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# Mechanics of fish skin: A computational approach for bio-inspired flexible composites

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ABSTRACT

Natural materials and structures are increasingly becoming a source of inspiration for the design novel of engineering systems. In this context, the structure of fish skin, made of an intricate arrangement of flexible plates growing out of the dermis of a majority of fish, can be of particular interest for materials such as protective layers or flexible electronics. To better understand the mechanics of these composite shells, we introduce here a general computational framework that aims at establishing a relationship between their structure and their overall mechanical response. Taking advantage of the periodicity of the scale arrangement, it is shown that a representative periodic cell can be introduced as the basic element to carry out a homogenization procedure based on the Hill-Mendel condition. The proposed procedure is applied to the specific case of the fish skin structure of the *Morone saxatilis*, using a computational finite element approach. Our numerical study shows that fish skin possesses a highly anisotropic response, with a softer bending stiffness in the longitudinal direction of the fish. This softer response arises from significant scale rotations during bending, which induce a stiffening of the response under large bending curvature. Interestingly, this mechanism can be suppressed or magnified by tuning the rotational stiffness of the scale-dermis attachment but is not activated in the lateral direction. These results are not only valuable to the engineering design of flexible and protective shells, but also have implications on the mechanics of fish swimming.

## 1. Introduction

As a result of evolution, biological materials and structures often possess optimized properties and organizations (Vogel, 2000); this has made them a great source of inspiration for engineers seeking to develop novel materials with unprecedented performances. Biomimetics (the science of imitating nature (Vincent et al., 2006)) has recently been investigating a number of materials with remarkable properties (Meyers et al., 2006) such as seashells (Barthelat et al., 2007; Tang et al., 2003; Barthelat, 2012), glass sponge skeleton (Aizenberg et al., 2005), and toucan beaks (Meyers et al., 2006). A fundamental understanding of the relationship between structure and function of these high-performance biological materials has already given invaluable insight in how to design tomorrow's engineering materials.

The ultra-thin structure of fish skin is another example of a natural material that combines desirable mechanical properties such as compliance, resistance to penetration and lightweight but surprisingly, it has received little attention from the materials development community. In a review article on mineralized tissues, Currey (1999) noted that some fish scales are so tough that they could not be fractured even after immersion in liquid nitrogen!". While the full range of this material's function is not known, it performs especially well in a variety of tasks. First, individual scales resist penetration and provide a physical barrier against attack from predator (Zhu et al., 2011; Bruet et al., 2008; Chen et al., 2011). At a larger length-scale, the arrangement of the scales provides a flexible skin that allows for changes in a fish shape during swimming. Indeed, in addition to its superior hydrodynamics properties (Sudo et al., 2002), the scaled skin has been shown to play a critical structural role in fish locomotion by regulating wave propagation (Long et al., 2002) and by acting as an external tendon (Hebrank, 1980; Hebrank and Hebrank, 1986). These multifunctional behaviors could not be achieved without the presence of highly organized structure across several length scales (Zhu et al., 2012), tailored to respond to environmental threats.

The scaled structure of fish skin seems to be optimized to provide resistance to penetration while retaining relative freedom of movement, features that are highly desirable for next generations of body armors. A systematic biomimetic "transfer of technology"

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from this material is therefore of interest, but requires a fundamental understanding of the mechanics of fish skin. In particular, the design of a fish skin targeted for specific applications necessitates the elaboration of experimental and computational approaches that can establish the structure–property relation of the material. Features to consider include for instance the stiffness and organic composition of the scales, the mechanical interactions between scales (via friction and contact), the nature of attachment of scales to the underlying dermis as well as their morphology, shape, size, and organization. As mentioned above, fish skin has a hierarchical organization which plays a crucial role in its overall mechanical performance. However the contribution and synergies of each scale has yet to be investigated. For example, while the source of toughness for a single scale and its modes of failure have been identified (Zhu et al., 2011; Chen et al., 2011) it is still not entirely clear how neighboring scales interact to prevent penetration and to minimize skin deflection.

To better understand the structure–property relationship of fish skin, we introduce here a general computational framework based on unit cell modeling and traditional homogenization. We particularly extend the traditional Hill-Mendel relation to derive a relationship between overall curvature and bending moments of a general class of composite thin shells. Taking advantage of the structural periodicity of fish-skin, we show that a representative periodic cell can be introduced as the basic element to carry out a homogenization procedure. The proposed procedure is then applied to two cases. First, we consider a type of fish skin that is characterized by a one-dimensional scale arrangement and that serves as a benchmark problem to verify the validity of our predictions. Second, we consider the specific case of the skin of the *Morone saxatilis* which is representative of a large variety of fish with teleost scales. For each example, we use the computational framework to elucidate how structure and material's response are related. Overall, the paper is organized as follows. The next section provides a general description of the structural organization of fish skin, discusses its mechanical role as a biological material and introduce a unit cell approach to represent the entire structure via a small periodic domain. Section 2 then lays out the proposed computational strategy to establish a link between properties and structure of fish scale composites. The approach is subsequently used in Section 3 in order to numerically determine the response (moment–curvature) of the two scale structures discussed above. A discussion of the results, followed by concluding remarks, is finally provided in Section 4.

