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Adhesion design maps for fibrillar adhesives: The effect of shape

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Abstract

The biomimetic reproduction of adhesion organs, as found in flies, beetles and geckoes, has become a topic of intense research over the past years. Successes, however, have so far been limited. This is due to the vast range of parameters involved, including fibril size, elastic modulus, contact shape, surface roughness and ambient humidity. In previous studies, design and materials selection charts to determine the optimum materials and design combination for dry adhesive systems have been established. The effect of shape on the adhesive properties of single fibers and fiber arrays has also been a research focus. In this paper both approaches are combined to provide more advanced guidelines for the design of optimal adhesive structures.

Keywords: Gecko adhesion; Contact mechanics; Surface patterning; Shapes; Materials selection

1. Introduction

The adhesion of fibrillar surfaces due to molecular (van der Waals) forces is subject to a strong size effect: the splitting of large contacts into many smaller ones leads to an improvement in adhesion [1,2]. This suggests an explanation for the finding that bigger animals exhibit finer adhesive structures. It has recently become clear that van der Waals interactions are mostly responsible for the adhesion of geckos [3–6], while capillary forces may contribute to the adhesion [7,8], in some cases significantly. In a recent paper [9], these concepts were distilled into "adhesion design maps" that can guide the implementation of artificial adhesion systems by suggesting optimal dimensions and material properties. In another paper, different scaling laws were found for various contact shapes [10]. The present paper attempts to extend the concept of adhesion design maps to non-spherical contact shapes, including those that exhibit an axial asymmetry and thus allow easy detachment in the appropriate pulling direction. The objective is to eventually develop predictive capabilities for reproducing biomimetic adhesion systems (Table 1).

A typical adhesion design map proposed previously for spherical contacts [9] is shown in Fig. 1. It displays graphically the propensity of different mechanisms which limit the adhesive strength (Fig. 1) and ultimately may guide the design process: fiber fracture, ideal contact strength, adaptability, apparent contact strength and condensation. The axes chosen describe the elastic modulus of the fibers and their radius. The "fiber fracture" criterion (blue) acknowledges that, for very thin fibers, the adhesion strength will exceed their theoretical fracture strength. The limit of "ideal contact strength" (red) is given by an ideally fitting contact between the two surfaces, without necessity for elastic deformation. As a certain elastic compliance is necessary to adapt to rough surfaces, the limit of "adaptability" (green) was introduced. The apparent contact strength σ_{app} (black), i.e. the pull-off force divided by the apparent contact area A_{app}, is shown as contours superimposed on the maps. When the fibers tend to stick to each other, rather than to the contact surfaces, the "condensation" (or clumping, matting) limit (cyan) has been reached. As suggested by Spolenak et al. [9] we can define a conode

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Table 1
List of symbols.

a	Contact radius (m)
A_{app}	Apparent contact area (m^2)
A_c	Actual contact area (m^2)
A_f	Contact area of single fiber (m^2)
b	Characteristic length of surface interactions (m)
C	Geometrical factor (-)
E	Young's modulus (Pa)
E^*	Reduced Young's modulus (Pa)
E_{eff}	Effective Young's modulus (Pa)
E_{opt}	Optimum Young's modulus (Pa)
f	Pillar packing density (-)
h	Tape thickness (m)
P_c	Pull-off force (N)
q	Shape parameter (-)
R	Fiber radius (m)
R_{opt}	Optimal fiber radius (m)
α	Peel-off angle of elastic tape (°)
γ	Work of adhesion (J/m^2)
γ'	Work of adhesion between two fiber tips (J/m^2)
γ_{eff}	Effective work of adhesion (J/m^2)
λ_{opt}	Optimal fiber aspect ratio (–)
ν	Poisson's ratio (–)
σ^*	Interfacial strength (Pa)
σ_{app}^{opt}	Optimum apparent contact strength (Pa)
σ_c	Pull-off strength (Pa)
σ_f	Axial fiber stress (Pa)
σ_m	Tensile strength (Pa)
σ_{th}	Theoretical contact strength of van der Waals bonds (Pa)
σ_{th}^f	Theoretical fiber fracture strength (Pa)

(orange) in the maps. The conode links the loci of optimum apparent contact strength, while avoiding condensation and ensuring adaptability. These loci are shown as black dots at the intersections of the green and cyan lines for different values of the fiber aspect ratio λ. The optimum adhesive is found at the intersection of the conode with the fiber fracture limit, as indicated in the map (red circle). In the following, new design maps based on this original principle are presented for a variety of shapes (Fig. 2).

