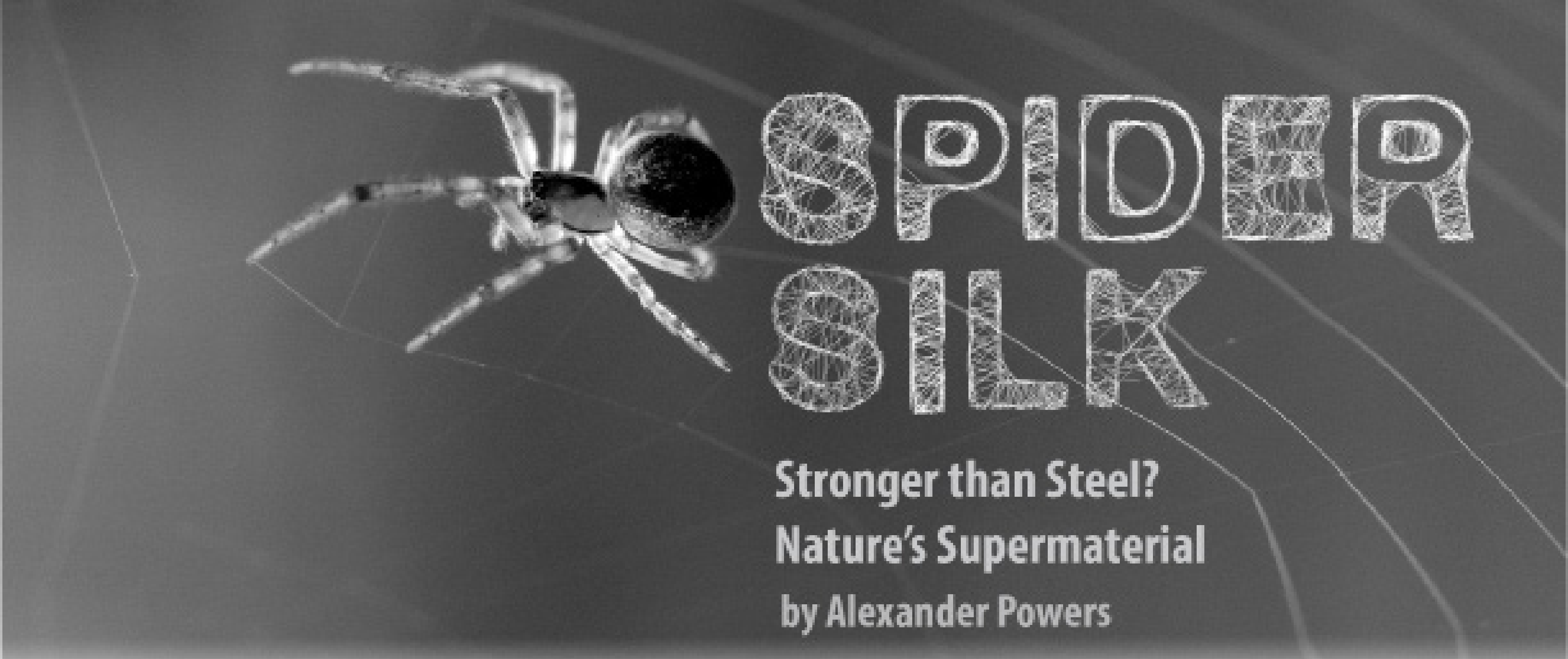


SPIDER SILK

Stronger than Steel? Nature's Supermaterial

by Alexander Powers

A train full of passengers is about to plummet into a river. The brakes are stuck. Who will save the day? Who else but Spider-man! He slings thick strands of spider silk onto adjacent buildings, bracing himself on the front of the train until it comes to a grinding halt at the last moment of safety. Spider-Man might be a fictional superhero, but the incredible properties of his spider webs are not so far-fetched. In a recent study published in *The Journal of Physics Special Topics*, graduate students at the University of Leicester decided to myth-bust the above scene from *Spider-Man 2*. To their surprise, theoretical calculations showed that spider silk is, in fact, strong enough to stop a runaway train (Bryan, 2012).

