Learning from Nature: Design of Lightweight Structures

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Abstract

Architects' recent interest in natural structures has relied heavily on the abstractions of natural geometry, often overlooking crucial issues such as scale and function. In this paper, a study is presented of structural concepts from the design of a spider web. In particular, focus is placed on the design and performance of webs in high wind. As the result of evolution, spiders modify the construction of their webs in such conditions to better withstand loads and to meet the essential requirement of lightness. This natural lightweight structure offers immediate possibilities for architects and engineers which go beyond mere analogy of form.

Introduction

Why study nature? Nature can provide architects and engineers with an endless array of concepts for buildings. Natural selection has ensured that natural structures have efficient forms, employ smart materials and have minimum energy construction. If beauty is defined not only by a visual aesthetic but also by good engineering, then spider webs are beautiful. They are a far cry from the rectilinear structures which seem to plague human designers.

How is lightness achieved in nature? And what can architects and engineers learn from Nature? In the case of a spider web, lightness is achieved by a tension-only structure made of a very strong material (spiders' silk) with intelligent geometry for the function and environment which it was designed. Rather than conceptualizing a building and its environment as distinct entities, natural structures are inseparable from their environment. Sea shells are designed to withstand hydraulic pressure, bones (compression elements) are designed to work in conjunction with tendons and muscles (tension elements), spider webs are designed for environments with air-borne insects. As it would be impossible to find a jellyfish functioning as intended on land, it would be equally bizarre to find a natural form scaled up to many times its natural size and functioning like a building structure.

Spider Webs as Natural Lightweight Structures

The silk of spiders first emerged 400 million years ago and orb-webs existed as long as 180 million years ago. Present day spiders' webs are structures efficiently engineered by nature.

An orb-web of a cross spider has the primary function of capturing fast-moving and, on a relative scale, massive insects while resisting gusts of wind. The web is mainly composed of two types of thread. There is a framework of dry radial, frame and mooring threads upon which is laid a single glue-covered capture spiral (figure 1). The stiff radial threads have strain-rate related (viscoelastic) properties and the pliant capture spirals function essentially independently from time.

Webs are build with north-south symmetry to fulfill a functional requirement: as spiders typically sit at a web's hub, such a design allows equal access to all sectors of the web. Gravity ensures that spiders travel faster down a web than up. Measurements on real webs reveal that the stiff radial, frame and mooring threads are pre-tensioned and form the primary structural elements of a web. The much less-stiff spiral threads form the secondary structure. Nature balances this trade-off in windy environments by design changes.

Design Innovations Found Within the Design of a Spider Web

Viscoelasticity and Strength of Silk: Silk of an orb-web spider is a biopolymer stronger than mild steel (breaking stress 1300 MPa) and can absorb up to 100 times the energy required to snap steel. In addition, the silk is viscoelastic which means it is sensitive to the rate at which loads are applied: loads applied quickly to a web are countered by larger resisting forces than those applied slowly. The advantage of such a material is that it reduces the amount of prestressing required in an in-situ web and dynamically dissipate energy (similar to a shock absorber).

Windlass Mechanisms: The capture spiral is coated with a hygroscopic glue which absorbs moisture from the atmosphere forming a cylinder of water of growing diameter around the thread. When the cylinder reaches a critical diameter, it breaks into a more stable configuration - a string of droplets (figure 2). The droplets act as "windlass" mechanisms driven by surface tension to reel in and out the thread under loading. The result is a thread that can contract up to 5% of its original length without sagging. This important feature in web design minimizes the formation of holes caused by the sticking together of threads as the tree branches to which the web may be attached, sway in the wind.

Air Resistance: Air resistance of threads plays a very important role in the functioning of a web. It is responsible for dissipating a large portion of the energy of motion (kinetic) of an impacting insect. The spider webs are designed to take advantage of aerodynamic damping How much air resistance could a thread about 1 micron in diameter have? At the scale of a web, quiet a lot. At the microscopic scale of an orb-web, the air flow through a web falls into a particular region of laminar flow with a low Reynold's number. The surprising result is that for this type of flow, the drag is proportional to the thread's length and velocity through the air, but is independent of its diameter. Significantly, when the direction of wind is other than normal to the axis of the thread, the parallel component of drag is negligible. Thus, the architecture of a web takes advantage of aerodynamic damping by providing a fine planar net that covers a large area, but with no penalty for using very fine threads. However, the trade-off is that a web designed with aerodynamic drag improves prey capture, but carries with it an increased risk of destruction by wind (figure 3).

