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

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ABSTRACT

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.

## 1. Introduction

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, this material has received little attention from the materials development community. In a review article on mineralized

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tissues, Currey noted that some fish scales are so tough that they could not be fractured “even after immersion in liquid nitrogen” (Currey, 1999). In a more recent study Ikoma et al (2003) characterized the structure of Pagrus Major (sea bream) and presented experimental data on the tensile behavior of a single scale, showing non-linearity and progressive failure, with a relatively high modulus (2.2 GPa) and tensile strength (90 MPa). Toughening mechanisms include pullout of mineralized collagen fibrils across cracks (Zhu et al., 2012b; Garrano et al., 2012; Yang et al., 2013b). For comparison, human skin, mostly composed of collagen has a modulus of 10–30 kPa (Pailler-Mattei et al., 2008) and a strength of 10 MPa (Silver et al., 2003). While the full range of the functions of this material is not known, it performs especially well in a variety of tasks. First of all, individual scales resist penetration and provide a physical barrier against predator attack (Yang et al., 2013a; Meyers et al., 2012; Bruet et al., 2008; Garrano et al., 2012; Zhu et al., 2013) in the form of, for instance, biting and puncture loads from other fish and marine birds. The intricate arrangement of the scales furthermore provides a flexible skin that possesses multiple mechanical functions. For instance, the skin has been shown to play a critical structural role in fish locomotion by regulating wave propagation (Long et al., 1996) and by acting as an external tendon (Hebrank and Hebrank, 1986; Hebrank, 1980) but also possessed inherent hydrodynamics properties (Sudo et al., 2002) that are crucial for swimming efficiency. These properties arise from a highly organized hierarchical structure, which is characterized by its simplicity, but nevertheless, as we report in this paper, which also display rich mechanical behavior and possess a high level of tunability, robustness and multifunctionality.

The macroscopic structure of scaled skin is reminiscent of the scaled armor used by ancient Roman military, to provide resistance to penetration while retaining relative freedom of movement. While such body armors share some mechanisms and duplicate some of the performance of natural fish scale, no systematic biomimetic “transfer of technology” was attempted so far because a fundamental understanding of the mechanics of fish skin is still lacking. The objective of this paper is thus to demonstrate, via a micromechanical model, that the mechanical interactions scales and dermis may, by themselves, be responsible for a number of features that are unique to fish scales. We particularly aim to show that when subjected to different modes of deformation including bending, stretch and compression, the skin displays a characteristic strain stiffening response and is able to resist bulking/wrinkling instabilities that are typical of such thin structures. Interestingly, the model points out the relative roles of mechanical factors influencing these responses; these include the properties of individual scales, the interactions between neighboring scales, as well as the behavior of the dermis and underlying tissues.

## 2. A simplified model to link fish skin structure and properties

In this study, we concentrate on the common leptoid scale type, which can be found on higher order bony fish and characterized by their arrangement in a head to tail direction, reminiscent of the structure of roof tiles (Jawad, 2005). As these scales greatly vary in shape, size and arrangement according to the fish, we propose here to develop a modeling approach that can be used to better understand the causality between structure and properties of fish skin. To compare model and experimental observations, we further propose to focus on four specific fish: the mullet (*Mugilidae*), the white perch (*Morone americana*), the striped bass (*Morone saxatilis*) and the milkfish (*Chanos chanos*), all distinguished by their similar, but different leptoid scales.

### *2.1. Structure of teleost fish skin*

The skin of teleost fish can be though of a soft asymmetric shell that comprises a highly elastic dermis on one side and a population of thin, but stiff scale on the other. The scale structure typically displays a quasi-periodic pattern comprised of alternate rows of overlapping scales running over the length of the fish (Fig. 1a and c). In the simplest description the scales can be characterized by their shape, size and overlapping distance (Fig. 1b and d) (Browning et al., 2013). Although size can significantly vary among species, we found that the normalized overlapping distance within a single row of scale is remarkably consistent. For instance, for the four fish considered in this study, the ratio $r$ of the scale spacing to the length of a single scale was comprised between $r=0.2$ for the milkfish and $r=0.3$ for the mullet (Fig. 1c and d). Striped bass and the white perch displayed intermediate configurations with $r=0.25$. Individual scales are attached to the underlying dermis by small pockets of skin, which overlap approximately half of the scale length (Fig. 1d). These pockets are characterized by an intricate net-like structure supported by a soft elastic film (the dermis) that gives the skin its high deformability. More importantly, these pockets function as elastic sleeves for individual scales (Fig. 1d) providing resistance to their out-of-plane rotation as the overall skin bends. The scales themselves are characterized by an elastic modulus that is several orders of magnitude larger than the dermis (Zhu et al., 2013). Meanwhile, their small thickness ensures a finite bending rigidity and low weight. Overall, the interactions between the scales and the underlying dermis offer a variety of mechanical functions that are essential to fish survivability, such as freedom of motion, swimming efficiency, lightweight, robustness, protection and escape mechanism. For instance, recent studies on artificial (Browning et al., 2013) and natural scale (Zhu et al., 2013) have shown that the interaction between scales plays a significant role to resist sharp puncture.

To first investigate the role of scales on skin bending, we first designed a simple pinching test in which a skin specimen (with scales) is removed from the fish body and immediately subjected to a force-couple (with forceps) which induced large skin curvature (Fig. 2a). This strategy ensured that the skin remained fully hydrated during the test but did not allow a direct measurement of the force–displacement relation. This test was however particularly useful to understand the synergy