They began by estimating the force needed to stop the train: about 300,000 newtons. After analyzing the web, the geometry, and the anchor points, they calculated the tensile strength required of the silk fibers (the maximum stress they can withstand while being stretched before breaking). This type of strength is reflected in a value called Young's Modulus which in this case worked out to be 3.12 gigapascals. As it turns out, spiders produce silk with Young's Moduli ranging from 1.5 to 12 gigapascals — meaning that Spider-Man could indeed have stopped a fast moving train with spider silk (Bryan, 2012). In fact, biologist William K. Purves (2003) writes that, "The movie Spider-Man drastically underestimates the strength of silk - real dragline silk would not need to be nearly as thick as the strands deployed by our web-swinging hero in the movie".

Over the past few decades, spider silks have attracted the attention of the scientific community for their amazing mechanical properties and endurance under stress. Of course, silk and its relationship to humanity is nothing new. According to Confucius, it was in 2600 B.C.E. that a silkworm cocoon fell into the tea cup of Chinese princess Leizu. Attempting to remove it from her beverage, she began to unroll the silken thread of the cocoon. By the 3rd Century B.C.E., Chinese silk fabrics were traded throughout Asia and the West by way of the famous Silk Road. However, silk production remained a closely guarded secret. Most Romans, who highly prized the cloth, were convinced that the fabric came from trees. The Chinese monopoly was defended by an imperial decree, condemning to death anyone attempting to export silkworms or their eggs. In 552 C.E., the Roman Emperor Justinian sent two monks on a mission to Asia, and they returned with silkworm eggs hidden inside their bamboo walking sticks. Soon, sericulture (silk farming) spread across the world (Silk Association, 2012).

During the 19th and 20th centuries, modernization and industrialization of sericulture in Japan made it the world's foremost silk producer. During World War II, western countries were forced to find substitutes as supplies were cut off. Recently invented synthetic fibers such as nylon became widely used. Now silk has largely been replaced by these artificial polymers which are far more cost effective. However, silk polymers (of which scientists have only recently understood the full potential) are poised for a possible comeback if they can be mass produced cheaply and efficiently (Silk Association, 2012).

Spider silk may seem weak and flimsy, useful for nothing better than haunted house decor. Yet for its miniscule weight and size it can absorb a surprising amount of energy. It's also stretchy - it can stretch 30% farther than the most pliable nylon. If spider silk were as thick as a steel beam, it would be very difficult to break, a lot more difficult than the comparatively sized and much heavier steel. In fact, it would take about 100 times more energy (Gosline, 1986). Actually, spider silk has a tensile strength comparable to that of steel, about 1.5 gigapascals, but silk's much lower density means that for equal weights of the materials, silk wins. "One strand of pencil thick spider silk can stop a Boeing 747 in flight," say Xiang Wu and colleagues at the National University of Singapore. Spider silk of the species *Caerostris Darwini* is among the strongest silk yet measured. These spiders spin some of the largest webs in nature, often spanning streams and canyons. In one study, spider were captured from the wild and allowed to build webs inside a greenhouse. The silk was then analyzed with a tensile tester - basically by tugging on the ends of the fiber. It was found that *C. Darwini* silk is far higher performing, absorbing about ten times more energy before fracturing, than the manmade fiber Kevlar (Agnasson, 2010). Silk's unusual combination of high strength and stretch leads to toughness values never attained in synthetic high-performance fibers. Even compared to silkworm silk, spider silk has a tensile strength 3 to 20 times greater, can strech almost 3 times further, and absorb 3 times as much energy (Shao, 2002). But what is responsible for spider silk's ability to endure so much stress?

