

Complex Web Construction: A Possible Clue to Mechanical Properties

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Collaboration among academia, industry, and public education can develop state-of-the-art classroom curricula and real research opportunities for students that were heretofore unavailable in public schools.

National initiatives have focused on enhancing the quality of education in Science, Technology, Engineering, and Math (STEM). Massachusetts recently enhanced and adopted new Science and Technology/Engineering Standards based on the national Next Generation Science Standards (NGSS) and placed emphasis on concepts and experience over the more traditional content-based curricula [1].

Materials science has risen to prominence in these standards and students are expected to understand the structure and mechanical properties including strength, stiffness, and response to existence of defects of various materials they encounter in both the natural and human-designed worlds at the macro- meso- and micro-scale as well as understand the dynamic process of how they will respond to forces acting on them. Moreover, these concepts will be incorporated in the comprehensive Science, Technology/Engineering (STE) exam–MCAS–required of all Massachusetts eighth graders by 2018. Unfortunately, most communities are unable or are ill-equipped to provide and support the advanced technology needed to permit middle school students to conduct research into the dynamics of material systems.

Collaborative outreach among academic institutions, and vendors of advanced instruments can offer substantial benefit to public schools. Presented here in poster format are the preliminary results of an investigation conducted by seven middle school students into the mechanical properties of spider webs being studied at MIT's Laboratory for Atomistic and Molecular Mechanics (LAMM) using images and technology provided by JEOL, USA. This program was conducted as part of ongoing cooperative outreach among MIT DCEE, LAMM, JEOL USA, and Concord Middle School.

The audience is the middle school introductory engineering student and the poster is intended to summarize student research efforts. Their investigation stems from an observation by Dr. Qin of an unusual repeating pattern in the web of a spider living at MIT. The student study is correlated with and conducted in conjunction with ongoing research by scientists, post docs, graduate students, and visitors at MIT's Laboratory.

This poster begins with a naturally occurring web that consists of rays that emanate from the center and attach the web to its support structure. These lines are in tension and support the dead, live, and environmental loads. Chords or cross threads link the rays to form a familiar net-like web. An optical micrograph presents a web segment made by a "sheet web" producing spider of the Araneidae family harvested at MIT. Micrographic enhancements, provided by JEOL, reveal a unique pattern in which rays of web are connected by chords that helically wrap each ray. At 1000x the complexity of junctions between ray and chord is revealed.

The goal of the investigation was to determine whether the helically wrapped chords in frames 2, 3, and 4 provided any mechanical advantage when it comes to managing normal tensile forces acting on the web. The coiling structure at the junction is geometrically so complex that it could not be printed by a 3D printer and studied as had been done by the collaborators [2], [3]. This offers good motivation to conduct the investigation with the current strategy.

Students evaluated several materials and selected polyester sewing thread to serve as an analogue for spider silk. Prototype looms were 3D printed and an open-sided octagonal design was selected (frame 5). The design allows for weaving the web so as to stress along the radial (Y) axis, the chord (X) axis, or diagonally [X-Y axis]. A vertical test apparatus was assembled to support the loom with the unattached member oriented downward so the web could be stressed by the addition of weight (Frame 6).


Preliminary results indicate the spider's design may not support any more weight than the "Control" weave and that the overall strength is determined by the number of load bearing threads (Frame 7). The data do suggest that the spider's weave distributes the load over several threads and may enhance the load bearing capacity of the X, Y, and X-Y (diagonal) orientations (Frame 8). The weave also appears to provide a level of resilience to the web that is greater

than that of the control (Frame 9). Moreover, we feel our data are consistent with findings of other researchers in the Laboratory [4], [5], [6] but warrant further study. Future investigations may focus on enhancing robustness of the apparatus and precision of the protocol.

In addition to reinforcing concepts developed during research, this activity dramatically demonstrates the links among public school learning, academic research, and the private sector that supports them.


