The Ganoid Scales of *Atractosteus spatula*: Potential for Bioinspired Flexible Armor

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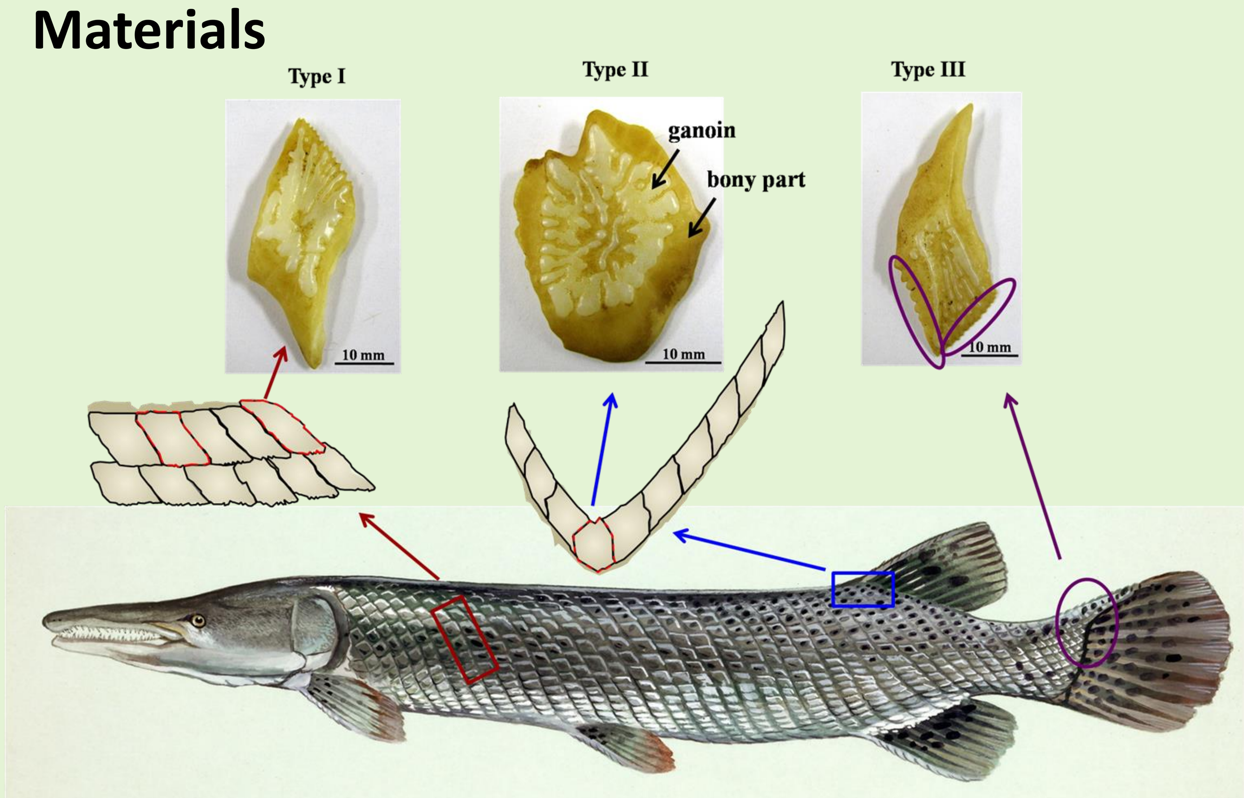
Introduction

The alligator gar (*A. spatula*) is covered with a configuration of bony scales that have an enamel-like surface layer. The scales form a tridimensional pattern in which neighboring scales overlap in such a manner that ensures flexibility. The mechanical properties, structure, and geometry are correlated and a magnified array of idealized, identical tiles is produced.

