Journal of the Mechanics and Physics of Solids 92 (2016) 195–209

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

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

Stability of hard plates on soft substrates and application to the design of bioinspired segmented armor

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ARTICLE INFO

Article history:
Received 6 October 2015
Received in revised form
7 April 2016
Accepted 8 April 2016
Available online 11 April 2016

Keywords:
Bio-inspiration
Segmented dermal armor
Structural stability
Hard coating

ABSTRACT

Flexible natural armors from fish, alligators or armadillo are attracting an increasing amount of attention from their unique and attractive combinations of hardness, flexibility and light weight. In particular, the extreme contrast of stiffness between hard plates and surrounding soft tissues give rise to unusual and attractive mechanisms, which now serve as model for the design of bio-inspired armors. Despite a growing interest in bio-inspired flexible protection, there is little guidelines as to the choice of materials, optimum thickness, size, shape and arrangement for the protective plates. In this work, we focus on a failure mode we recently observed on natural and bio-inspired scaled armors: the unstable tilting of individual scales subjected to off-centered point forces. We first present a series of experiments on this system, followed by a model based on contact mechanics and friction. We condense the result into a single stability diagram which capture the key parameters that govern the onset of plate tilting from a localized force. We found that the stability of individual plates is governed by the location of the point force on the plate, by the friction at the surface of the plate, by the size of the plate and by the stiffness of the substrate. We finally discuss how some of these parameters can be optimized at the design stage to produce bio-inspired protective systems with desired combination of surface hardness, stability and flexural compliance.

1. Introduction

Over millions of years, evolutionary pressures have led to high-performance protecting materials and systems, emerging from an “arm's race” between predators and preys. These natural armors, which include mollusk shells, testudines carapace and arthropods exoskeleton, display a wide range of compositions, architectures and sizes to resist a variety of threats such as sharp puncture, laceration or crushing. The armor of animals with fast locomotion presents particularly interesting features. These protective materials must be hard to resist puncture, yet compliant and light to allow for unimpeded movement. In natural organisms this design contradiction is often resolved by segmentation of the hard protective layer into plates of finite size. Typical examples of segmented armors include the scaled skins of fishes and snakes or the osteoderms of armadillos and crocodiles. These natural dermal armors are light-weight, locally hard to resist puncture and yet flexible at larger length scales to allow for motion (Vernerey and Barthelat, 2010).

Manmade segmented armors were already used in ancient times, for example in Roman antiquity (Hamblin, 1996) or

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http://dx.doi.org/10.1016/j.jmps.2016.04.009
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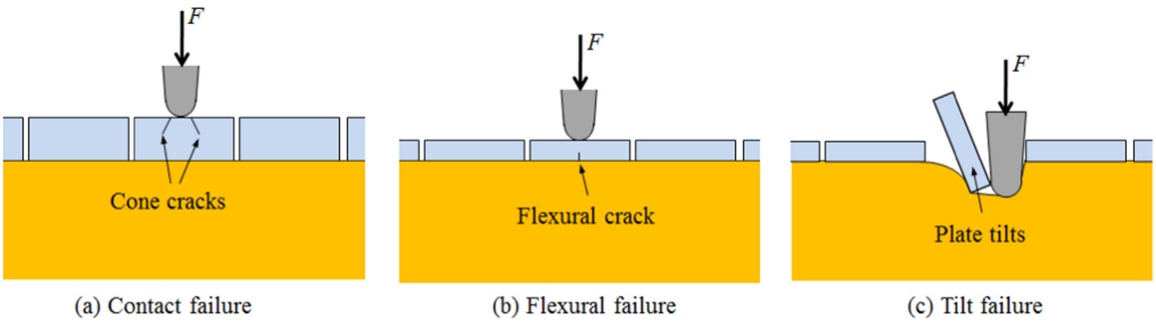

Fig. 1. Three possible failure modes for segmented stiff plates on soft substrate subjected to indentation.

