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# Surface protection in bio-shields via a functional soft skin layer: Lessons from the turtle shell

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ABSTRACT

The turtle shell is a functional bio-shielding element, which has evolved naturally to provide protection against predator attacks that involve biting and clawing. The near-surface architecture of the turtle shell includes a soft bi-layer skin coating – rather than a hard exterior – which functions as a first line of defense against surface damage. This architecture represents a novel type of bio-shielding configuration, namely, an inverse structural–mechanical design, rather than the hard-coated bio-shielding elements identified so far. In the current study, we used experimentally based structural modeling and FE simulations to analyze the mechanical significance of this unconventional protection architecture in terms of resistance to surface damage upon extensive indentations. We found that the functional bi-layer skin of the turtle shell, which provides graded (soft-softer-hard) mechanical characteristics to the bio-shield exterior, serves as a bumper–buffer mechanism. This material-level adaptation protects the inner core from the highly localized indentation loads via stress delocalization and extensive near-surface plasticity. The newly revealed functional bi-layer coating architecture can potentially be adapted, using synthetic materials, to considerably enhance the surface load-bearing capabilities of various engineering configurations.

## 1. Introduction

Being the product of natural selection over millions of years of evolution, bio-shielding elements have evolved to provide mechanical protection against a variety of load-bearing conditions. As such, they can both resist structural loads (e.g., bending moments and torsion) that tend to macroscopically deform the shield shape (e.g., (Vincent, 2005; Chen et al., 2008a, 2008b; Krauss et al., 2009; Damiens et al., 2012; Magwene and Socha, 2013; Fish and Stayton, 2014)), and they can sustain localized surface tractions, which are typically associated with predator biting attacks, which tend to crack the shield (e.g., (Bruet et al., 2008; Wang et al., 2009; Yao et al., 2010; Song et al., 2011; Amini et al., 2014, 2015)). The two functions are achieved through the complex hierarchical structure of bio-shields; while resistance to structural loads is associated with the macro-structural–mechanical characteristics of the shield as a whole, the ability to sustain localized surface tractions is related to the near-surface characteristics and, in particular, to the mechanical rigidity and hardness of the shield exterior.

Natural bio-shielding elements are fundamentally structured as hierarchical bio-composites that comprise several micro-scale layers, each of which is structured as an integrated array of small-scale reinforcing elements (nano-fibrils, nano-platelets, etc.) and bio-polymers (Barth, 1973; Vincent and Wegst, 2004; Chen et al., 2008a, 2008b; Dunlop and Fratzl, 2010; Dunlop et al., 2011; Bar-On and Wagner, 2013; Meyers et al., 2013; Moussian, 2013; Barthelat et al., 2016; Naleway et al., 2016). In recent years, intensive research has addressed the structure and the mechanical behavior of various shielding materials, most notably seashells, teeth, fish scales, arthropod exoskeletons, and the armored osteoderms of the armadillo, alligator, and the shell of the turtle. Seashells, for example, possess an external hard prismatic layer, which serves as a first line of defense against predator attacks; this layer is underlaid with a high-toughness nacreous layer, which resists crack propagation and reduces the risk of catastrophic damage to the shell (Meyers, 2008). Similarly, teeth possess a highly mineralized hard-but-brittle enamel coating, which serves as a grinding surface for food and is underlaid with a more compliant and less mineralized dentin region (Chen et al., 2008a, 2008b; Bar-On and Wagner, 2012). The enamel and dentin are linked by an interfacial dentin–enamel junction, which has a lower degree of hardness and stiffness than either dentin or enamel, thus providing crack-arresting capabilities and preventing enamel cracks from propagating toward the inner part of the tooth (Chai et al., 2009; Imbeni et al., 2005; Shimizu and Macho, 2007). The protective exoskeleton of various arthropods,

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including insects (Barth, 1973; Vincent and Wegst, 2004; Moussian, 2013; Barbakadze et al., 2006), spiders (Politi et al., 2012; Bar-On et al., 2014), lobsters (Raabe et al., 2005), and crabs (Chen et al., 2008a, 2008b), typically includes a lamellar architecture of chitin nanofibrils arranged in helical lamellar patterns (twisted plywood). These lamellae form external and internal layers (exocuticle and endocuticle, respectively) of increasing densities, and, thereby, enhance the mechanical properties of the cuticle toward its exterior. In addition, the near-surface region of the arthropod exoskeleton is commonly associated with an increase in the mineralization and sclerotization levels and with the presence of metal ions, which stiffen and harden the exoskeleton (Amini et al., 2014; Politi et al., 2012; Degtyar et al., 2014). Surprisingly, despite the obvious distinctive evolutionary origin of the various natural shielding elements across taxa, all these elements share the same generic structural–mechanical design: a hard exterior underlaid with a softer interior. In contrast, the osteoderms of the armadillo and alligator and the shell of the turtle demonstrate an alternative structural strategy (Krauss et al., 2009; Damiens et al., 2012; Magwene and Socha, 2013; Fish and Stayton, 2014; Rhee et al., 2009; Balani et al., 2011; Chen et al., 2011, 2014, 2015; Achrai and Wagner, 2013, 2015 Achrai et al., 2014, 2015, 2015; Sun and Chen, 2013 and see the review on turtle shells by Achrai and Wagner in this issue), which incorporates a soft skin coating (namely, a keratin–collagen bi-layer) overlaid with a harder boney core (Fig. 1). The skin coating is mechanically inferior to the underlying boney core, and, obviously, induces a negligible effect on the macro-structural rigidity of the shield (Achrai et al., 2014). However, it appears to play a significant role in adsorbing impact energy, and thereby to increases the damage resilience of the bio-shield against sudden mechanical loads (Achrai et al., 2015).

