Journal of the Mechanical Behavior of Biomedical Materials 72 (2017) 1–5

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

journal homepage: www.elsevier.com/locate/jmbbm

Non-ideal effects in bending response of soft substrates covered with biomimetic scales

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ARTICLE INFO

Keywords:
Biomimetic scales
Fish scales
Edge effects
Self-contact
Nonlinear response

ABSTRACT

Biomimetic scales are known to substantially alter the mechanics response of the underlying substrate engendering complex nonlinearities that can manifest even in small deformations due to scales interaction. This interaction is typically modeled using a-priori homogenization with an enforced periodicity of engagement. Such a framework is fairly useful especially when dealing with the structural length scale which is at least one order of magnitude greater than the scales themselves since individual tracking of a large number of scales become insurmountable. On the other hand, this scheme makes several assumptions whose validity has not yet been investigated including infinite length of the substrate and rigidity of the scales. The validity of these assumptions and the accuracy and limitations of associated analytical models are investigated. Finite element based numerical studies were carried out to identify the critical role of edge effects and other non-ideal behavior such as violation of periodicity and nonlinear constitutive response on scale rotation. Our investigation shows that several important quantities show a strong saturation characteristic which justify many of the simplifying assumptions whereas others need much greater care.

Matter and topology can both be used in conjunction to endow materials with highly non-traditional properties as evident in recently expanding research in metamaterials (Dimas et al., 2013; Dimas and Buehler, 2014; Ebrahimi et al., 2017; Haghpanah et al., 2016; Mousanezhad et al., 2015a, 2015b; Silverberg et al., 2014; Zhu et al., 2012). Such 'topological' strategies are also common in biological materials which are denuded of material choices. Topological organization can also boost multifunctionality to a great degree due to greater freedom in organization of material (Cowin, 2001; Gibson et al., 2010; Oftadeh et al., 2015). In this context, scales which are ubiquitous in animal kingdom are an ideal template for study. They are highly variegated and yet universal exhibiting a wide array of material properties, geometrical shapes and functions (Bruet et al., 2008; Ghiradella, 1991; Huang et al., 2006; Naleway et al., 2016; Yang et al., 2015; Zimmermann et al., 2013). Therefore, investigating materials which mimic the overall strategy of scaly surfaces can provide us with an important avenue of materials research.

Substrates with biomimetic scales demonstrate a classic biological strategy of structural and functional enhancements using topology of material organization (Li et al., 2015; Martini and Barthelat, 2016a, 2016b; Rudykh et al., 2015). This leverage partly relies on modulating the mechanics of deformation using intricate self-contact of scales driven by the geometry of the deforming structure (Ghosh et al., 2014; Vernerey and Barthelat, 2010, 2014). The difference in scales engagement geometry which depends on the curvature of the substrate, dictates the contact behavior kinematics of the scales as shown in Fig. 1(a). Here, a lab-scale sample of biomimetic scaly substrate was constructed using two polymers of highly contrasting stiffness such as Vinylpolysiloxane(VPS) and Acrylonitrile Butadiene Styrene (ABS) with the stiffer material used as scale and the softer as substrate material. This scales self-contact can substantially change the bending characteristic of the biomimetic substrate with enhanced stiffness even in small deformations, Fig. 1(b).

This general paradigm to introduce reversible stiffness gains has been studied in several recent studies which demonstrated the potential of biomimetic scales as high performance modern materials (Funk et al., 2015; Martini and Barthelat, 2016a; Wang et al., 2016; Yang et al., 2014). Specifically, this high contrast (materials with widely different stiffness) archetypical system has been modeled using a rigidity assumption on the scale and a linear elastic assumption for the substrate in the past (Ghosh et al., 2014, 2016). Although seemingly simple, using direct numerical simulation such as using finite elements (FE) to probe the behavior of more complicated scales distribution and geometry even for simple material behavior is prohibitively expensive especially for more densely packed scales. Therefore, investigations till date have used FE for less densely packed scales and homogenization

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http://dx.doi.org/10.1016/j.jmbbm.2017.04.019
Received 31 January 2017; Received in revised form 11 April 2017; Accepted 14 April 2017
Available online 15 April 2017

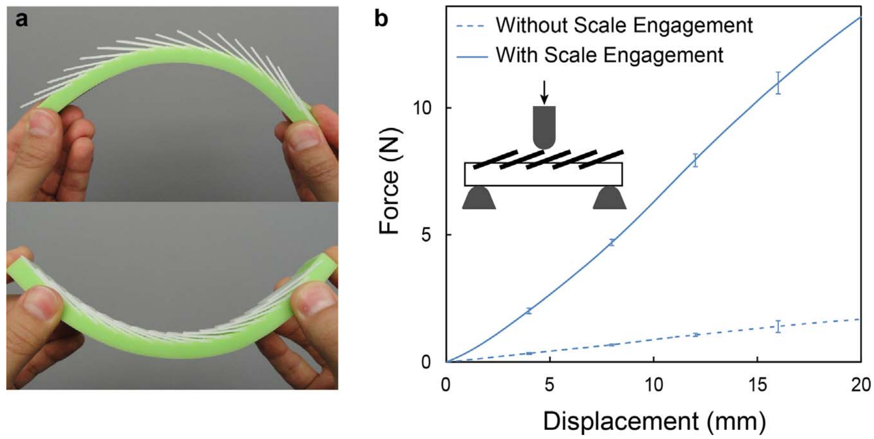

Fig. 1. (a) A manual illustration of the system deformation under bending in two opposite directions. (b) Comparative force response of biomimetic substrate-scale system and substrate with no scale under three-point bending experiment. (Adopted from Ghosh et al. APL (2014)).