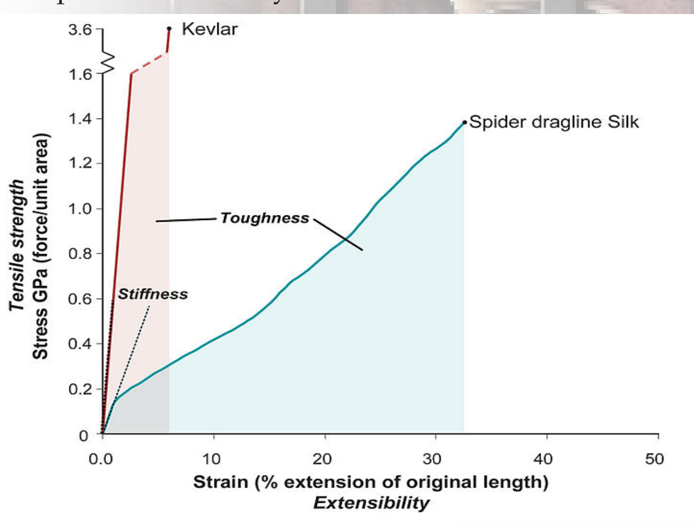


Fig 1. Tensile Strengh of Spider Silk

All silks are proteins; they reflect millions of years of evolution toward a material perfectly suited for its biological purpose. Although silk has been a well-known material for decades the intricacies of its chemical and molecular properties only recently became a subject of interest. The first basic model of silk was introduced in only 1994 and described "amorphous flexible chains reinforced by strong and stiff crystals"(Termonia, 1994). A more thorough analysis was published in Science in 1996. Silk consists of very repetitive blocks of mainly glycine and alanine (glycine and alanine are types of amino acids - the molecules that make up the long protein chains) (Simmons, 1996). These are the simplest and smallest amino acids allowing strands to be packed together. Strands are "glued" together by hydrogen bonds to form tightly packed, highly ordered crystalline regions. The hard crystals make up only 10-15% of the total volume (Keten, 2010). Other regions contain bulky amino acids like tyrosine or arginine that prevent close packing. These regions form amorphous, disordered areas that allow the silk to stretch. The interplay between the hard crystalline segments and the elastic regions gives spider silk its extraordinary properties.

"One strand of pencil thick spider silk can stop a Boeing 747 in flight,"

Spider silks hold great promise as a material with an impressive array of potential applications ranging from artificial body parts to microelectronics. Randy Lewis, a professor at Utah State University, writes that "The major efforts for the commercial use of spider silk are for artificial ligaments, tendons and bone repair materials." Silks are scleroproteins, the same protein type used to provide support in collagen, tendons, and muscle fibers. Yet, silks are 100 times stronger than natural ligaments. During ACL reconstruction (the anterior cruciate ligament), surgeons often replace the torn knee ligament with a ligament transplanted from a cadaver or the patient's own hamstring muscle. However, the new ligament is weak and at high risk for reinjury. Spider silks could be used to construct tear-resistant artificial ligaments. In addition, spiders silks are biocompatible, triggering little, if any, immune response. "We can make something that mimics the size, shape, and elasticity [of a ligament] without any trouble at all," says Lewis (USTAR, 2012).

Spider silk proteins may one day mimic not only connective tissues but actual muscles. Researchers at the University of Akron are designing biomimetic muscles utilizing another little explored property of spider silk; contraction. When morning dew or rain drops weigh down a spider web, rather than collapse or stretch, the fibers actually contract and tighten to maintain tension. At high humidity spider silk ‘supercontracts’ - shrinking up to 50% of its length due to disruptions and changes in protein bonding. This change is enough for a single 40 mm long, 5 micrometer diameter fiber (more than 3 times smaller than human hair) to lift at least 100 mg (1/10 weight of paperclip). This may seem insignificant but the work density is actually 50 times higher than biological muscles. Scaled up, a 1 mm diameter fiber could lift as much as 5 kg and a 2 cm diameter fiber could lift 2 metric tons. Driven by humidity alone, silk offers potential for lightweight and compact actuators for robots and micro-machines (Agnarsson, 2009).

