Gardeners tend their plants to produce a beautiful display in the garden or to harvest fruits and vegetables. Botanists study the anatomy, life cycles, and evolution of plants. Engineers, too, are interested in plants, although from a different perspective. Historically, engineers have been interested primarily in wood, because of its widespread use in everything from furniture to boats to buildings. But more recently, engineers have recognized that plants are very effective at resisting the loads they are subjected to (for instance, from the wind or from their own weight). Today, engineers study plants to learn what features make them so effective mechanically, with a view towards “bio-inspired design” of engineering materials and structures that exploit these features. In this article, I will take you for a walk through the Arboretum and describe a variety of plants and how they work from an engineering perspective.

**THE TOUR BEGINS**

Across from the Hunnewell Visitor Center, east of Meadow Road, lies the Meadow, a marshy area largely filled with cattails (*Typha* spp.). The leaves stand close to vertical and reach an impressive height, often over 6 feet tall. As you walk past, you can see the leaves bend in the wind; occasionally, a sparrow or red-winged black bird lands on the stem or its fuzzy, cylindrical seed head and bends that over, too. If you look at the leaves up close, you can see that they have fibers running along their length; if you draw your thumbnail across the width of the leaf you can feel the ridges of the fibers. How do the long, thin leaves stand up so tall?

A look at the cross section of a cattail leaf reveals the answer. The cross section shows two outer faces connected by a number of ribs. At the very outer top and bottom surfaces, you
The Mechanics of Bending

PLANT LEAVES and stems, as well as tree trunks and branches, typically bend, either from the wind or from their own weight. If we look at a bent rubber beam on which we have marked a rectangular grid, we can see that the vertical lines rotate about the middle of the beam when it is bent. The horizontal lines on the top half of the beam get shorter and shorter the further they are away from the middle of the beam and, correspondingly, the horizontal lines on the bottom half of the beam get longer and longer the further they are away from the middle of the beam. The top half of the beam is in compression (pushing) while the bottom half is in tension (pulling) and the very middle sees no internal force at all. The material at the top and bottom surface of the beam is the most compressed or stretched, and sees the highest internal loads. The outer faces of the cattail leaves and the dense fibers at the top and bottom of the cross section of iris leaves resist the high internal loads at the outermost part of the leaves.
and grasses. A cross-sectional view of an iris leaf shows that it has large dense fibers (called sclerenchyma) at the outer surface and a thick inner layer of foamlike cells (called parenchyma). When the leaf is bent, the dense fibers carry most of the high internal loads at the outside of the leaf. The separation of the denser, stiffer fibers by the inner foamlike layer increases the resistance of the iris leaf to bending. Engineers make use of the same concept (a “sandwich structure”) in the design of downhill skis, lightweight panels for aircraft, and the blades of windmills, which often have two outer skins of carbon-fiber-reinforced plastic separated by a foam (or sometimes an engineering honeycomb) core.

**SUPPORTING ACT**

If we walk back towards the Arborway Gate and look along Willow Path, we see the huge leaves of the butterbur (*Petasites japonicus*). How does the stem support such large leaves without falling over? The stem bends under the weight of the leaf and from wind acting on the leaf. The stem is roughly circular in cross sec-
Butterbur leafstalks must support very large leaves (often 2 feet or more in diameter).

Cross section of a butterbur leafstalk.

Bending stresses in plant stems require an arrangement, so that it can resist bending in any direction equally. If we look at a cross section of the stem in a scanning electron microscope, we see that it has a dense outer layer surrounding an inner foamlike layer of cells that are reinforced with bundles of fibers. At the center of the stem is a void. This combination of foamlike cells surrounded by a thin, denser outer layer is common in plant stems and is often called a “core–rind” structure. The dense outer layer resists most of the internal loads from bending on the stem, which are highest at the outer extremity of the stem. The inner foamlike core also plays a role: it helps resist kinking of the stem. The dense outer cylindrical shell of the stem is a little like a drinking straw. When a straw is sufficiently bent, it tends to fail by forming a crease or kink in the middle. If the drinking straw is filled with foam and then bent, the foam pushes back against the kinking, increasing the straw’s resistance to this type of failure (see photos on page 13, lower right). The interior foamlike cells in the butterbur stem also help resist kinking by pushing back against the outer layer if it tends to kink inwards.

