A star in the world of ceramic engineering

February 10 2022

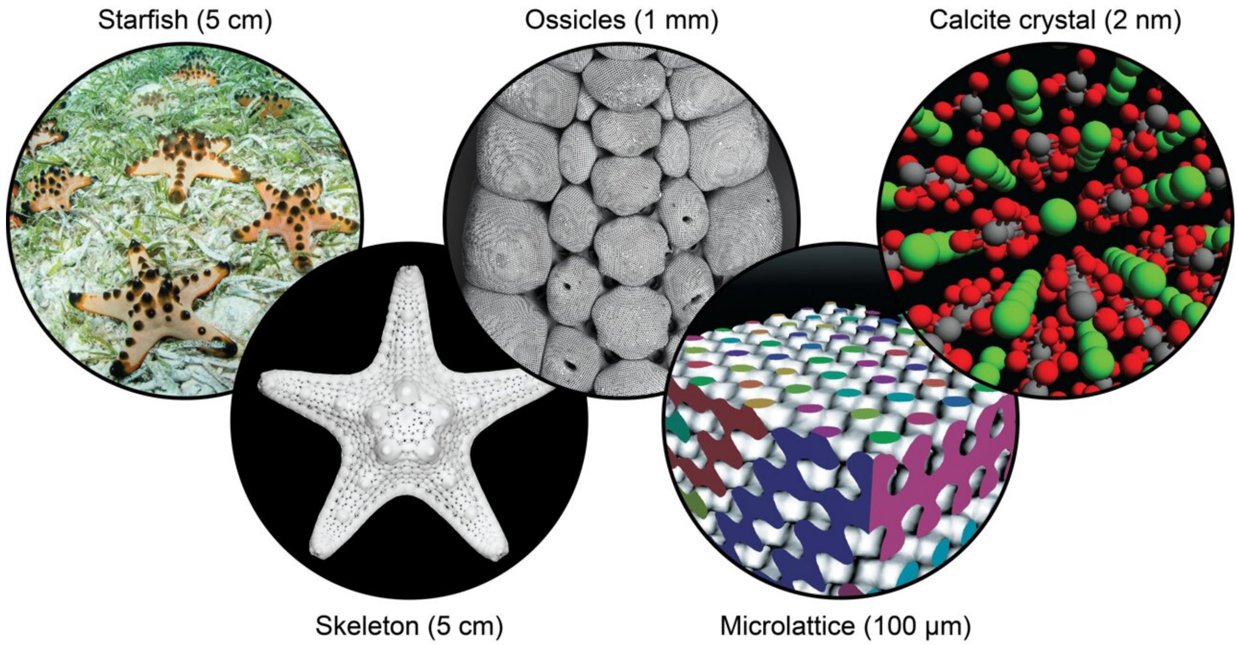


Illustration of the dual-scale single-crystalline microlattice of starfish. Credit: Ling Li (Virginia Tech) and James C. Weaver (Harvard University)

Compared to metal and polymer-based materials, ceramics can better withstand high temperatures and corrosive environments, but their brittle nature often makes them susceptible to breakage. This behavior potentially causes problems for innovators trying to create lightweight porous versions of these materials, explaining why ceramic foams are not typically used as structural components.

Facing the challenging task of developing lightweight, high-strength ceramic materials, Mechanical Engineering Assistant Professor Ling Li has turned to an unexpected collaborator for design inspiration: the knobby starfish from the tropical Indo-Pacific. By investigating the complex and highly ordered mineralized skeletal system of this unusual marine species, Li and his research team discovered an unexpected combination of characteristics that may lead to developing an entirely new class of high-performance lightweight ceramic composites. *Science* magazine featured their findings in a recent cover story.

Going light by going porous

Industries such as those in automobile and aerospace manufacturing have a strong interest in designing both strong and lightweight materials, combining the economy of better fuel efficiencies with strength. Industries find this balance difficult to strike, since stronger materials commonly possess high densities, and thus weigh more.

Nature, through millions of years of evolution, has come up with an ingenious way of solving this problem: using porous materials. The introduction of internal porosity potentially creates both extremely lightweight and mechanically efficient materials.

Several examples of porous materials exist in nature. These include the human skeletal system, the stems of plants, and the hives of honeybees. If ones places these natural materials under a microscope, then one quickly discovers that they are filled with tiny voids or chambers. Natural growth forms these porous biological constructions very efficiently, and that formation often results in unexpectedly complex internal geometries.