Deformation of Spirals: Contrary to intuition, it can be shown that a thread that bows in the wind always exerts less force on the web than when it is straight, although the former has a longer length (see Appendix. This can be explained by considering the parallel and normal components of air resistance on a thread. It is not accidental that the main contributors of drag forces to a web, the spirals, also exhibit a large degree of deformation under wind loads due to their relatively small stiffness. This appears to explain the evolution of two types of silk in the construction of a web - one for the main structural threads and another for the spirals.

Web Design in Windy Environments

Orb webs are modified for windy environments. It has been shown that webs built in a wind tunnel displayed some curious design modifications. The most significant of these changes affects web geometry. Such webs are designed with slightly stiffer silk threads, smaller capture areas, a shorter total length of silk to minimize drag, and highly asymmetrical mooring (i.e. guy) threads (figure 4). As the top radial threads are usually the first to snap because of the north/south symmetry typical in all webs, asymmetric rotation of the capture area limits the tension in these threads. The net effect of these alterations in the web design is the ability to withstand higher wind velocities before the onset of structural failure. The equivalent for a man-made structure is lower tensile forces in cables, thus lighter members, for a given wind speed. To further reduce drag, webs are sometimes oriented at an angle to the principle direction of wind for a site. This requires maintaining a delicate balance between maximizing the harvest of wind-borne prey and the risk of having the web blow away in the wind. Web loss is serious for a spider as the web in normally eaten to recycle the silk.

Lessons for Architects and Engineers

1) Study of spider webs illustrates the fallacy of literal abstraction of the geometry of a natural structure by designers. Webs are designed for impact loading and function only at the scale for which they exist (particularly in relation to wind and glue droplets). This is also true for the skeleton of dinosaurs, wings of birds, and sea shells. Copying their forms at a much larger scale for roof structures will not lead to the same efficiency of design as found in the original organisms. However, that does not mean architects and engineers cannot learn lessons from nature. A more sound approach is to understand how and for what is their function? Any intelligent building design which draws upon concepts from nature need not look identical to the natural structure which gave the designers inspiration, but requires only a thorough understanding of its (bio)mechanics. For this task, structural engineers are better equipped to take the lead and educate architects.

2) Viscoelastic materials, as already used in earthquake engineering in the form of viscous dampers, could be effectively employed in building design to minimize deformations due to wind. In addition, structures could be actively designed for deflections, rather than merely limiting them to an acceptable criteria. This pro-active approach, as seen often in nature, allows structures to respond actively to loads as necessary. Economy of material and lightness could be achieved by more interactive materials and geometry. This has already been achieved in design of the Pavilion of the Future in Seville by Martorell, Bohigas, Mackay and the late Peter Rice, where restoring forces are activated by deformations.

3) Natural structures are always designed for a particular context. Although architects are already sensitive to designing their buildings in relation to their surroundings, this can be taken a step further with architects designing for environmental factors such as principle direction of wind. Intelligent orientation of buildings and designing geometric shapes with respect to the physical environment could greatly reduce loads, leading to lighter structures.

4) Finally, if spiders could design fabric roofs for windy environments, studies suggest that they would probably design many small canopies to cover a space instead of a single large one.

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Appendix: Force Reduction with a Bowed Thread

Assume a single horizontal thread is held at both ends. It is initially straight of length $2 \cdot x$, but without a prestress force. When a wind load of magnitude w (force per unit length) is applied perpendicular to the axis of the thread, the thread sags downward. At each support, the tangent of the deformed thread makes the angle θ with the horizontal axis. F is the horizontal reaction force at each support (or the force exerted by the thread on the rest of the web in wind). We assume that the tension is constant throughout the thread and that wind only makes a contribution normal to the axis of the thread. By taking a free body diagram of a short increment of thread and summing forces in both directions, we can show that the ratio of forces on the support to the original wind force equals:

$$\frac{2 \cdot F}{2 \cdot w \cdot x} = \frac{\sin \theta}{\theta}$$

This ratio approaches unity when the thread does not sag (θ = 0). For a very large sag (as $\theta \to \pi/2$), the ratio approaches its limit of $2/\pi$. Therefore, increased bowing in a thread lead to a greater reduction in the forces applied to the web.