Slightly further along Meadow Road we pass by the cork trees (*Phellodendron* spp.) with their thick, deeply grooved bark. If you press your thumbnail into the bark you’ll notice that it is quite soft and springy. Cork stoppers, such as those used in wine bottles, come from the bark of a different tree, however: the cork oak, *Quercus suber*, that grows in Mediterranean climates, particularly in Portugal and Spain. Remarkably, unlike most other trees, after the
bark of the cork oak is removed, it regrows, allowing harvesting of cork every 10 to 15 years. The cork cells are like little bellows: they are roughly box-shaped, but with corrugations running in one direction. When you compress the cork in the direction of the corrugations, they simply fold up, like a bellows, so that they do not expand in the lateral direction. This feature of cork is one reason cork works well at stoppering bottles. A rubber stopper, on the other hand, bulges out laterally when compressed, making it difficult to press into a bottle; for this reason, rubber bottle stoppers are always tapered.

**TREES = WOOD**

When we think of the Arnold Arboretum, we think of trees. And when engineers think of trees, they inevitably think of wood. Wood is one of the structural materials used for the longest time in human history and is still one of the most widely used. The oldest known wooden boat is Cheops’s 4,600 year old barge, found dismantled in a pit next to the Great Pyramid in Egypt. In the late 1600s, eastern white pines (*Pinus strobus*) from New England were a strategic resource for the British Royal Navy. The tall, straight trunks of the pines were used as masts for ships; the taller the mast, the more sail area, the larger the ship, and the more cannons it could carry. And most houses in North America are still wood framed.

North American woods are divided into hardwoods (deciduous trees that drop their broad leaves annually) and softwoods (conifers with needles that are typically, but not always, evergreen). While hardwoods tend to be denser and harder than softwoods, that is not always the case: for example, Douglas fir, a softwood,
longitudinally along the trunk and branches of the tree.

Walking across the grass towards Valley Road, we next come to the Conifer Path, with its hemlocks, pines, spruces, and firs. Softwoods have two types of cells: tracheids, which make up the bulk of the cells and provide structural support and conduct fluids (via small holes called pits along their sides), and rays, which again store sugars.

To a first approximation, the structure of both hardwoods and softwoods resembles a honeycomb, with roughly square, instead of hexagonal, prismatic cells. Forces applied to wood are largely carried by the fibers in hardwoods and by the tracheids in softwoods. Since these wood cells resemble an elongated honeycomb, the mechanical properties of woods can be modeled, to a first approximation, as a simple honeycomb with identical cells. It is well known that the stiffness and strength of woods are much higher along the grain than across the grain; the reason for this can be explained by modeling the wood cells as a honeycomb.

When a model honeycomb is loaded in compression (pushing) along the length of the cells (along the prism axis), the cell walls simply compress, and the stiffness and strength just depend on the amount of material in the cross section, or the fraction of the area that is solid. Wood cells loaded along the grain in compression also simply shorten axially, just like the honeycomb model. Using the honeycomb model, we see that the stiffness and strength of wood along the grain, too, depend on the fraction of the area of the cross section that is solid; for prismatic cells as in the honeycomb and

The tall, straight trunks of white pine were once used for ship masts.

is denser and stronger than quaking aspen, a hardwood.