## 2. Structure, mechanics and modeling of scaled skin

As presented in Fig. 1, we here concentrate on three distinct hierarchical length scales of fish-skin, ranging from the millimeter (size of a single scale) to several centimeters (size of a fish). The size and thickness of fish scales vary significantly across species (Jawad, 2005), and this very likely influences their overall mechanical performance. For example, the thickness and diameter of the scale influences the stresses resulting from a predator's bite, which in turn influences the overall strength of the scale (Chen et al., 2011). In case of a predator's attack, the scales act collectively to prevent penetration and minimize the deflection of the skin, and therefore delay damage to the underlying tissues. Important factors influencing the behavior at this level are the mechanical behavior of individual scale, the interactions between neighboring scales, as well as the behavior of the dermis that support the scales. It was shown in Vernerey and Barthelat (2010) that these factors drive the rotation of individual scales with respect to the underlying dermis (Fig. 1), a mechanism that controls the response of the skin during longitudinal bending. Besides its organized hierarchical nature, the structure of fish scales is distinguished by the presence of both an organic and mineral phase.

The present work concentrates on a teleost fish, the *Morone saxatilis* (common name striped bass) as a model for scale geometry and arrangement. Indeed, while other scale types, such as ganoid and cosmoid, are usually stiffer and harder than teleost scales, they are currently found in only a few living fish species. Teleost scales have however largely prevailed over the course of evolution, and are now found in more than 99% of living species. This suggests that the lighter and thinner teleost scales may offer better tradeoffs between swimming speed, agility and protection. The *Morone saxatilis* is characterized by its ctenoid scales, which have a spiny posterior margin, an overall circular shape and are comprised of two main layers: a layer of bony organic structure and an inner layer of collagen (Zhu et al., 2011). The imbricate pattern of ctenoid scales gives the fish greater flexibility than in fish with cosmoid and ganoid scales and often leads to unique combinations of stiffness, hardness and toughness (Vernerey and Barthelat, 2010; Zhu et al., 2012). Due to the variety of building blocks across lengthscales, the mechanical properties of fish scale may be modified by slight changes at any level of its structure.

### 2.1. The mechanical role of scales: a simple experiment

Penetration tests, which essentially duplicate the biting attack of a predator, were performed on *Morone saxatilis* and the resulted load–deflection assessed. The tests consisted of driving a sharp needle ($\approx 30\ \mu m$ tip radius) through the skin of a fish cadaver in order to determine its resistance to puncture. More precisely, a whole, fresh striped bass (Morone saxatilis) fish, a common teleost from the northern Atlantic Ocean, was acquired from a local fish store (Montreal, QC, Canada). The fish had a length of about 30 cm. Penetration specimens were prepared by first removing the head and tail of the fish. Then, the fish was cut in half along the dorsal line. One of the halves, which included the spine, bones, muscle, epidermis (about 400 μ thick) and scales (about 300 μ thick) was placed in a bath of water (Fig. 2a), skin upwards and under the crosshead of a universal tensile machine mounted with a sharp steel needle (radius 35 μ). Using the loading machine the needle was then driven into a through the skin of the fish at a rate of about 10 μ/s, while needle displacement and force were recorded. The test was interrupted after the needle fully punctured the skin, characterized by a sharp and significant drop in force. Both load and displacement were then recorded simultaneously as shown in Fig. 2a. Penetration was performed at various skin locations and the mechanical response was evaluated in three cases: (a) when the skin was stripped off all scales (epidermis only), (b) when only one scale at the location of indent was present and (c) when all scales were present. After averaging the response over a number of different locations, the force–deflection curve shown in Fig. 2b were obtained. Generally, results show that the presence of scales increases the penetration resistance of the skin by almost tenfold. The normalized penetration force, often used to compare the performance of body armors (force divided by mass per unit surface area of protection) is 100–200 N/(kg/m2) for fish scales, which is comparable to Kevlar fabric (Termonia, 2006). This is a remarkable performance considering the relatively weak constituents of fish scales (soft collagen and brittle mineral); this gives a hint on the performances that could be achieved in a biomimetic artificial system based on stronger constituents. Interestingly, when all scales except the target scale are removed, the slope of the force–displacement decreases, suggesting some type of collective mechanism involving scales adjacent to the contact point. A thorough understanding of mechanisms responsible for this behavior can be accessed via the numerical strategy devised in this paper.