Nonlinear behavior of silk minimizes damage and begets spider web robustness from the molecules up

*Markus J. Buehler**

**Laboratory for Atomistic and Molecular Mechanics, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

E-mail: mbuehler@MIT.EDU

Nature presents an array of materials to provide selective means for a multitude of functions. The elasticity of blood vessels, the toughness of bone or the protection of nacre illustrate the apropos of Nature's material selection. The behavior of spider silk and webs, ranging from its protein sequence to spiral geometry, have intrigued scientists as a highly adapted natural system, well-known for its exemplary mechanical properties and enhanced toughness. How the role of silk's material behavior, architecture, as well as its failure properties, together serve to benefit the integrity of a spider web formation, however, remains unknown. Here we show using a combined multiscale modeling and experimental approach that the nonlinear material behavior of silk fibers, softening at the yield point to dramatically stiffen at large deformation until point of failure, is what allows for localization of deformation upon loading, and is precisely what makes spider webs robust and extremely resistant to defects, as compared to other linear-elastic or elastic-plastic softening materials. Through *in situ* experiments on webs of a European garden spider, we confirm that locally applied loading results in minimal damage. We further show that under global loads such as wind, the material behavior of silk under small-deformation is key to maintaining the web's structural integrity. The superior functionality of silk in web-like structures is therefore not merely due to the exceptional ultimate strength and strain of the material, but is more importantly based on the nonlinear behavior and architectural formation of silk in webs. Our work unveils a material design strategy that enables silk to achieve superior material properties despite its simple and structurally inferior material constituents. Exploiting this concept could lead to a novel biomaterials design paradigm, where enhanced functionality is not achieved using complex building blocks but rather through the utilization of universal repetitive constitutive elements arranged in hierarchical structures that range from the atomistic scale to macroscopic scale. We present general approaches towards the design of adaptable, mutable and active materials that rely on simple, abundant and cheap building blocks to realize highly functional materials.