Japanese medieval times (Robinson, 2002). More recently, a protective equipment based on individual ceramic plates was patented under the name of “Dragon Skin” (Neal, 2003). Modern applications include personal armor systems, industrial protective gear or compliant robotics. Despite a growing interest in bio-inspired flexible protection, there is little guideline for the choice of materials, optimum thickness, size, shape and arrangement for the protective plates. Flexible natural armors can provide a powerful source of inspiration to design and optimize better synthetic protective systems. In recent years, the performance and mechanics of armadillo's carapace (Chen et al., 2011) and fish skin (Zhu et al., 2012; Yang et al., 2013a, 2013b, 2014) was systematically studied. These studies mainly focused on the mechanical response of individual scales subjected to indentation and/or uniaxial tension (Bruet et al., 2008; Zhu et al., 2012; Yang et al., 2014; Lin et al., 2011; Marino Cugno Garrano et al., 2012). Scale-substrate and scale-scale interactions play an important role in resisting predator

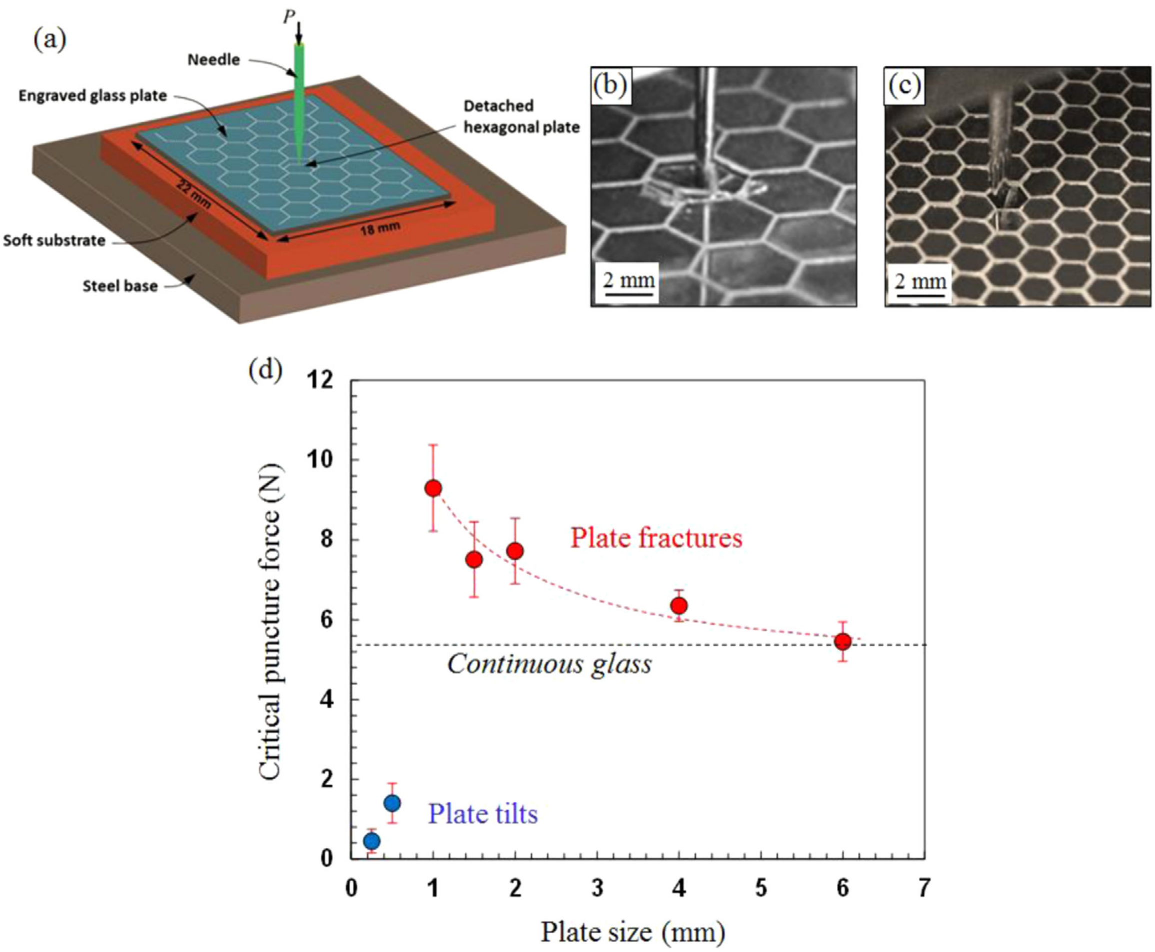

Fig. 2. Puncture experiments on segment glass layer on a soft substrate: (a) experimental setup; in-situ images showing (b) flexural failure and (c) tilt failure; (d) critical puncture force as function of plate size: the critical puncture force increases when the plate size is reduced, but below a critical threshold (plate size ~ 0.75 mm) the critical force is much lower because the plate tilts (adapted from Chintapalli et al., 2014).