Ever notice spiderwebs glinting in the sunlight? Light can propagate along strands of spider silk just as it does through a fiber optic cable. Physicist Nolwenn Huby of the Institut de Physique de Rennes in France recently demonstrated silk fibers in a small photonic chip (which uses light instead of electricity to relay

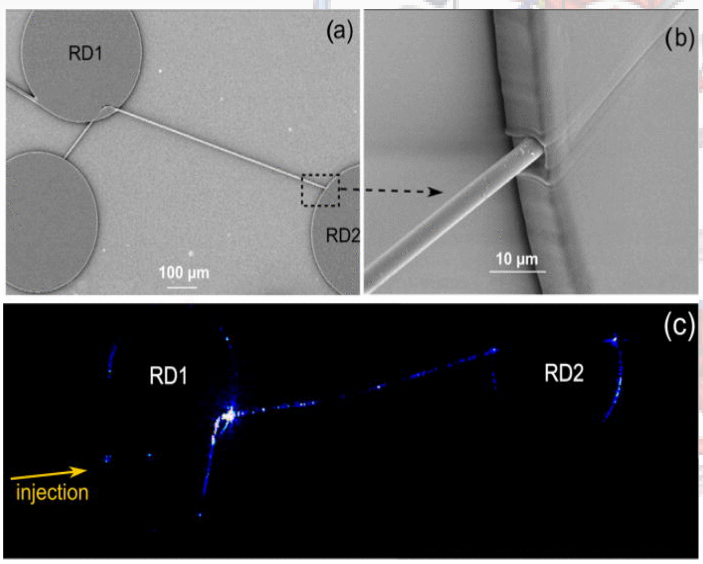
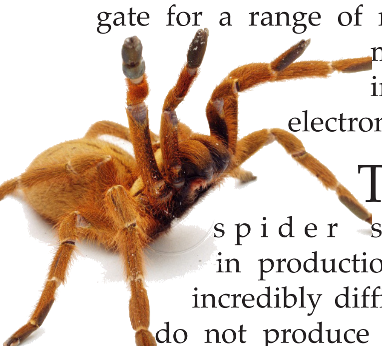


Fig. 2. Physicist Nolwenn Huby of the Institut de Physique de Rennes in France recently demonstrated silk fibers in a small photonic chip. Light propagates along strands of spider silk just like fiber optic cables.

information). Although the silk fibers had brightness losses much higher than glass or plastic, they are much thinner than conventional fibers while maintaining strength and flexibility. Plus, tiny glass cables and metals wires are expensive and not very compatible with human tissue. Silk’s biocompatibility opens the gate for a range of medical applications including minimally invasive internal imaging or even implanted electronics (Huby, 2013).



The current problem with using spider silk-based material lies mainly in production. Farming spiders would be incredibly difficult for obvious reasons: they do not produce a lot of silk, like to eat each other, and aren’t necessarily easy to handle. For example, it took over 4 years and a million golden orb spiders to produce only an 11ft by 4ft tapestry now hanging in the American Natural History Museum (Legget, 2009). One current approach uses genetic engineering in which the spider genes responsible for producing silk are placed in other more easily controlled organisms with more efficient protein production. So called recombinant spider silk proteins have been produced in bacteria, yeast, and plant systems with limited success. The complexity and size of the genes have made expression in bacterial systems nearly impossible (Romer, 2008). Research continued with eukaryotic cells such as yeast which manufactured the desired proteins but posed problems for purification and extraction in a useful form. Similar problems were encountered with plants (such as potato or tobacco) which are particularly attractive for larger scale production. Production in mammalian cells is the subject of current research. A study employed bovine mammary cells and baby hamster kidney cells as expression systems with some success (Lazarus, 2002). The researchers successfully spun these proteins into fibers. However, the highest tenacity value (tenacity is the strength of a fiber) obtained was 2.26. This is much lower than the reported values for dragline silk (7 to 11).

