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Research paper

Mechanical properties and the laminate structure of Arapaima gigas scales

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ABSTRACT

The *Arapaima gigas* scales play an important role in protecting this large Amazon basin fish against predators such as the piranha. They have a laminate composite structure composed of an external mineralized layer and internal lamellae with thickness of 50–60 μm each and composed of collagen fibers with ~1 μm diameter. The alignment of collagen fibers is consistent in each individual layer but varies from layer to layer, forming a non-orthogonal plywood structure, known as Bouligand stacking. X-ray diffraction revealed that the external surface of the scale contains calcium-deficient hydroxyapatite. EDS results confirm that the percentage of calcium is higher in the external layer. The micro-indentation hardness of the external layer (550 MPa) is considerably higher than that of the internal layer (200 MPa), consistent with its higher degree of mineralization. Tensile testing of the scales carried out in the dry and wet conditions shows that the strength and stiffness are hydration dependent. As is the case of most biological materials, the elastic modulus of the scale is strain-rate dependent. The strain-rate dependence of the elastic modulus, as expressed by the Ramberg–Osgood equation, is equal to 0.26, approximately ten times higher than that of bone. This is attributed to the higher fraction of collagen in the scales and to the high degree of hydration (30% H_2O). Deproteinization of the scale reveals the structure of the mineral component consisting of an interconnected network of platelets with a thickness of ~50 nm and diameter of ~500 nm.

1. Introduction

Arapaima gigas is one of the largest freshwater fish in the world, reaching a length of about 2–2.5 m and a mass over 150 kg. The fish inhabits the Amazon River Basin in South America. Interestingly, it lives in harmony with the piranha, fish known for their voraciousness and sharp teeth. It has been proposed that the scales of Arapaimas serve as an armor-like protection against the sharp piranha teeth (Currey, 2010). This function of scales as armor has been demonstrated for *Polypterus senegalus* (Song et al., in press).

A number of studies on fish scales have been conducted addressing the structural arrangement, and collagen formation and orientation (Zylberberg and Nicolas, 1982; Zylberberg et al., 1988, 1992; Olson and Watabe, 1980). Most fish scales have similar material components to other hard tissues such

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