MAKING THE MOST OF IT

How nature turns weakness into strength

BY AIMEE CUNNINGHAM

Marc A. Meyers came up with the idea for his most recent research project on a walk with his father some 40 years ago. They were in the forest near their home in a small town in Brazil, and Meyers stopped to rest. That's when he noticed a toucan skull lying on the ground. The bird's previously bright-yellow beak had faded, he recalls, but was otherwise intact. He picked it up. "The beak was so light, yet it was reasonably strong and stiff," he says.

Another researcher likes to browse through shell shops for some of her study subjects. On one visit a few years ago, Joanna Aizenberg of Bell Laboratories in Murray Hill, N.J., came upon a type of deep-sea sponge that she had never seen before. "It was clearly, incredibly beautiful design-wise," she says. After having studied its strength in detail, she adds, "I would now say it's the most perfect design I have ever seen."

These materials scientists are not the first to be inspired by nature's engineering skill. For decades, researchers have been marveling at seashell nacre, commonly called mother-of-pearl. But as engineers continue to seek stronger, lighter, more durable materials, they are increasingly looking to examples from nature. "We develop all of these wonderful synthetic materials—metals, polymers, ceramics, composites—but we are kind of running out of ideas," says Meyers, a materials scientist at the University of California, San Diego.

Nature's design secrets are particularly valuable because organisms, unlike engineers, must make do with whatever materials are at hand. "In biological systems, resources are often limited," says Aizenberg. For example, silica and chalk, two building materials in tough sponges and seashells, aren't usually known for strength.

DESIGNER GLASS — The crisscross beams in the walls of the silica sea sponge *Euplectella aspergillum* make up one of several strength-bestowing levels of design.

A recent crop of studies, including the first to describe the structures and mechanics of the glass sea sponge *Euplectella aspergillum* and the Toco toucan's beak, exemplify how nature finds strength in unlikely places. But while such blueprints are illuminating, borrowing designs from nature to build structures from synthetic materials remains technically challenging.

Identifying the structure "is the easy part," says Meyers. "More difficult is trying to reproduce it."

GLASS HOUSE The strength of the sea sponge *E. aspergillum* impressed Aizenberg. It lives in the western Pacific Ocean as deep as 1,000 meters. The sponge consists of a thin layer of cells that coats an intricate silica, or glass, cylindrical skeleton roughly 2(centimeters long and a few cm in diameter.

"It's almost 100 percent glass, but it's very rigid," Aizenberg says. "You have to really jump on top of this glass cylinder to intro- duce some cracking, and you still won't break the whole structure."

In the July 8, 2005 *Science*, Aizenberg and her colleagues in Cal- ifornia and Germany described how the sponge's design avoid the normal brittleness of glass.

The first, visible level of design consists of vertical and hor- izontal beams that form the grid making up the cylinder's walls Every second square of that grid contains two diagonal beams and every third set of diagonal beams is thicl enough to stick out of the grid's plane. Thi three-dimensional structure prevents the cylin- der from being crushed when it's squeezed, note Aizenberg. Think of how much sturdier a sod can would be if its sides had ridges.

The researchers employed visible-light an scanning electron microscopy to dig further int the design. At the micrometer scale, they foun that each beam consists of thinner cylinder cemented together by more glass. These paral- lel bundles of cylinders are stronger than eacl cylinder alone, says Aizenberg, because if on cylinder fails, its neighbors can take up the slack

Furthermore, each thin cylinder consists c concentric rings, like tree rings, of glass glue together by an organic material. The rings ar thicker toward the center of the cylinder: Out side rings are roughly 0.2 micrometer (μm) thicl while inner rings span about 1.5 μm.

This structural characteristic is what make the sponge "almost unbreakable," says Aizen- berg.

A regular glass rod will crack easily, but in layered glass rod, the incoming energy from mechanical load dissipates into the glue betwee the layers. A crack in one of the thin, outer lay- ers of the cylinder doesn't travel very far befor it reaches the organic glue, which diverts th crack from the next layer.

