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Credit: Steve Woods Photography/GettyImages

BIOINSPIRED MATERIALS

A whale of a material

Baleen whales, such as bowhead whales and humpback whales, use a keratin-based biomaterial — the baleen — to separate food from water. Whale baleen has to be very strong and flexible to withstand collisions with prey and to allow filtering of food. Now, reporting in *Advanced Materials*, Bin Wang, Marc Meyers and colleagues created 3D-printed polymer-based baleen-mimetics, revealing how the hierarchical structure of baleen enables high fracture toughness, high impact resistance and large deformability.

"Baleen plates require sufficient stiffness and strength to sustain external forces, adequate visco-elasticity to absorb energy and they must be lightweight to efficiently function for a whole whale life, which can span up to 100 years," says Bin Wang.

Using X-ray microcomputed tomography and scanning electron microscopy, the researchers identified that the baleen of bowhead whales is composed of a solid shell that encloses a tubular core, made of keratinized cells. The tubules, with a diameter of 60–900 μm, consist of concentric layers of microscale lamellae with randomly distributed hydroxyapatite crystals along the keratin filaments, as well as unmineralized lamellae. This hierarchical architecture — lamellae formed from nanoscale keratin filaments and minerals organizing into microscale tubules and intertubular material, resulting in a sandwich-tubular structure — is unique to whale baleen and differs from other keratinous materials, such as horns or hooves.

The researchers demonstrated that the structure of bowhead whale baleen causes anisotropic fracture behaviour. "In the longitudinal direction, cracks propagate with ease, leading to delamination, fraying and the formation of bristles, which are required for filtering," explains Meyers. "However, in the transverse direction, crack propagation is resisted by the tubular structure, providing the required resistance to water flow and prey impact."

Therefore, material toughness is higher in the transverse than in the longitudinal direction. Hydrated baleen shows the same toughening mechanisms, including crack deflection and fibre bridging; this property is crucial for the filtering function of baleen. However, a ductile-to-brittle transition at increasing strain rates occurs only in dry conditions, but not if the material is hydrated. Thus, the architecture of baleen is optimized for performance in water.

Based on the structural characterization of bowhead whale baleen, the researchers created 3D-printed structural baleen models using polymers of different degrees of stiffness to mimic its individual components. "The 3D-printed baleen mimetics reproduce the essential structural features of biological baleen," says Wang. "We applied fracture toughness and compression tests on the prototypes and demonstrated that the bioinspired material shows similar mechanical responses in terms of crack propagation, toughening and damage mechanisms to baleen."

> "The 3D-printed baleen mimetics reproduce the essential structural features of biological baleen"

These findings may provide clues for the design and manufacturing of fibre-reinforced composites, for example, for autonomous underwater vehicles or for devices to harness wave energy. The researchers are also investigating the nanoscale structure of the keratin filaments and mineral crystals of baleen to create baleen-inspired composites using techniques such as electrospinning and vacuum-assisted infusion.

Christine-Maria Horejs

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