In the Laboratory of Biological and Bio-Inspired Materials, Li and his team are investigating natural lightweight ceramic structures, with the goal of developing new material design principles for addressing the mechanical weakness of ceramic foams and architected materials.

"Our overall goal is to learn and take inspiration from nature to develop novel porous materials," Li said. "Nature offers many good material lessons for designing porous materials that are both strong and damage-tolerant."

Previously, the team discovered that the unique chamber-based bioceramic structure of cuttlebone (the internal skeleton of cuttlefish) is simultaneously strong, stiff, and fracture-resistant, while still allowing for buoyancy regulation. This project and others like it motivated the team to investigate additional applications for nature's porous designs at the microscale.

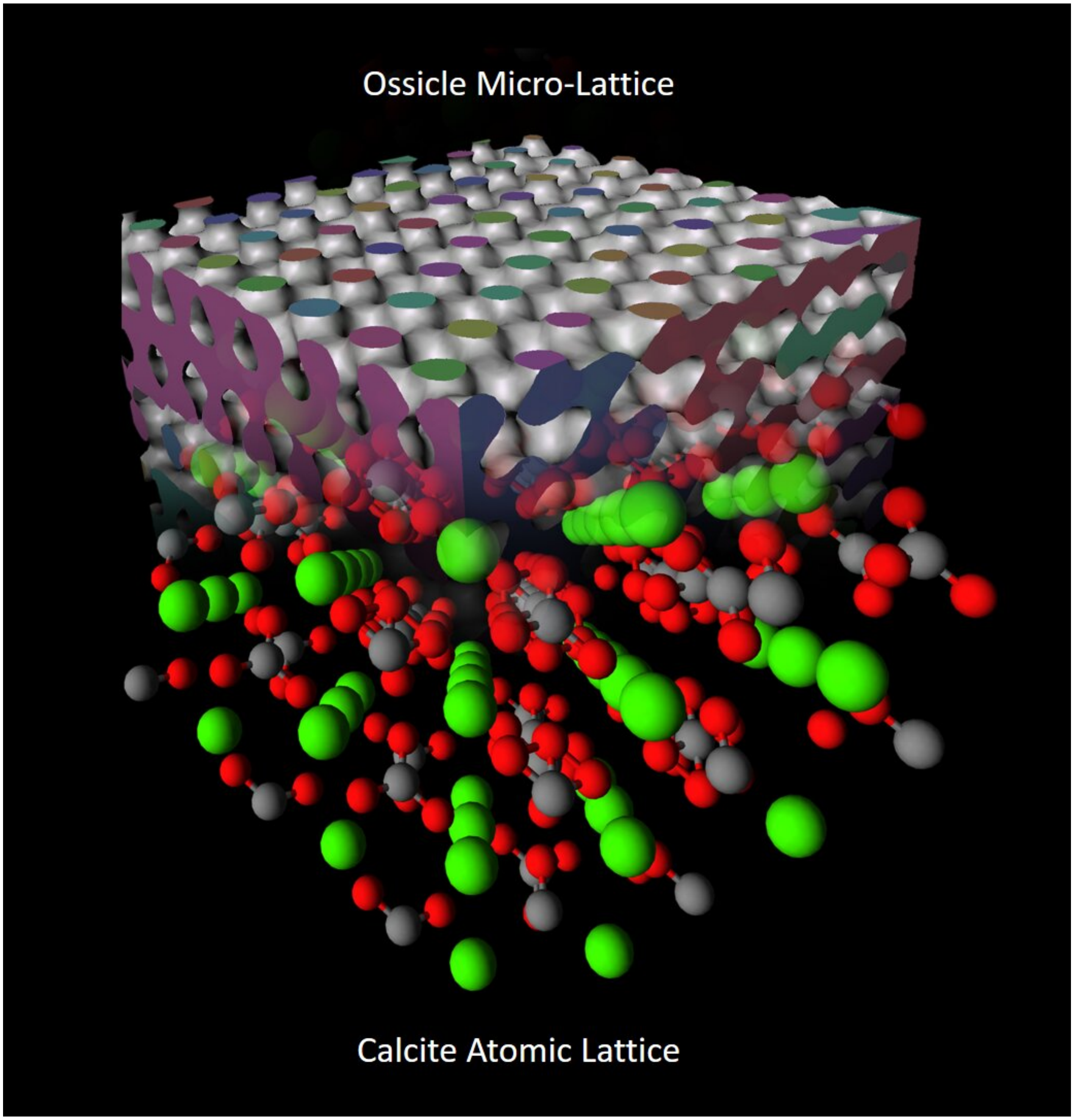


Illustration of the dual-scale single-crystalline microlattice of starfish. Credit: Ling Li (Virginia Tech) and James C. Weaver (Harvard University)