References:

[1] Massachusetts Department of Elementary and Secondary Education, Revised Science and Technology/Engineering Standards, (January, 2016).
 [2] Zhao Qin, Brett G. Compton, Jennifer A. Lewis & Markus J. Buehler "Structural optimization of 3D-printed synthetic spider webs for high strength", Nature Communications, 2015
 [3] Zhao Qin, Markus J. Buehler "Spider silk: Webs measure up", Nature materials, 2013
 [4] S.W. Cranford, A. Tarakanova, N. Pugno, M.J. Buehler, "Nonlinear material behaviour of spider silk yields robust webs," *Nature*, Vol. 482, pp. 72-76, 2012
 [5] N. Pugno, S. Cranford, M.J. Buehler, "Synergetic material and structure optimization yields strong and robust spider web anchorages," *Small*, Vol. 9(16), pp. 2747-2756, 2013
 [6] Anna Tarakanova, Markus J. Buehler "The role of capture spiral silk properties in the diversification of orb webs", J. R. Soc. Interface, 2012




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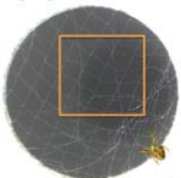


Forces Acting on Natural Webs



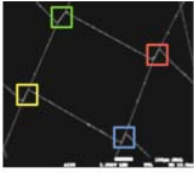
Spider webs consist of rays that emanate from the center and anchor to supporting structures and chords that tie rays together at a constant distance to form a net-like structure. All members of the web are in tension with little or no compressive force acting on them.

Intriguing Web Harvested at MIT



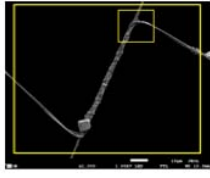
This investigation began as LAMM scientists noticed a ragged texture in the web and an expanded junction between the rays and chords. This appears to be a "sheet web" generated by a member of the Araneidae family

100X Enlargement



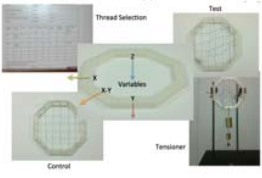
This enlargement provided by JEOL reveals a consistent pattern in which the spider crossed from ray to ray and reinforced the junction by joining the threads for approximately 50 microns before moving to the next ray

Wrapping and Cementing



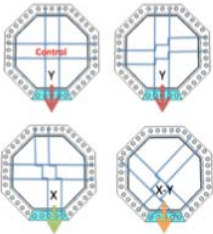
Enhanced magnification show consistent right-hand wrapping of the chord thread around the ray with some inclusions. This observation raised the question of the possible mechanical advantage to the stability and function of the overlap

Experimental Apparatus



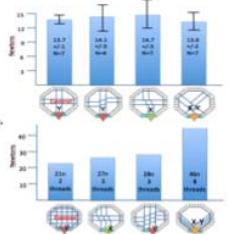
Students evaluated several materials and experimental designs to assess the tensile advantage of the spider's web. An octagonal loom was 3D printed allowing tension to be applied to create failure. Depending on the orientation of the weave, tension could be drawn along the rays (Y), chords (X), or diagonally (X-Y). Pictured here are the loom, test weave, and control (tennis racket) weave

Experimental Design



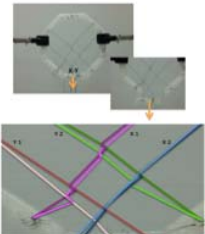
Threads in the control weren't wrapped so pulling on the Y threads shouldn't have much impact. Pulling on the X threads would have a lot of impact on the Y. And, pulling on the diagonal X-Y - one of each - should impact all of them. Or so we thought.

Findings - Strength



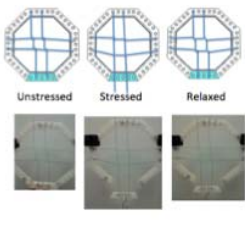
Initial trials showed the web might be strongest in the diagonal direction. After reviewing the design we found that the strength correlates with the number of threads being pulled and not the direction.

Findings - Force Distribution



Preliminary indications show that the "chord wrapping" technique observed in the MIT web results in distribution of tensile forces over a larger number of threads.

Findings - Resilience



The web design is resilient and able to reform after a tensile force is relaxed. When the X threads are stressed, the cross-over joints rotate in the direction of the tension then revert back when the force is relaxed. This is independent of any elastic property of the thread.

Conclusions and Future Investigation

Based on our preliminary activity, we feel the web pattern displays two advantages over "conventional" webs:

- It distributes forces over several threads giving the web the ability to mitigate the impact of some forces
- Increases resilience of the web independently of the elastic properties of the thread
- It does not make the web stronger but strength increases as the number of threads under tension increases


Areas for Improvement


- Incorporate a Force Table into the research to quantify the geometry of deflection and changes in force
- Improve the loom to allow consistent tension in webs

Future Investigations


- Redesign the experiment to test multiple (more than 2) threads
- Design a method to measure the resilience more accurately

Biological materials such as spider webs display unique mechanical properties that can be emulated to develop useful synthetic materials as well as fabrication processes.





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