Objective

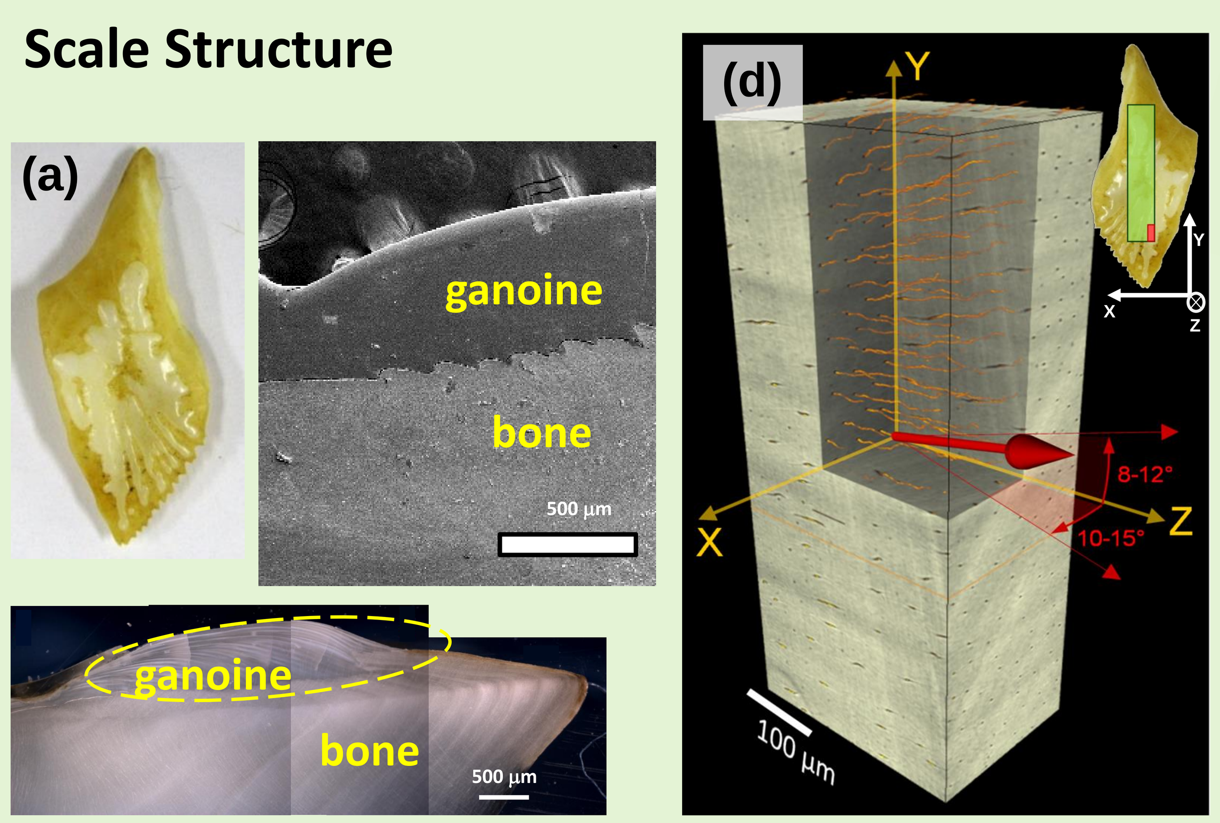
To produce a bioinspired flexible armor which incorporates key features of the alligator gar scale.