Starfish skeletons: A natural architected ceramic lattice

In this work, Li and his team turned their eyes to the skeleton of the knobby starfish. Widely distributed throughout the Indo-Pacific region, the species' dried skeletons are often used for home decoration. These starfish feature cone-shaped projections that rise from their dorsal surface and discourage predators.

While observing samples of these starfish skeletons at the Nanoscale Characterization and Fabrication Laboratory (NCFL), Li and Ph.D. student Ting Yang (co-first author of the paper and now a post-doctoral fellow at the Massachusetts Institute of Technology), made an observation that piqued their interest: At the microscale, the starfish skeleton exhibited a lattice architecture with very regular arrangements of branches quite different from the porous structures of the cuttlebone and sea urchin spines previously studied. In fact, the unique skeletal organization of this starfish exhibits the highest structural regularity ever reported from this group of invertebrates. Such regular lattice-like structures display remarkable similarities with space frame truss structures commonly employed in modern human construction projects.

The team wondered how this natural ceramic lattice material achieved mechanical protection, since starfish skeletons are made of calcite, a crystalline form of calcium carbonate (chalk). Any child familiar with playing outside knows that sidewalk chalk is very brittle and easily broken. However, the body of the starfish demonstrates high strength and flexibility. Uncovering the underlying principles of this structure may help solve the challenges of making stronger porous ceramics.

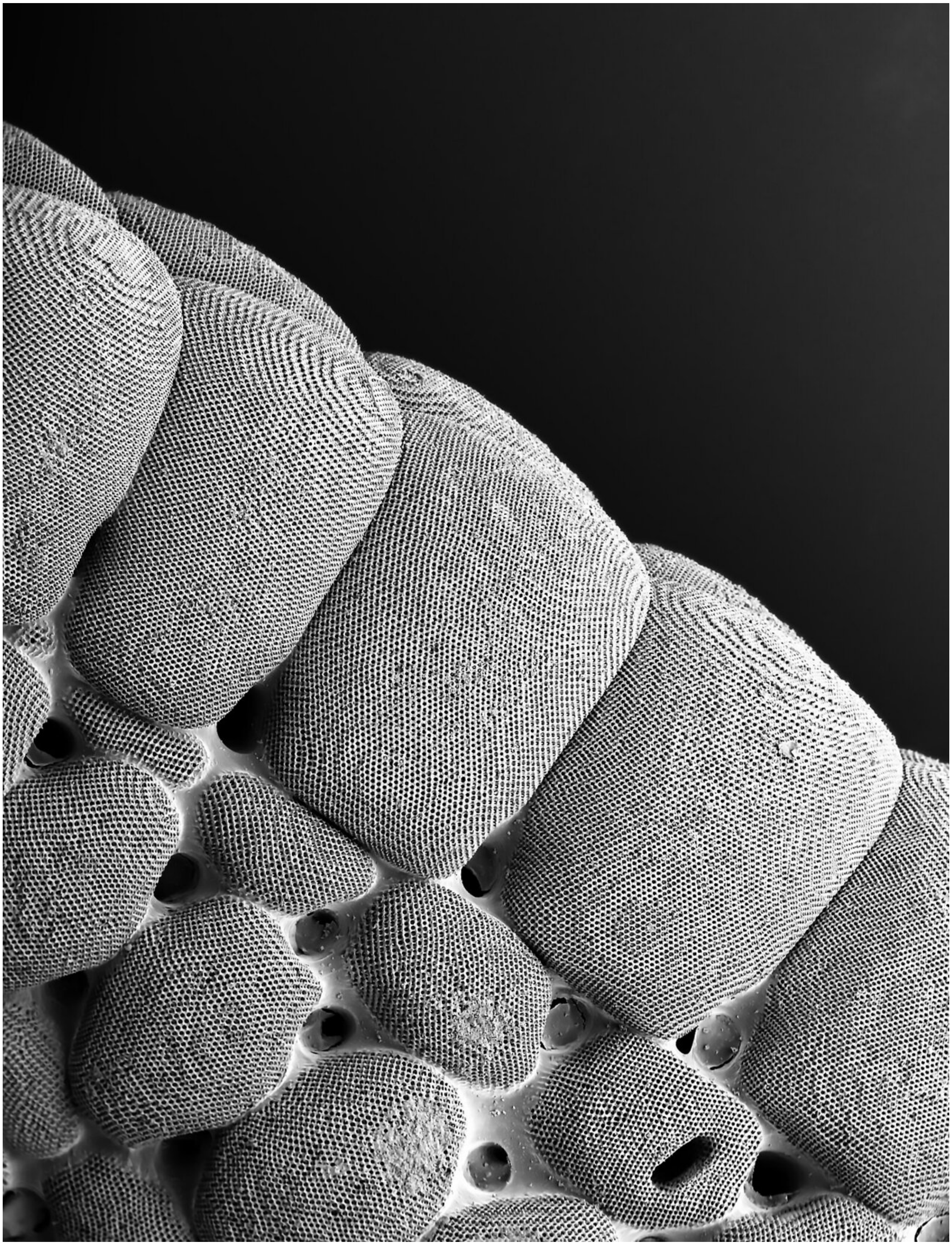
What the team found was unexpected. As in other starfish species, the skeleton of the knobby star consists of many millimeter-sized skeletal elements called ossicles. These ossicles connect with soft tissue, allowing the animal to be flexible and move. Li and his team discovered that each ossicle is constructed of a microlattice structure so uniform that it can be described mathematically, composed of branches connected through nodes in similar vein to the structure of the Eiffel Tower. Even more interesting, the team found the uniform structure of the microlattice, because of the alignment of its atoms, is essentially a single crystal structure at atomic level.

