

## Complex Web Construction: Additional Clues to Mechanical Properties—An Investigation by Middle School Students in Collaboration with MIT and JEOL, USA

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Continuing, multi-year, collaboration among academia, industry, and public education has developed state-of-the-art classroom curricula and real research opportunities for students that were heretofore unavailable in public schools.

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 a continuing investigation conducted by ten middle school students into the mechanical properties of spider webs being studied at MIT's Laboratory for Atomistic and Molecular Mechanics (LAMM). Students began with images and technology provided by JEOL, USA for MIT and this program was conducted as part of ongoing cooperative outreach among MIT DCEE, LAMM, JEOL USA, and Concord Middle School.

This poster begins with a photo of naturally occurring web of a well-fed Orb Weaver (frame 1) that consists of rays emanating from the center that 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 (frame 2) presents a web segment made by a "sheet web" producing spider of the *Araneidae* family harvested at MIT. Micrographic enhancements, provided by JEOL, (frames 3, 4, and 5) 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 3, 4, and 5 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 [1], [2]. This offers good motivation to conduct the investigation with the current strategy.

Students evaluated several materials and selected polyester sewing thread, monofilament fishing line, and packaging cord, to serve as analogues for spider silk. Prototype webs were hand woven (frame 6) along with other means for comparison. The design allows for weaving the webs so as to stress them along the radial (Y) axis, the chord (X) axis, and across (normal to) the X-Y plane [Z-axis]. Horizontal force tables and other apparatus were assembled to support the investigation.


Preliminary results indicate the *Araneidae* design may not support any more weight than the "Control" weave but that the design may have the ability to mechanically absorb force in conjunction with the elastic properties of the silk (Frames 7 & 8). The data suggest that the spider's weave distributes the load

over several threads and may enhance the load bearing capacity in the X, Y, and Z directions (Frame 9). The weave also appears to provide a level of resilience to the web that is greater than that of the control (Frame 8). Moreover, we feel our data are consistent with findings of other researchers in the Laboratory and elsewhere but warrant further study [3], [4], [5], [6]. 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 [7].


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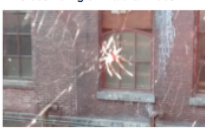
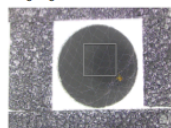


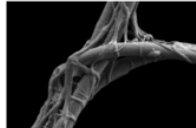
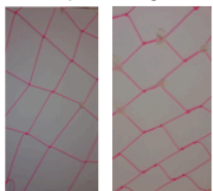
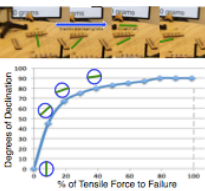
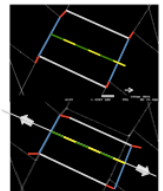
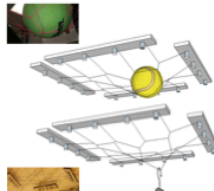
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<p><b>Forces Acting on Natural Webs</b></p>  <p>Spider are ubiquitous and known for consuming insects and other creatures around the world. Their webs consist of rays and crossing chords. Rays emanate from the center and anchor to supporting structures while chords that tie the rays together. All members of the web are in tension and handle intrusive forces from all directions. Shown here is an Orb Weaver and its web.</p>	<p><b>Intriguing Web Harvested at MIT</b></p>  <p>This investigation follows earlier work of middle school students in MIT's LAMM who noticed a ragged texture in the web spun by a member of the Araneidae family. It included expanded junctions between the rays and chords. The initial question was whether the configuration offers any mechanical advantage in addressing external forces.</p>	<p><b>100X Enlargement</b></p>  <p>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. The overlapping portions range from 50 to 90 microns; approximately 10-15% of the size of each cell.</p>	<p><b>Wrapping and Cementing</b></p>  <p>Enhanced magnification shows consistent right-hand wrapping of the chord thread around the ray with some inclusions. This appears to form a tightly bound and possibly stiffer segment of the web whose elastic properties may vary from those of the thinner threads.</p>	<p><b>Experimental Apparatus</b></p>  <p>At 10,000X, the cross-over junction is shown to be a complex of multiple fibers and reinforcing "glue." Students hypothesize that these junctions function as mechanical fulcrums between the stiffer and more flexible components of the web. The complexity of these joints make it impossible to replicate synthetic analogs using a 3D printer.</p>
<p><b>Experimental Design</b></p>  <p>Students hand wove webs in patterns displayed by Orb Weavers (above) and MIT's Araneidae using a variety of material including package twine, monofilament line, sewing thread, and jewelry wire. All were tested to failure under tension in X-Y plane and along the Z axis.</p>	<p><b>Findings – Force Distribution</b></p>  <p>By using a "strike" line to highlight the overlapping joint on sequential frames of X-Y and Z-axis tensioning, we tried to correlate the declination with the force to failure. At 9% (0.9n), the joint had shifted 45° and lengthened the cell by around 8%.</p>	<p><b>Findings – Mechanical Change</b></p>  <p>Preliminary indications show that, assuming no elasticity in the silk, the web could lengthen (and contract) elastically more than 10% in response to linear force.</p>	<p><b>Findings – Z-Axis</b></p>  <p>Preliminary work conducted in 2016 and currently ongoing suggest that the web distributes forces over a number of threads by mechanically deforming adjacent cells as well as by absorbing energy through the elasticity of their silk.</p>	<p><b>Conclusions and Future Investigation</b></p> <p>Based on our preliminary activity, we feel the Araneidae web pattern displays two advantages over "conventional" webs:</p> <ul style="list-style-type: none"> <li>• It distributes forces over several threads giving the web the ability to mitigate the impact of some forces.</li> <li>• Increases resilience of the web independently of the elastic properties of the thread.</li> <li>• It does not make the web stronger but strength increases as the number of threads under tension increases.</li> </ul> <p><b>Areas for Improvement</b></p> <ul style="list-style-type: none"> <li>• Develop more quantitative methods to enhance the accuracy and precision of investigations.</li> <li>• Improve the apparatus to allow consistent tension in webs.</li> </ul> <p><b>Future Investigations</b></p> <ul style="list-style-type: none"> <li>• Design a realistic test by which we can document and measure the impact of an object (prect) on a web.</li> <li>• Design a method to measure the resilience more accurately.</li> </ul> <p>Biological materials such as spider webs display unique mechanical properties that can be emulated to develop useful synthetic materials as well as fabrication processes.</p>



Laboratory for Atomistic and Molecular Mechanics



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