Materials



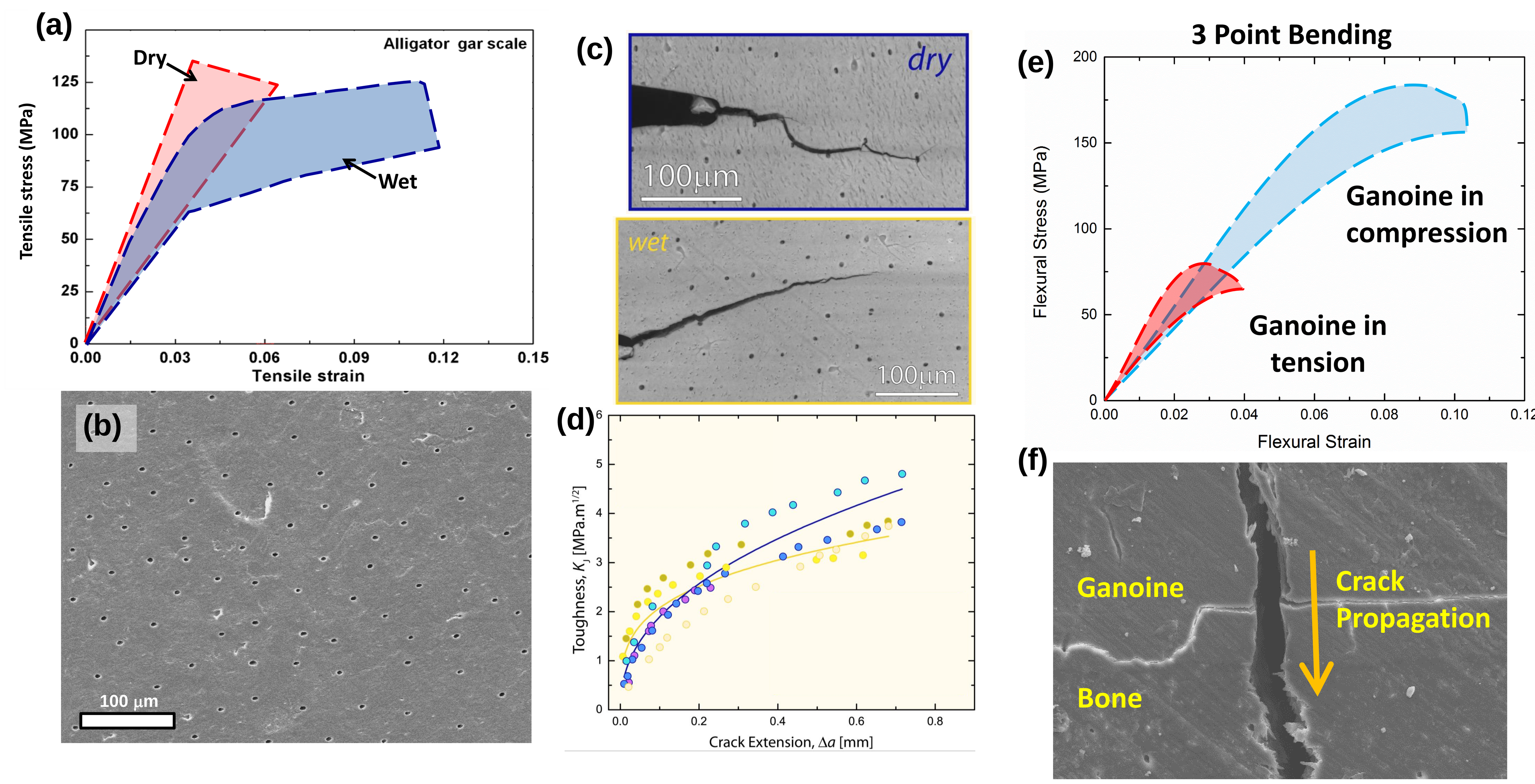
Type I scales are collected from the deceased *Atractosteus spatula*.