A final design detail is the glass wires tha attach the sponge to the ocean floor. Anchor points are typ- cally weak spots in structures, notes Aizenberg. Rather tha thickening the point of attachment, the sponge employs flex bility, loosely incorporating additional thin cylinders into th vertical beams at the bottom of the sponge. This way, the spong can swing freely, moving with whatever force it encounter says Aizenberg.

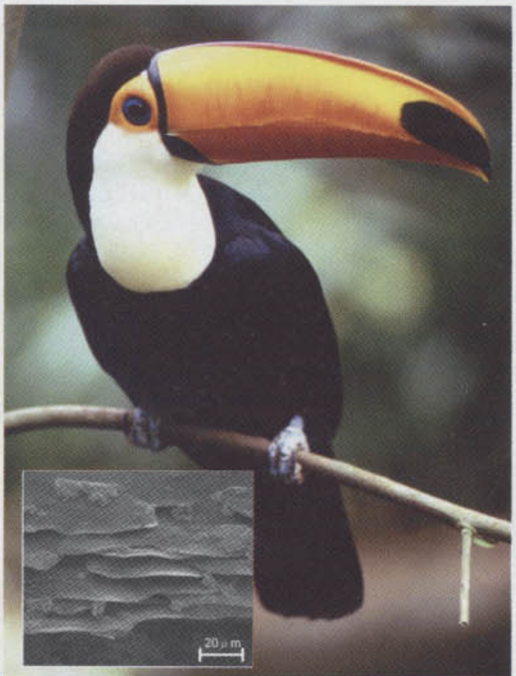
The mechanical principles integral to the sponge's design- diagonal ridges, bundled beams, and layered rods—can be foun in structures that engineers build every day. But Aizenbe points out that engineers tend to use these principles separatel

Combining these design elements to create even stronger materials "is something that nature can still teach us," she says.

"This is probably the strongest glass structure that one can imagine," she continues. "In a way, it's a glass house at which you can throw stones."

A BETTER BEAK The Toco toucan (*Ramphastos toco*) has a thick, roughly 20-cm-long beak that makes up a third of the bird's length. The Toco, which lives in the jungle canopies of South America, dines on tree fruits growing at the ends of branches. The birds perches on sturdier portions of a branch and relies on its beak's length to reach a meal. Once the toucan secures a piece of fruit in the tip of its beak, the bird tosses the food into the air and catches it closer to its throat.

The beak must be rigid enough to resist bending and twisting forces, and yet this stiffness can't come with great weight, or the bird couldn't get off the ground, says Meyers. Indeed, despite its dominating size, the beak makes up only one-twentieth of the toucan's body mass. In the December 2005 *Acta Materialia*, Meyers and his colleagues described how the toucan beak accommodates the need for both strength and agility.



TILE PILE — A scanning electron micrograph (inset) of the layered and staggered keratin tiles that make up the outer shell of a Toco toucan's beak.

KEVIN SCHAFER/VIREO; (INSET) MEYERS

The outer shell of the beak is a 0.5-millimeter–thick layer of the protein keratin, the same material found in human fingernails. As tough as keratin is, a uniform layer the size of a toucan beak would be subject to cracks, says Meyers.

To prevent such damage, the toucan adopts a strategy that's analogous to the layering of the glass sponge. The beak's outer shell is made of hexagonal keratin tiles—each about 50 µm in diameter and 1 µm thick—cemented together with an organic glue and piled in several staggered layers. As among the rings in the thin cylinders of Aizenberg's glass sponge, this arrangement diverts cracks along the path of the glue, making them less likely to penetrate deep into the beak.

The beak's internal structure is also critical to its strength, the researchers found. It consists of a scaffold made of calcium-rich beams draped with keratin membranes. The scaffold's closed, air-filled spaces reduce overall weight without loss of rigidity, says Meyers. Without its scaffold, the long, almost tubular beak would collapse under bending forces, much as an aluminum cylinder would.