"This unique material is like a periodic lattice carved from a piece of single crystal of calcite," Li said. "This nearly perfect microlattice has not been reported in nature or fabricated synthetically before. Most highly regular lattice materials are made by combining materials with small crystals to create composites, but this is new. It's grown as a single piece."

This structure allows a starfish to reinforce its skeletonstrategically in particular directions, offering enhanced protection. In addition, it appears the animal can thicken branches along selected directions and in particular regions, improving its mechanical performance in a similar manner to how the human body possesses the ability to alter the local geometry of its porous bones to adapt to physical activity. In the starfish, researchers also found regions where the structure appeared to modify the regular lattice pattern of its design, a feature that inhibits crack expansion when the microlattice fractures.

Patricia Dove, an expert in biomineralization, a University Distinguished Professor, and the C.P. Miles Professor of Science in the Virginia Tech Department of Geosciences, said this biological discovery could have a major impact on the field of bio-inspired innovation.

"Starfish and other echinoderms living in highly predatory sea floor environments are revealing a world of materials innovations that are critical to survival," Dove said. "Using little more than seawater and some organic components, biology directs the formation of remarkable skeletons such as those in starfish. This novel study of the underlying mechanical engineering properties has tremendous potential as a frontier for new materials design."

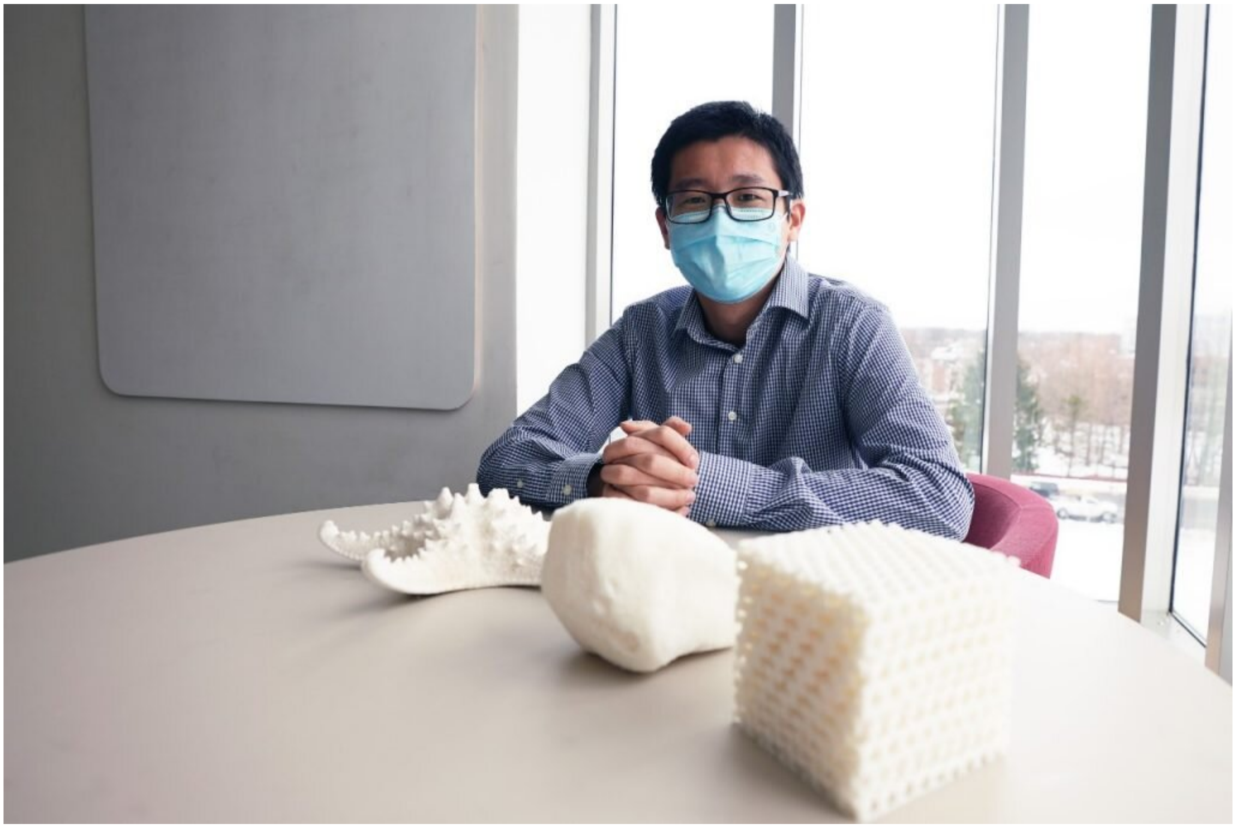


Scanning electron microscopic image showing the starfish skeletal system composed of many ossicles, which exhibit a periodic microlattice structure. Credit: Ling Li (Virginia Tech)

What's next?