Scale Structure



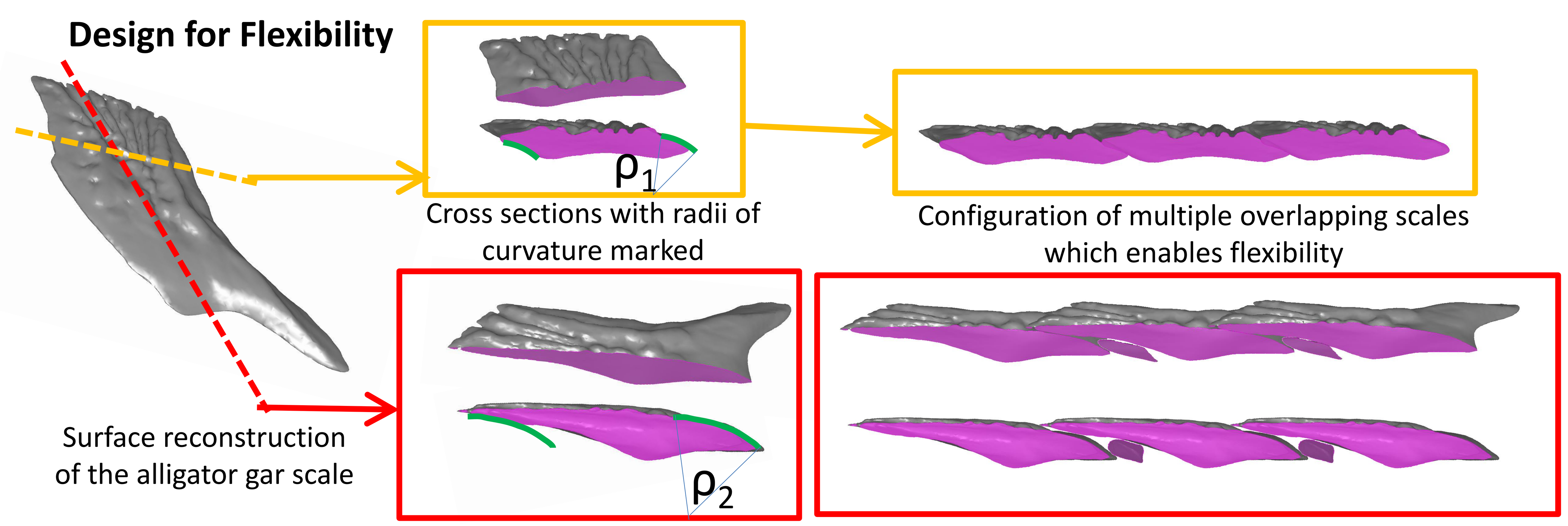
The alligator gar scale (a) consists of a yellowish boney base layer and a hard white enamel like ganoine layer (a-c). Small tubes, or tubules run from the interior to exterior surface of the scale (d).

Design for Toughness



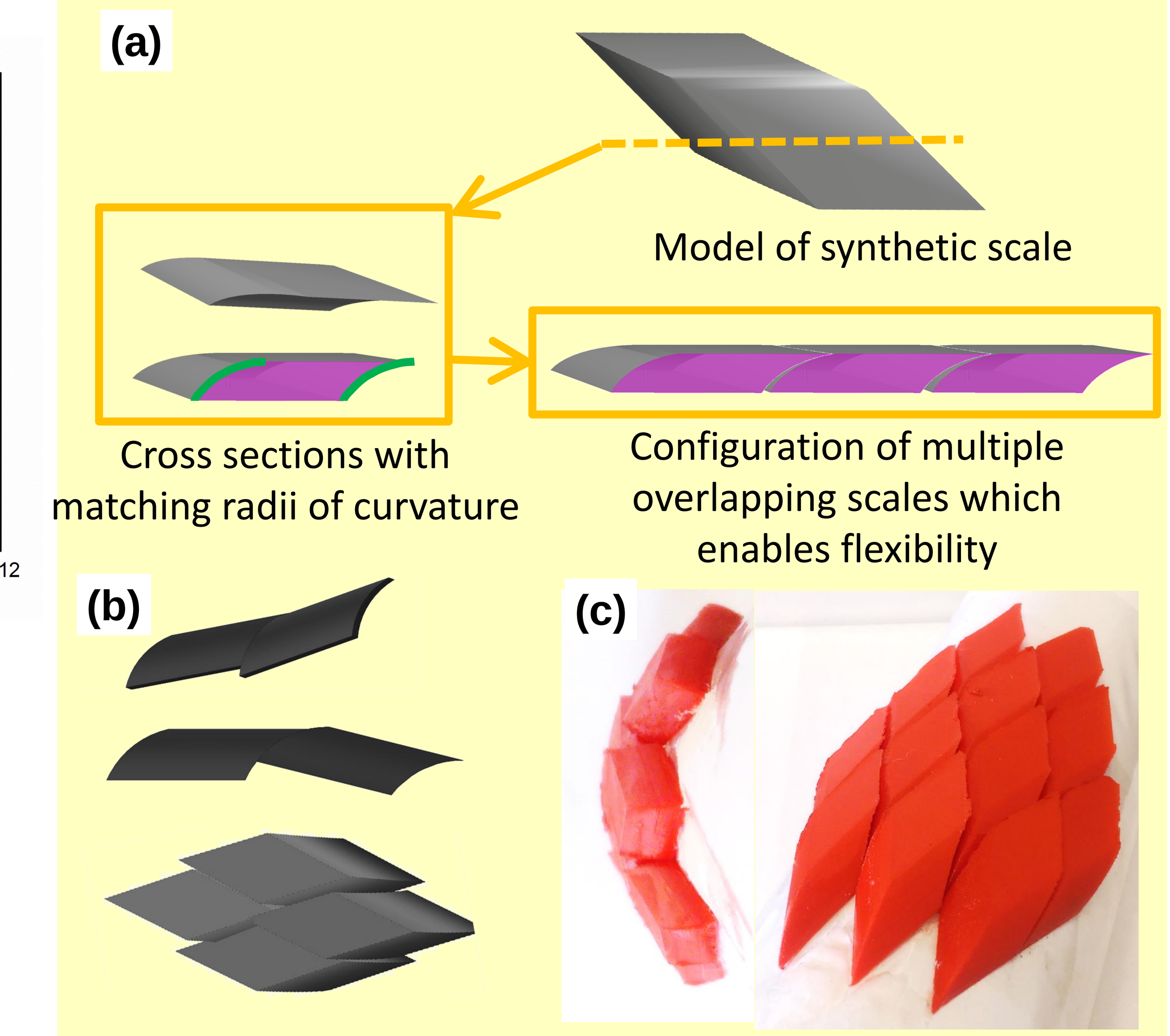
Under various conditions, different mechanisms contribute to the toughening of the scales. (a) In a wet state, water molecules act as plasticizers and post-yield plasticity allows for large energy absorbance. But in a dry state, hydrogen bonds form directly between collagen molecules, thus limiting plasticity. To compensate, tubules (b, c) create stress concentrations and cause significant crack deflection shown in (d). This crack deflection increases the toughness, K_J, for the dry samples so that it is both wet and dry samples are of similar toughness. (e) 3 point bending tests of samples with a ganoine layer and a boney layer reveal that when the ganoine is in compression, the maximum flexural stress and strain nearly double with respect to when it is in tension. (f) Observation of the fracture shows that cracks which initiate in the brittle ganoine propagate into the bone causing premature failure. In a lifelike situation such as a predatorial attack, the ganoine is in compression; this corresponds to the ideal loading situation of the scale.