for more densely packed regime invoking an implicit continuum level averaging of scales behavior with the imposition of strong periodicity. This periodicity provides a classical representative volume element (RVE), a natural averaging unit for material behavior. These idealized frameworks have improved our understanding of the most fundamental mechanisms of nonlinear behavior as well as revealed quantitative broad contours of performance of biomimetic scales (Browning et al., 2013; Ghosh et al., 2014, 2016; Vernerey and Barthelat, 2014; Vernerey et al., 2014).

However, these simplifying assumptions themselves have not been tested for limits of applicability for simple realistic imperfections. Understanding the effect of such imperfections would provide greater confidence in extending these models to more complex systems and also introduce empirical design parameters for extending purely theoretical models. The first step in that direction entails the determination of the limits of simplifications of the existing models to ascertain their extension. In this paper, we carry out extensive numerical studies to highlight the effectiveness and limitations of the simplifying assumptions typically employed in the high contrast biomimetic substrates (Ghosh et al., 2014) and set the stage for future more complex numerical and semi-analytical models for a more expansive biomimetic scaly substrates design.

At a broad level, using the regularity of scales engagement, modeling of local and global bending modes has traditionally relied on extracting performance characteristics through closed form relationships using a combination of elasticity, homogenization and imposition of periodicity (Ghosh et al., 2014, 2016; Vernerey and Barthelat, 2010, 2014; Vernerey et al., 2014) which leads to a classical representative volume element (RVE), a unit of averaging (Ghosh et al., 2014), Fig. 2.

The elasticity of the scales manifests itself in two different ways. First, elastic energy is absorbed by the substrate itself and thereafter additionally from the rotation of the scales themselves if the scales are sufficiently stiff neglecting their own deformation. Assuming linear elasticity for the substrate and rigidity for the highly stiff scale, the effect of scales rotation is often modeled as a torsional linear spring characterized by a fixed spring constant (Ghosh et al., 2014; Vernerey and Barthelat, 2010). A closed form expression for the torsional spring constant can be found by assuming that individual scales are well isolated from the adjacent scales (dilute scale distribution) as well as from the boundaries (remote scale location). At this point, imposing rigidity on the scale, the spring constant can be shown follow the analytical relationship (Ghosh et al., 2014) $K_{B,Ideal} = C_B E_B D^2 (\frac{L}{D})^n$ where E_B is the young's modulus of the base, D is the thickness of the scale and L is the embedded length of the scale, Fig. 3a (inset) and C_B,n are constants. Using an elastic system consisting of a very large substrate with a rigid prismatic body embedded in it simulates the remoteness and dilution of scales distribution. Extensive parametric FE simulations on this system yielded a very close fit for $L/D>10$ with $C_B \approx 0.66$. ,n = 1.75 (Ghosh et al., 2014).

However, in a non-ideal case, the thickness of the substrate is often only a few times more than the embedded length of the scales L which can influence the remoteness assumption. To this end, we define an index of deviation $\phi_h = \log\,(K^h_{B,NonIdeal}/K_{B,Ideal})$ where $K^h_{B,NonIdeal} = K_{B,NonIdeal}(h)$ is the FE computed stiffness for different values of normalized substrate thickness h/L whereas the width of the substrate is taken to be sufficiently large (dilute). In the FE models, rigid body constraint was imposed on the scales and two dimensional plain strain elements with sufficient mesh density was employed to achieve convergence. Substrate was clamped at the bottom and free at sides while a linear elastic material of E_{base}=2e4 Pa was assigned to the substrate. Initial angle of scale was 90° and rotation was applied on the scale at surface of the substrate and then exerted reaction moment was read to calculate K_B. The results plotted in Fig. 3(a) for various embedding aspect ratios L/D show a very strong deviation even when the substrate thickness is a

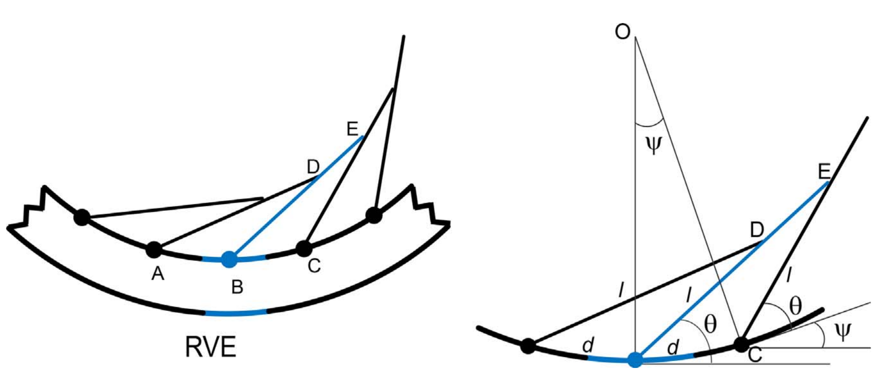

Fig. 2. RVE geometry of the biomimetic structure under bending load. (Adopted from Ghosh et al. APL (2014)).