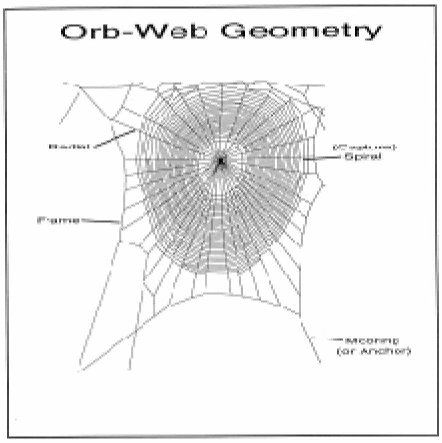

Figure 1

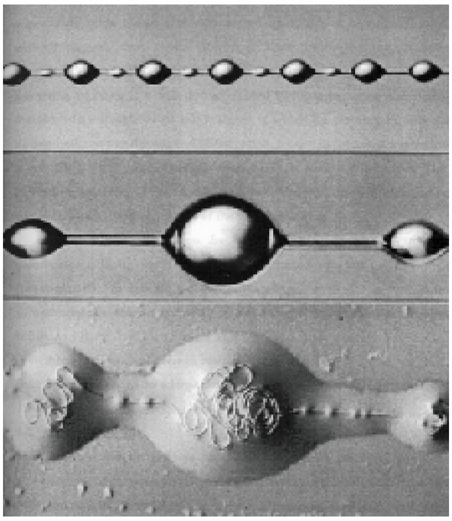

Figure 2: Spiral Thread

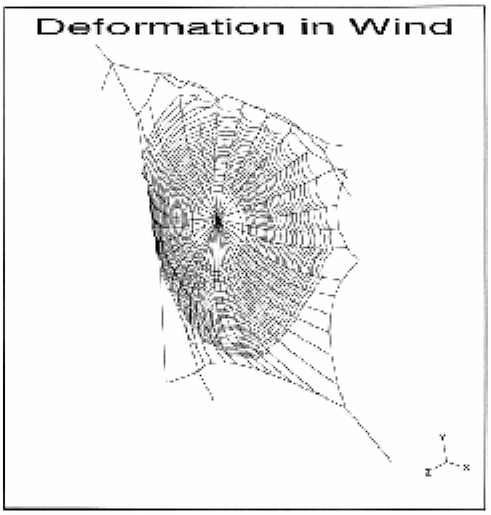

Figure 3

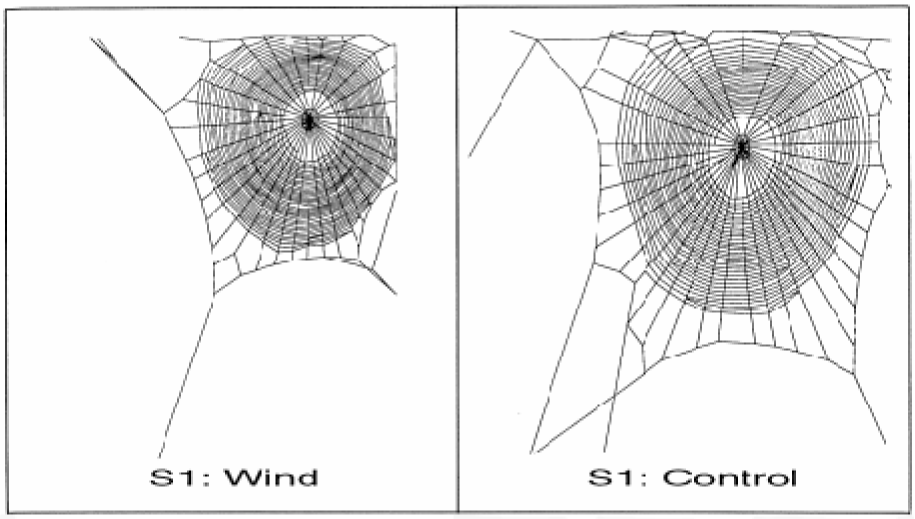

Figure 4