Design for Flexibility



Scales with high stiffness require the specialized geometry in order to allow the fish to swim. In order to maintain flexibility, the gar scales overlap in such a way that they can rotate across the surface of adjacent scales. This allows for movement, in spite of a large amount of scale overlap. A microCT scan is dissected to show two cross sections. ρ_1 is the radius of curvature on both sides of the cross-section made by the yellow dashed line and ρ_2 is from the cross-section marked by the red dashed line. P_1 matches to both sides of the cross-section, while ρ_2 matches once the contributions of a third overlapping scale are considered.

Mimicking key features of the scale



The key feature which allows for flexibility and efficiency of the scale is the matching curvatures on either side of the scale. In (a), a simplified version of this design was produced where the curvature on all sides of the scale is equal, and the scale is symmetric across the long direction of the rhombus. These synthetic scales are able to bend and stretch in all directions while maintaining protective coverage, as shown in (b). (c) shows an ABS printed version of the model scale conforming to a curve.

Toughness and strength are also key. Similar to the actual scale, a tougher inner layer will make up the body of the scale, while a hard outer layer will contribute to strength and penetration resistance.

Conclusions

- The alligator gar scale has unique features which allow for movement and protection including a unique scale overlapping pattern and crack deflecting tubules throughout.
- Studying and replicating these features may lead to the production of more effective armors.
- A simplified geometry based on an alligator gar scale is designed, produced, and shown to be capable of conforming to curvature.

References

W. Yang et al., Structure and fracture resistance of alligator gar (Atractosteus spatula) armored fish scales. Acta Biomater **9**, 5876 (Apr, 2013).
W. Yang et al., Natural Flexible Dermal Armor. Adv Mater **25**, 31 (Jan, 2013).

We gratefully acknowledge partial financial support from a Multi-University Research Initiative through the Air Force Office of Scientific Research (AFOSR-FA9550-15-1-0009). Dianne Ulery generously provided scales which were used for testing.