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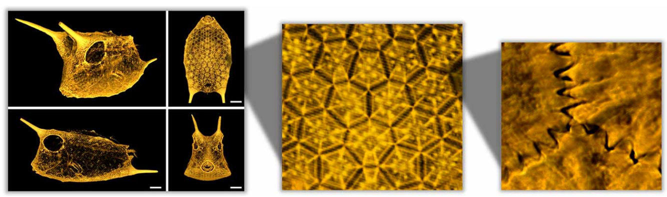
UC San Diego News Center

July 30, 2015 | By Wen Yang, Steven E. Naleway, Michael M. Porter, Marc A. Meyers and Joanna McKittrick

Boxfish Shell Inspires New Materials for Body Armor and Flexible Electronics



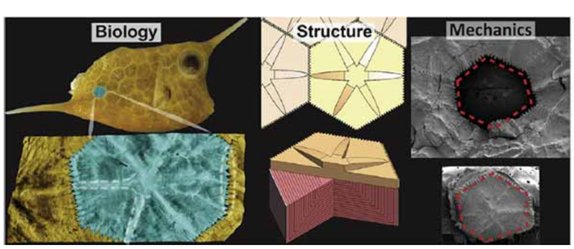
The boxfish gets its name from its boxy shape (left). Its carapace (or shell) is composed of several hexagonal scutes that provide body support and armored protection (center). These scutes are connected by tooth-like joints called sutures, which provide some level of combined strength and flexibility (right).

The boxfish's unique armor draws its strength from hexagon-shaped scales and the connections between them, engineers at the University of California, San Diego, have found.

They describe their findings and the carapace of the boxfish (*Lactoria cornuta*) in the July 27 issue of the journal *Acta Materialia*. Engineers also describe how the structure of the boxfish could serve as inspiration for body armor, robots and even flexible electronics.

"The boxfish is small and yet it survives in the ocean where it is surrounded by bigger, aggressive fish, at a depth of 50 to 100 meters," said Wen Yang, a UC San Diego alumna now working at Swiss Federal Institute of Technology in Zurich in Switzerland and the paper's first author. "After I touched it, I realized why it can survive - it is so strong but at the same time so flexible."

The boxfish's hard frame and flexible body make it an ideal animal to study for inspiration for armor materials. The hexagon-shaped scales are called scutes. They are connected by sutures, similar to the connections in a baby's skull, which grow and fuse together as the baby grows.



Most fish have overlapping scales, said Steven Naleway a materials science and engineering Ph.D. student and co-author on the paper. "That means that there are no weak points, should a bite from a predator land exactly in between scales," he said. "We are currently investigating what mechanical

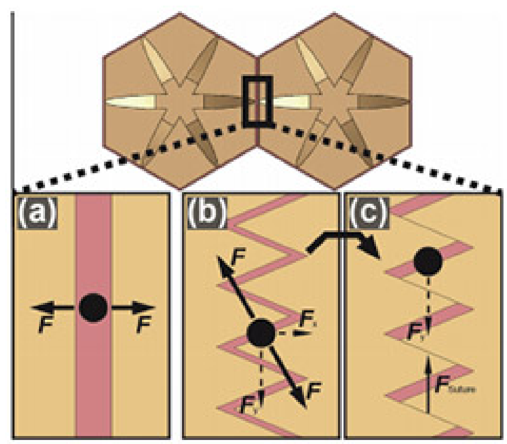
Each hexagonal scute in the boxfish's armor has a raised, star-like structure in the center that distributes stress across the entire surface. Underneath the scutes lies a flexible, yet hard to penetrate, inner layer of interlocking collagen fibers.

advantage scutes and sutures might provide. We know that the boxfish has survived for 35 million years with this armor, so the design has proved very successful in nature."

Each hexagonal scale, or scute, has a raised, star-like structure in the center that distributes stress across the entire surface. Under the scutes, the team found an inner layer that forms a complex structure in which collagen fibers interlock. This structure creates a flexible inner layer in the armor, which is difficult to penetrate due to the interlocking collagen fibers. Together, the outer and inner layers of the boxfish armor provide the fish with protection unique in the natural world.

The team also tested the scutes' ability to withstand tension by pulling them apart both horizontally and vertically, as well as their ability to withstand penetration. "We were able to demonstrate that even if a predator manages to generate a crack in the outer layer, the collagen fibers will help to prevent the structure from failing," said Yang. Her current research focuses on the characterization of bio-inspired materials.

Meanwhile, the connections between the scutes, called sutures, make the armor even stronger. Upon impact, the sutures' zigzag patterns essentially lock in and keep the scutes from breaking apart. These sutures are different from many of those found elsewhere in nature, Naleway said.



Proposed mechanical advantage of sutured interface: (a) Straight interface with penetration by sharp tooth separating neighboring scutes; (b) Sutured interface with force F having tangential and normal components; (c) Tangential component of force, Fy, pushing opposite sides of teeth against each other in a locking-in mechanism.

"The most common form of suture structures in nature are those that have a roughly triangular shape and consist of two important components: rigid suture teeth and a compliant interface," he said. "To the best of our knowledge, there is no compliant phase in the interface of the boxfish's sutures. In addition, the teeth themselves have a much lower aspect ratio — meaning that they are shorter and wider — than most other examples."

"Our approach is unique as we use engineering principles to understand the biological design," said professor Joanna McKittrick, a materials science expert and one of the senior authors on the paper.

Researchers used scanning electron microscopy to characterize the surface structure of the scutes. They also took cross sections and used micro-computer tomography to characterize the dense regions. The results of mechanical testing left the researchers wanting to know why the boxfish would choose a design that excluded overlapping scales.

“These damage-resisting structures have evolved for millions of years in nature and are being studied with support of the U.S. Air Force to hopefully guide us to bioinspired designs that will offer more protection against impact than our conventional ones,” said Marc Meyers, one of the two senior authors on the paper and Distinguished Professor of Materials Science at UC San Diego.

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