In the past few years, the resilience of hard-coated bio-shields to surface damage was extensively analyzed in a wide range of biological systems, among which are fish scales, which typically comprise a highly mineralized hard-and-brittle exterior, underlaid by a less mineralized softer layer (Bruet et al., 2008; Song et al., 2014; Zhu et al., 2012; Dastjerdi and Barthelat 2015). Experimental and numerical studies of fish scales demonstrated that low-force indentations (i.e., indentations that do not cause coating failure) produce shallow penetrations, which only damage the hard surface layer. Higher indentation forces, i.e., beyond the coating failure point, severely fracture the hard surface layer and damage the softer underlying material. Finite-Element (FE) simulations indicate that the hard coating functions as a load barrier by confining the high-stress fields to the scale exterior and screening the indentation effects from the inner regions. Other hard-coated biological and bio-inspired shielding elements demonstrated similar effects (e.g. (Wang et al., 2009; Yao et al., 2010; Amini et al., 2014, 2015; Chintapalli et al., 2014; Rudykh et al., 2015)).

Whereas the surface protection capabilities of the hard-coat bio-shielding architectures are straightforward, it is less intuitive to understand how soft-coat architectures promote surface protection, if, indeed, they do. Nevertheless, several studies on synthetic materials have implied that a soft skin coating overlaid on a rigid substrate may protect against surface damage (Jayachandran et al., 1995; Suresh, 2001; Choi et al., 2008) and even detain near-surface crack propagation (Kolednik, 2000; Simha et al., 2003). In line with these studies, experimental evidence from impact tests on the turtle shell, which is overlaid with two layers of soft skin, indicate that the skin plays a critical role in shielding against impact damage (Achrai et al., 2015). In the current investigation, we focused on the turtle shell as a specific case study, representative of the large family of soft-coated bio-shielding elements, and analyzed its resistance to surface damage upon extensive indentations. First, we used experimental measurements to establish a numerical structural–mechanical model for the turtle shell. Then, we investigated the role of each individual skin layer in protecting the turtle shell against extensive indentations. Finally, we studied the effect of the difference in the mechanical properties of the two layers comprising the turtle-shell skin and analyzed the effect of indenter sharpness and physiological hydration conditions on the resultant damage patterns.

## 2. Materials and methods

### 2.1. Experimental

Two carapaces from red-eared slider turtles (*Trachemys scripta elegans*) were used for the mechanical testing. The samples were kept frozen (−70 °C) and were allowed to defrost and dry under ambient conditions for 24 h prior to measurement; no further treatment was conducted to the samples. Micro-indentation experiments were conducted by using a Hysitron TI 950 TriboIndenter, equipped with a high-load cell (3D OmniProb) allowing extensive indentations of a few tens of micrometers in depth and a few Newtons in load. A conical diamond probe tip (tip radius: 5.26 µm; angle: 57.03°) was used for the experiments. The experiments included a 5-s loading-up stage (linear ramp) up to a maximal load, which was kept steady for 20 s to exclude creep effects, followed by a 5-s unloading stage (linear ramp). The indentation locations were carefully selected to avoid natural roughness problems of the native (unpolished and untreated) carapace surface.

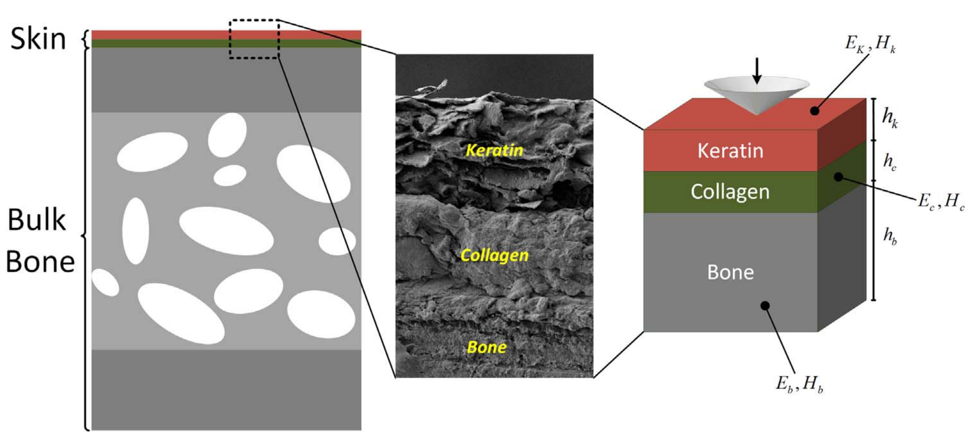


**Fig. 1.** Schematic description and a SEM image of the near-surface architecture of the turtle shell (adapted from (Achrai and Wagner, 2013; Achrai et al., 2015)). The shell is viewed as a layered composite material with a thick boney bulk (porous boney interior enclosed by dense boney layers) overlaid with a thin keratin–collagen bi-layer skin. The near-surface region of the shell is modeled as a tri-layered segment, composed of a boney core of thickness $h_b$, coated by keratin and collagen layers of thickness $h_k$ and $h_c$, respectively. Young's modulus (E) and the hardness (H) of the keratin, collagen, and bone layers are indicated by $E_k$, $E_c$ and $E_b$, and $H_k$, $H_c$ and $H_b$, respectively. Note that, typically, $(E_c,H_c) < (E_k,H_k) < (E_b,H_b)$.