Knowing the architecture of natural microstructures represented a huge step forward, but Li and his team had more questions. Was there a key to the way in which the creatures grow their skeletons that might shed some light on a way to reproduce them?

Li and his collaborators used 3D printing to model and generate large-scale versions of these complex lattice structures for both research and educational purposes, a useful approach in understanding the complexity of these unique geometries. While the 3D-printed models created by Li's team were indeed visually inspiring, the technology needed to bring new, stronger ceramic micro-architectures to market still lay in the future. Currently, 3D printers produce structures at the micrometer level, but printing ceramics still requires firing the final product, which possibly introduces many uncontrolled tiny pores and cracks. These defects make the structures extremely fragile. Li hopes that continued advances in the field of 3D printing and further understanding of the formation mechanisms of biological structures like starfish skeletons eventually offers a solution.



Ling Li with a starfish skeleton and 3D-printed scale models. Credit: Alex Parrish for Virginia Tech

"Nature is able to assemble mineral precursors to form complex architectures at room temperature and ambient pressure," Li said. "That is something that modern human technology cannot currently achieve. Virginia Tech has a strong research interest in mineral structures found in nature, and I am hopeful that this exciting research direction may one day lead to the development of a wide range of bio-inspired, stronger, and more lightweight materials."

Other authors on the paper include Virginia Tech graduate students Hongshun Chen, Zhifei Deng, Liuni Chen, and postdoc Zian Jia, James C. Weaver from Harvard University, and Emily Peterman from

Bowdoin College.

More information: Ting Yang et al, A damage-tolerant, dual-scale, single-crystalline microlattice in the knobby starfish, Protoreaster nodosus, *Science* (2022). DOI: 10.1126/science.abj9472. www.science.org/doi/10.1126/science.abj9472

Provided by Virginia Tech