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# Lamellae Spatial Distribution Modulates Fracture Behavior and Toughness of African Pangolin Scales

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**ABSTRACT**

Pangolin scales are a durable armor whose hierarchical structure offers an avenue towards high performance bio-inspired materials design. In this study, the fracture resistance of African pangolin scales is examined using single edge crack three-point bend fracture testing in order to understand toughening mechanisms arising from the structures of natural mammalian armors. In these mechanical tests, the influence of material orientation and hydration level are examined. The fracture experiments revealed an exceptional fracture resistance due to crack deflection induced by the internal spatial orientation of lamellae. An order of magnitude increase in the measured fracture resistance due to scale hydration, reaching up to ~25 kJ/m$^2$ was measured. Post-mortem analysis of the fracture samples was performed using a combination of optical and electron microscopy, and X-ray computerized tomography. Interestingly, the crack profile morphologies are observed to follow paths outlined by the keratinous lamellae structure of the pangolin scale. Most notably, the inherent structure of pangolin scales offers a pathway for crack deflection and fracture toughening. The results of this study are expected to be useful as design principles for high performance biomimetic applications.

Keywords: Pangolin scale; Fracture toughness; Hierarchical structure; Bio-inspired design principles; Biomaterials



## 1. INTRODUCTION

Through millions of years of evolution, biological organisms have developed a variety of strategies for their protective systems in order to increase their survivability in response to environmental constraints. In this regard, natural dermal armors have been one of the most diverse protection systems employed by species against their predators (Yang et al., 2013b). These armors, which are commonly protecting the softer body organs, can be found as rigid shell materials such as nacre (Mayer, 2005) in mollusks or segmented flexible armors atop the skin, as in fish (Zhu et al., 2012). The latter armors, which commonly present in the form of scales, are found in a wide range of animals such as reptiles (Abdel-Aal and El Mansori, 2011), mammals (Chen et al., 2011) and most fish (Porter et al., 2016). The main differences in between these armors are rooted in their hierarchical structure and compositions, which make them differentiable from each other. For example, in the case of fish, collagen-based biopolymer fibers (Dastjerdi and Barthelat, 2015) play a key role in providing flexibility, whereas nacre is comprised primarily of mineral tablets (Espinosa et al., 2009) which provides significant rigidity and excellent crack-arresting properties (Barthelat et