Engineers use a similar strategy when they create light-but-sturdy structures by packing synthetic foam between hard layers in car bumpers and some construction materials. But the toucan's calcium scaffold is lighter and stiffer than that foam, notes Meyers.

If engineers could develop foams with some of the scaffold's characteristics, they might create stiffer, yet lighter, crash-resistant car panels than those that exist today, says Meyers.

SHELLS NOT SHOCKED Since researchers described the source of the surprising toughness of most mollusk shells almost 3 decades ago, the shells have become a model for bio-inspired materials research. The source of their strength is nacre, which makes up their inner layer. Current research is providing nanoscale details that indicate how parts of this layer contribute to nacre's strength.

Nacre is made of about 95 percent aragonite, a form of a calcium carbonate, and 5 percent organic material (*SN: 1/28/06, p. 51*). On its own, calcium carbonate—which is basically chalk—is brittle, says Christine Ortiz of the Massachusetts Institute of Technology.

In nacre, 3,000 to 4,000 layers of offset, aragonite bricks are locked together by thin layers of organic glue. Most bricks are hexagonal, with thicknesses between 0.3 and 1.5 µm and diameters ranging from 5 to 20 µm. Each layer of glue is just tens of nanometers thick. This structure makes nacre 3,000 times as fracture resistant as calcium carbonate alone.

Ortiz and her colleagues have tested mechanical properties of an individual nacre brick by pressing on it with the tip of an instrument called an atomic-force microscope. The force left an impression in the brick, but it didn't cause a fracture. The integrity of each brick enhances the structure's overall strength, further encouraging cracks to follow the energy-sapping, zigzag path of the mortar, says Ortiz. The researchers reported their results in the September 2005 *Journal of Materials Research*.

The group is now investigating how the mortar adheres to the bricks. Ortiz suggests that this design information could lead to improvements in body armor and other impact-resistant materials.

BEYOND BLUEPRINTS Among the design principles displayed by the sea sponge, toucan beak, and seashell, a common theme is the diversion of crack-causing energy into the adhesive holding subunits together. If this principle could be brought to bear on building designs, says George Mayer of the University of Washington in Seattle, it could make structures more resistant to earthquakes or explosions. The more that a structure can absorb such intense energy, the longer it should hold up, and the more time that its occupants would have to get out before its collapse, he says.

With that in mind, Mayer's group designed a 20-cm-long prototype beam with a structure mimicking the brick-and-mortar design of nacre. The researchers chose aluminum oxide, a material tougher than nacre's calcium carbonate, for 5-to-7.5-cm-long bricks. They also tried out several materials for the mortar.

Their best brick-and-mortar beam, with each layer of bricks offset from the next, was six times as tough as a beam of solid aluminum oxide is. This improvement occurred in what is just a crude approximation of nacre, Mayer points out. "We built beams with six layers," he says, which doesn't get down to the scale of thousands of layers in a seashell. He and his team describe their results in an upcoming *Materials Science and Engineering C*.

It will be no small feat to copy all the elements of natural structures, especially features at minute scales. While scientists can manufacture nanosize components, incorporating them into the macrosize structural materials necessary for machines and buildings isn't yet cost-effective, notes Mayer.

Engineers must also consider the conditions under which natural structures form and thrive. For instance, the proteins in the organic glue holding together glass rods in the sea sponge *E. aspergillum* wouldn't withstand the high temperatures that engineers use to manufacture glass, says Mayer.

But researchers remain enthusiastic about the natural blueprints they now have and those still to be unrolled. Meyers plans to study bird beaks other than the toucan's, while Ortiz is interested in what lies behind the strength of antlers. Aizenberg is comparing the glass sponge's structure with that of sponges living in other habitats.

"I do believe that fundamental studies are very important," Aizenberg says. "They will ultimately lead to new materials." ■