Skin and scales of teleost fish: Simple structure but high performance and multiple functions

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Natural and man-made structural materials perform similar functions such as structural support or protection. Therefore they rely on the same types of properties: strength, robustness, lightweight. Nature can therefore provide a significant source of inspiration for new and alternative engineering designs. We report here some results regarding a very common, yet largely unknown, type of biological material: fish skin. Within a thin, flexible and lightweight layer, fish skins display a variety of strain stiffening and stabilizing mechanisms which promote multiple functions such as protection, robustness and swimming efficiency. We particularly discuss four important features pertaining to scaled skins: (a) a strongly elastic tensile behavior that is independent from the presence of rigid scales, (b) a compressive response that prevents buckling and wrinkling instabilities, which are usually predominant for thin membranes, (c) a bending response that displays nonlinear stiffening mechanisms arising from geometric constraints between neighboring scales and (d) a robust structure that preserves the above characteristics upon the loss or damage of structural elements. These important properties make fish skin an attractive model for the development of very thin and flexible armors and protective layers, especially when combined with the high penetration resistance of individual scales. Scaled structures inspired by fish skin could find applications in ultra-light and flexible armor systems, flexible electronics or the design of smart and adaptive morphing structures for aerospace vehicles.

[illegible]

Scaled skins are a very common structure in the animal kingdom: lizards, snakes, fish and even butterflies all possess a similar structure, which can however, significantly vary in size, morphology and function across species. The abundance of this structure generally is a hallmark of multifunctionality and ease of adaptation, a feature that is highly desirable in future generations of smart engineering materials. Fish skin is known for its remarkable mechanical properties: compliance, resistance to penetration (Yang et al., 2013a; Zhu et al., 2012a; Meyers et al., 2012; Zhu et al., 2012b; Vernerey and Barthelat 2010; Bruet et al., 2008) lightweight, all of them within an ultra-thin membrane structure. Despite these attractive features,

between scale and dermis deformation during bending, as shown in Fig. 2. For concave bending (scales are on the inside of the curve), Fig. 2b clearly shows that skin bending involves a significant rotation of individual scales, a feature that is associated with a rise on the skin's bending resistance with curvature. On the other hand, for convex bending the scales play no role in the skin mechanics and the structure remains extremely soft.

2.2. r r r r r

In order to facilitate the development of models and to unveil new mechanisms and features, we idealized the scaled skin as a one-dimensional substrate layer onto which a regular arrangement of scales of length separated by a distance $=r$ is attached (Fig. 3a). In this simplified model we assume that the scales are homogenous. While more elaborate computational models of the full three-dimensional structure can be found in the literature (Vernerey et al., 2014), such simplified analytical models are powerful at extracting the essence of fish skin mechanics without relying on computa-

The overall bending of the structure (on the concave side) can then be conveniently described in terms of the normalized curvature $\bar{\kappa} = \ell /$ where is the radius of curvature as shown in Fig. 2b.

2.2.1. *w* *r* *r* *r*

Now invoking Fig. 3

the investigation of the moment-curvature response of the fish skin for a variety of geometrical (r, ℓ) and material parameters (( ) ,( ) ,) as shown below.

Befo)1052(oh10528a51l4424(m20.o)14.8.6d)0a512.57(l1l4408.6i)7.84sousfdTl4466(th)289(foTl44384en)-401(v)21.2(a)13.9(fs)198

3.3. r - r r

In contrast, the compression regime is largely dependent on the presence of scales, which plays an essential role in stabilizing the material (Fig. 5c). Indeed, similar to a majority of thin films and membranes, the dermis alone cannot sustain large compressive loads due to the early appearance of mechanical instabilities in the form of buckling and wrinkling (Fig. 5c). When scales are present, however, in-plane compressive strains can be sustained up to unusual levels (∼100% as seen in Fig. 5

3.1. r r w

A particular feature of scale/dermis interaction is the ease by which scales rub off when a force is applied tangentially to the scale in a direction pointing toward the back of the fish (Fig. 7a). Such deciduous scales (Benoit et al., 2012) are key to

Pailler-Mattei, C., Bec, S., Zahouani, H., 2008. in vivo measurements of the elastic mechanical properties of human skin by indentation tests. Med. Eng. Phys. 30 (5), 599–606. (June).