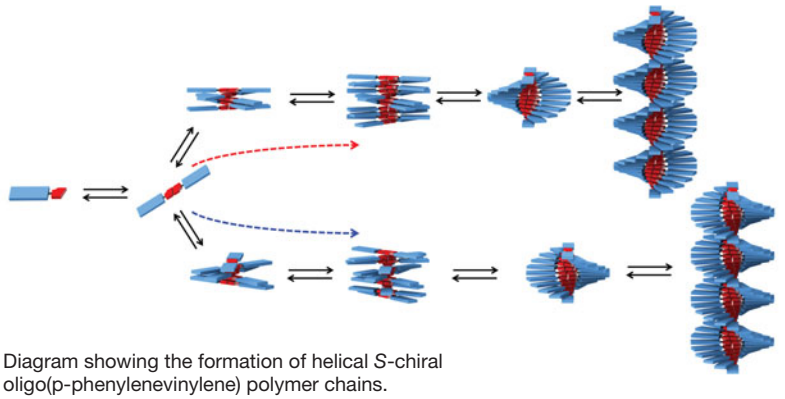


Diagram showing the formation of helical *S*-chiral oligo(p-phenylenevinylene) polymer chains.

the assembly process, SOPV first forms unstructured clusters, which ultimately grow into neatly organized left-handed "spiral staircase"-like helical structures. Detailed time-resolved investigation of this assembly process importantly showed that at early reaction times, aggregates with the opposite helicity were also present. These right-handed helices are metastable and convert to the thermodynamically favored left-handed helices with time.

Aggregation of SOPV therefore involves two competing pathways which lead to assemblies with opposite helicity, one of which is favored kinetically and the other thermodynamically. Based on this understanding, the researchers demonstrated that the assembly process could be controlled to uniquely select the kinetic product. Addition of tartaric acid, a small molecule that attaches itself to the SOPV molecules, forces the assembly process toward the right-handed helices.

"This knowledge has significant impact on an optimal self-assembly process, and we can now use it for more applied supramolecular systems which are much more difficult to study," said Korevaar.

Nano Focus

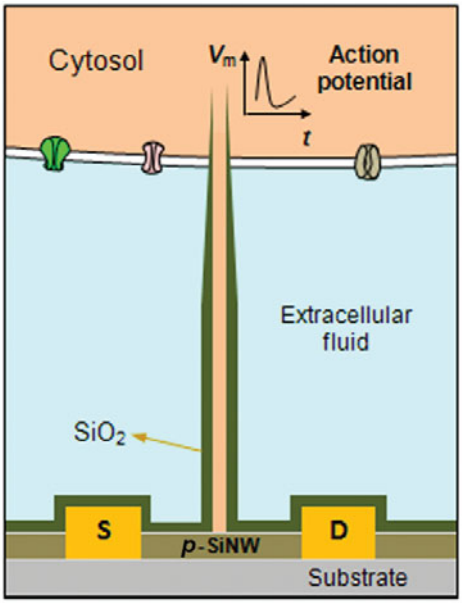
Nanoscale transistor measures living cell voltages

Forming an electrical interface with living cells, including muscle cells and neurons, is crucial for studying fundamental electrophysiological processes. These cells use ion-transport channels to create a potential difference across their membrane (action potentials) that can be used to convey a nerve signal or trigger muscle contraction. In order to measure these potentials with high spatial precision and minimal cell disturbance, the research team of C.M. Lieber at Harvard University recently developed a nanowire field-effect transistor (FET) that employs a branched silica nanotube as a nanoscale syringe.

Their article in the December 18 advanced online issue of *Nature Nanotechnology* (DOI: 10.1038/NNANO.2011.223) describes the formation of silica nanotubes using germanium nanowires as a sacrificial template, themselves grown radially out from a silicon nanowire substrate. After depositing metal sources and drain electrodes on the silicon on either side of the germanium nanowires, the whole structure is coated in SiO_2 and the germanium nanowires are removed by chemical etching. This leaves tapering silica nanotubes several micrometers in length and 50–150 nm in diameter that allow imbibed liquid to contact the silicon channel between the electrodes. The conductance in solution of transistors constructed using the nanotubes was much more sensitive to changes in applied voltages than those prepared with solid germanium. This demonstrates that the solution in the hollow tube was responsible for the gate voltage experienced by the nanowire, and that this cavity could therefore serve as an effective cellular probe.

The device was used to study the action potentials in a culture of cardiomyocytes (heart muscle cells), after first modifying the nanotube with phospholipids to improve its interaction with the cell membrane. Upon contact with a cell, the nanotube spontaneously penetrated the membrane and filled with cytosol, and a clear trace of the intracellular action potential typical of beating cardiomyocytes could be recorded by the transistor.

A principal advantage of these devices over existing techniques using glass micropipettes which form the basis of the "patch clamp" technique is that they appear to interfere minimally with the cell. A biomimetic seal provided by



A schematic diagram of a cell coupled to the branched nanotube field-effect transistor during an action potential V_m. S and D indicate source and drain electrodes. Reproduced with permission from *Nature Nanotech.*, DOI: 10.1038/NNANO.2011.223. © 2011 Macmillan Publishers Ltd.

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