Canadian company Nexia Biotechnologies continued the use of mammalian cells for silk protein expression. Scientists removed the genes that encodes dragline silk from an orb-weaver spider and placed them into the DNA responsible for milk production in the udders of goats. The altered genes were then inserted into an egg and implanted into a mother goat (the process used in mammalian cloning). It was thought that the manner in which mammary glands create long amino acid chains found in milk would enable the formation of spider silk proteins. Nexia then precipitated the proteins from the milk, creating a web-like material trademarked as BioSteel (Mansoorian, 2006). Although this technique initially produced promising results, the concentration of soluble protein in the milk was found to be low and the proteins could not be efficiently purified for thorough analysis. Although the company went bankrupt, Professor Randy Lewis at Utah State University, has continued research with the so-called “spider goats” at a university-run farm (Romer, 2008).

Spider silk technology is still in the very early stages and it may be decades before it enters into the lives of the average consumer. However, the future is bright considering dozens of universities and labs are focusing their efforts on unraveling the secrets of nature’s toughest fiber.

References

Agnarsson, I., Dhinojwala, A., Sahni, V., Blackledge, TA. (2009). Spider silk as a novel high performance biomimetic muscle driven by humidity. Journal of Experimental Biology, 21. 1990-1994. doi: 10.1242/jeb.028282.

Agnarsson, I., Kuntner, M., Blackledge, T. (2010) Bioprospecting Finds the Toughest Biological Material: Extraordinary Silk from a Giant Riverine Orb Spider. PLoS ONE, 5. Retrieved from http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0011234.

Bryan, M., Forster J. (2012). A2 4 Doing Whatever a Spider Can. Journal of Physics Special Topics, 10. 1-2. Retrieved from https://physics.le.ac.uk/journals/index.php/pst/article/view/548/354.

Gosline, J., DeMont, E., Denny, M. (1986). The Structure and Properties of Spider Silk. Endeavour, 10. 37-43. doi: http://dx.doi.org/10.1016/0160-9327(86)90049-9.

Huby, N., Vie, V., Renault, A. (2013). Native spider silk as a biological optical fiber. Appl. Phys. Lett. 102. http://dx.doi.org/10.1063/1.4798552.

Keten, S., Buehler, M. J. (2010). Nanostructure and molecular mechanics of spider dragline silk protein assemblies. Journal of The Royal Society Interface. Retrieved from http://hdl.handle.net/1721.1/61713.

Lazaris, A., Arcidiacono, S., Huang, Y., Zhou, JF., Duguay, F., Chretien, N. (2002). Spider silk fibers spun from soluble recombinant silk produced in mammalian cells. Science, 295. 472-476. doi: 10.1126/science.1065780.

Legget, H. (2009) 1 Million Spiders Make Golden Silk for Rare Cloth. Wired. Retrieved from
http://www.wired.com/wiredscience/2009/09/spider-silk/.

Mansoorian, A. (2006). Comparing Problem Solving in Nature and TRIZ. The TRIZ Journal. Retrieved from http://www.triz-journal.com/archives/2007/04/04/.

Purves, W. (2003). Why is Spider Silk So Strong?. Scientific American. Retrieved from http://www.scientificamerican.com/article.cfm?id=why-is-spider-silk-so-str.

Römer, L., Scheibel, T. (2008). The elaborate structure of spider silk. Prion, 2. 154-161. Retrieved from http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2658765/.

Shao, Z., Vollrath, F. (2002). Surprising strength of silkworm silk. Nature, 418. 741.
doi:10.1038/418741a.

Image Source

http://www.flickr.com/photos/aviansky/10907613954/

http://www.sandstormreptiles.com/#!invertabrates/c1bbt

http://d3gtl9l2a4fn1j.cloudfront.net/t/p/original/waZqriYTuBE3WqXI3SDGi3kfDQE.jpg

http://pbmo.files.wordpress.com/2011/03/spider-silk-protein.png