Up Bussey Hill Road, past the lilac collection, and past the turnoff to Bussey Hill, we come to the shady Oak Path, with its many species of magnificent oak trees (Quercus spp.). Oaks and other hardwoods have three types of cells: fibers that provide structural support, larger diameter vessels that conduct water and sap up and down the tree, and rays that store sugars: all three are visible in the images of the cross-section and longitudinal section of oak. The fibers and vessels, which make up the bulk of the cells, run longitudinally along the trunk and branches of the tree.
Inside Plants

The distance up or down from the middle of the beam increases: the thickness of a beam plays a greater role in resisting deflection or internal loads than the width. When loaded across the grain, the wood cell walls bend, giving much lower stiffness and strength across the grain than along the grain. This effect can be analyzed in more detail to show that the stiffness of woods loaded across the grain depends on the cube of the volume fraction of solid, and the strength (loaded across the grain) depends on the square of the volume fraction of solid. This leads to the great difference in the stiffness and strength in woods when loaded along and across the grain, a difference that is greater in lower density woods, such as pine, than in high density woods, such as oak. For instance, in Eastern white pine the compressive strength of wood, this is equivalent to the fraction of the volume that is solid.

In contrast, when a model honeycomb is loaded across the cells, it is much easier to deform the honeycomb, as the cell walls bend. Wood cells loaded across the grain also bend in a manner similar to the honeycomb; this can be seen most easily in a low density wood like balsa (Ochroma pyramidale) (see upper right images on page 18).

If you take a ruler and bend it, it deforms much more than if you rest one end on a table and compress it from the opposite end with the same load. It is also less strong when bent: it is much easier to break the ruler in bending than by compressing it on end. We have already seen how, in a bent beam, the amount that the material stretches or compresses increases as the distance up or down from the middle of the beam increases: the thickness of a beam plays a greater role in resisting deflection or internal loads than the width. When loaded across the grain, the wood cell walls bend, giving much lower stiffness and strength across the grain than along the grain. This effect can be analyzed in more detail to show that the stiffness of woods loaded across the grain depends on the cube of the volume fraction of solid, and the strength (loaded across the grain) depends on the square of the volume fraction of solid. This leads to the great difference in the stiffness and strength in woods when loaded along and across the grain, a difference that is greater in lower density woods, such as pine, than in high density woods, such as oak. For instance, in Eastern white pine the compressive strength...
A rubber honeycomb model shown unloaded (top left) and, when loaded in compression from the left, with bent cell walls (bottom left). The set of four images (right) shows the same area in a piece of balsa wood under increasing load in a vice in a scanning electron microscope. The top left image (a) is unloaded, and images (b), (c), and (d) are at increasing compressive load.

along the grain is about 11 times that across the grain while in white oak the compressive strength along the grain is about 7 times that across the grain.

THE END OF THE TOUR

At the end of the Conifer Path, off to the right near Centre Street, is a group of bamboo accessions (mostly *Phyllostachys* spp.). Bamboo is a member of the grass family and is exceptionally fast-growing. Moso bamboo (*Phyllostachys edulis*), native to China, can grow 3 feet in a day and the stem, or culm, can have a 6-inch diameter. While the initial growth is remarkably fast, it takes several years for the stem to mature and fully densify and lignify. In countries where it is indigenous, it has been used traditionally for houses and other small structures.

A cross section through a bamboo culm shows vascular bundles surrounded by dense sclerenchyma tissue and separated from one another by ground tissue of low density parenchyma cells. There is a radial density gradient: towards the periphery of the culm there are more vascular bundles (and each one is denser) than at the inside surface of the culm. As we have already seen, placing dense material away from the center of a beam (where the deformation and internal loads are zero) increases the resistance of the beam to bending. Bamboo culms are
typically loaded in bending from the wind—the increase in denser material towards the outside of the cross section increases the resistance of the culm to bending deflections and loads, compared with a section with the same amount of material evenly distributed across the section.

On our walk through the Arboretum, we have seen a variety of plants with different internal structures. Plants are often mechanically efficient, using material to resist internal loads where they are greatest. Engineers studying the mechanical behavior of plants take inspiration from them for the design of engineering materials and structures.

Acknowledgements


Additional Reading


Lorna J. Gibson is the Matoula S. Salapatas Professor of Materials Science and Engineering at the Massachusetts Institute of Technology. She has lived near the Arnold Arboretum for 25 years and visits in all seasons and weather.