2. Design map for flat tips

First we wish to formulate the equations for flat-tip ended fibers. Lacking a simple analytical solution otherwise, we assume that the fibers are stiff in relation to the substrate and in perfect contact. The contours of apparent contact strength σ_{app} require an expression for the pull-off force P_c of a flat punch [10–12]

$$P_c = \sqrt{8\pi E R^3 \gamma}, \quad (1)$$

where E is the Young's modulus, R the fiber radius and γ the work of adhesion. With an apparent contact area of $A_{app} = R^2\pi/f$, where f is the area fraction of fibers, and setting $\sigma_{app} = P_c/A_{app}$ the maximum fiber radius for a specified value of σ_{app} is defined as follows:

$$R \leqslant \frac{8E\gamma f^2}{\pi\sigma_{app}^2}. \quad (2)$$

Note that for flat tips the maximum radius scales linearly with Young's modulus, in contrast to spherical contacts, where it was independent of E ([9], see also Fig. 1).

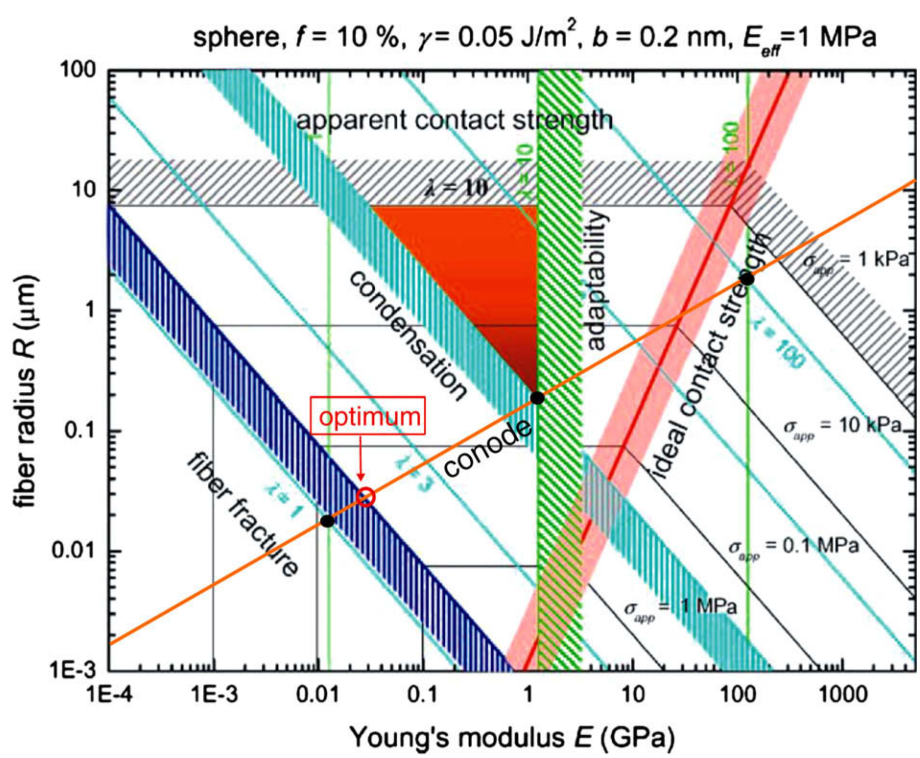

Fig. 1. Typical adhesion design map for spherical contact elements as developed in a previous publication by Spolenak et al. [9]. The blue line indicates the criterion of fiber fracture, the red line the ideal contact strength. The limit of fiber condensation is indicated by the cyan lines and the adaptability by green ones. The black lines are contours of equal apparent contact strength. In addition, the conode and the optimum design parameters are indicated.