Boxfish Skin Could Inspire New Materials for Body Armor, Robots and Flexible Electronics

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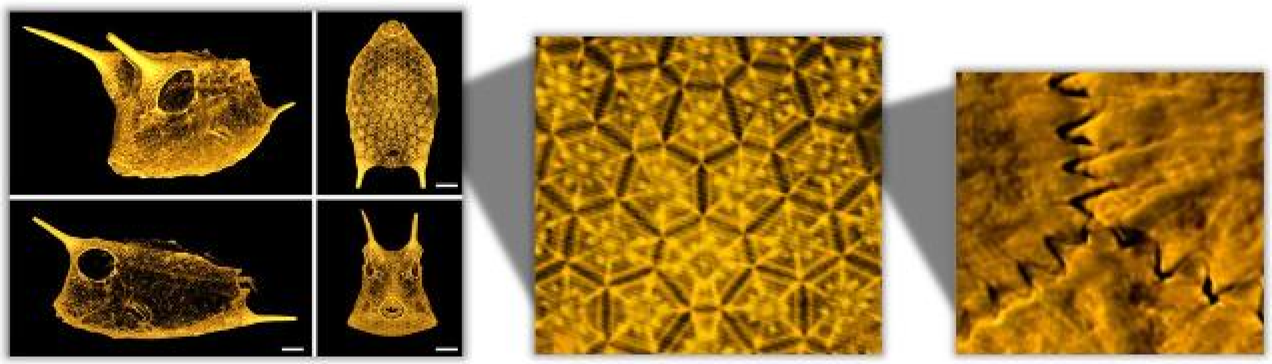
Researchers from the University of California, San Diego have closely studied the armor of the boxfish, so its unique structure can be applied to creating robots, body armor and flexible electronics. The hexagon-shaped scales of the boxfish's armor and the connections between them give the armor its exceptional strength.



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).
Credit: Michael M. Porter/Clemson University.

The researchers have published their findings on the carapace of the boxfish (Lactoria cornuta) in the journal Acta Materialia (July 27 issue). The boxfish has a hard frame, and is also flexible, which makes it an interesting model for new advanced armor materials.

> *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.*
>
> *After I touched it, I realized why it can survive - it is so strong but at the same time so flexible.*
>
> ***Wen Yang, lead author***

The hexagon-shaped scales on the boxfish's body are referred to as scutes, and they are connected by sutures similar to the connections in a baby's skull, which grow and combine 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.

"We are currently investigating what mechanical 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.”

At the center of each scute is a raised, star-like structure that enables stress distribution across the total surface. The researchers noticed that under the scutes, there was an inner layer with a complex structure where collagen fibers interlocked.

This structure provides a flexible inner layer in the armor, which is hard to penetrate because of the presence of the interlocking collagen fibers. The protection offered by the exclusive inner and outer layers of the boxfish armor is truly amazing, and is thought to be unique in nature.

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The researchers also analyzed the ability of the scutes to endure tension, by pulling them apart both vertically and horizontally. Likewise they also observed their ability to endure 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 present research is on the classification of bio-inspired materials.

The connections or sutures between the scutes provide the extra strength of the armor. It was noticed that when penetrated or pulled, the zigzag patterns of the sutures tended to lock in and prevented the scutes from deformation. Naleway highlighted how these sutures are unusual when compared to anything found in nature.

> 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.
>
> 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.
>
> **Steven Naleway, co-author**

"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.

The team made use of a scanning electron microscope (SEM) to distinguish the surface structure of the scutes. They also obtained cross sections of them, and used micro-computer tomography to characterize the thicker portions. Subsequent to mechanical testing, the results left the researchers wondering as to why the boxfish would select a design that did not contain 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 bio-inspired 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.

This research was supported by the National Science Foundation, Division of Materials Research, Ceramics Program Grant (1006931). Partial financial support was received from a Multi-University Research Initiative through the Air Force Office of Scientific Research (AFOSR-FA9550-15-1-0009).

References and further reading

- Boxfish shell inspires new materials for body armor and flexible electronics - UC San Diego
- The armored carapace of the boxfish - Yang et al, Acta Biomateriala, 2015

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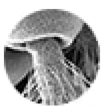
- 
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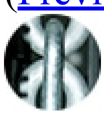
- 
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