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Numerical simulation of the edge stress singularity and the adhesion strength for compliant mushroom fibrils adhered to rigid substrates

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ABSTRACT

Bio-inspired adhesion of micropatterned surfaces due to intermolecular interactions has attracted much research interest over the last decade. Experiments show that the best adhesion is achieved with compliant "mushroom"-shaped fibrils. This paper analyses numerically the effects of different mushroom shapes on adhesion to a rigid substrate. When a remote stress is applied on the free end of a fibril perfectly bonded to a rigid substrate, the resultant stress distribution along the fibril is found to change dramatically between the straight punch and mushroom fibrils. A singular stress field is present at the edge of the fibril where it contacts the substrate and, in this work, the amplitude of the singularity is evaluated for fibrils perfectly bonded to a flat substrate so that sliding cannot occur there. This exercise is carried out for fibril geometries involving combinations of different diameters and thicknesses of the mushroom cap. By assuming a pre-existing detachment length at the corner where the stress singularity lies, we predict the adhesive strength for various mushroom cap shapes. Our study shows that a smaller stalk diameter and a thinner mushroom cap lead to higher adhesive strengths. A limited number of results are also given for other shapes, including those having a fillet radius connecting the stalk to the cap. The results support the rational optimisation of synthetic micropatterned adhesives.

1. Introduction

Animals in nature possess different hairy contact structures such as straight punches, spherical and conical caps, toroidal suction cups, etc. The climbing abilities of geckos have inspired many researchers to develop reusable, reversible adhesives. Gecko feet are covered with millions of hierarchically structured hairs or setae with sizes ranging from millimetres to nanometres (Autumn et al., 2000; Gorb, 2007; Hiller, 1968). The smallest level of hierarchical structure is patterned with finer fibrils; these observations suggest that finer fibrils are associated with better adhesion (Arzt et al., 2003). This insight has led to formulation of the concept of "contact splitting" (Arzt et al., 2003). The present group (Huber et al., 2007; Huber et al., 2005a; Huber et al., 2005b; Huber et al., 2008; Orso et al., 2006), as well as Autumn et al. (Autumn et al., 2006; Autumn et al., 2002; Jin et al., 2012) and Jagota et al. (Jagota and Bennison, 2002; Jagota et al., 2000) have done extensive research on this topic to understand the mechanism behind gecko adhesion. Experiments reveal that either intermolecular van der Waals forces (Autumn et al., 2002) or capillary forces (Huber et al., 2005b) play a major role in the adhesion mechanism.

Polydimethylsiloxane (PDMS) is one of the most widely used materials for the fabrication of gecko inspired adhesives. PDMS has a Poisson's ratio close to 0.5 and a Young's modulus ranging from approximately 100 kPa to approximately 10 MPa, depending on the amount of crosslinking. It is chemically inert, non-toxic and during preparation hardens quickly at elevated temperatures. It has been experimentally proven that PDMS surfaces patterned with fibrils offer better adhesion against a stiff smooth substrate than an unpatterned PDMS surface (Greiner et al., 2007; Hui et al., 2004; Sitti and Fearing, 2003; Yurdumakan et al., 2005).

Experiments with artificial patterned structures have shown that contact cap shape plays an important role in improving adhesion; compared to several different contact geometries, the mushroom fibril has generally been found to adhere best (Del Campo et al., 2007; Gorb et al., 2007; Greiner et al., 2007;

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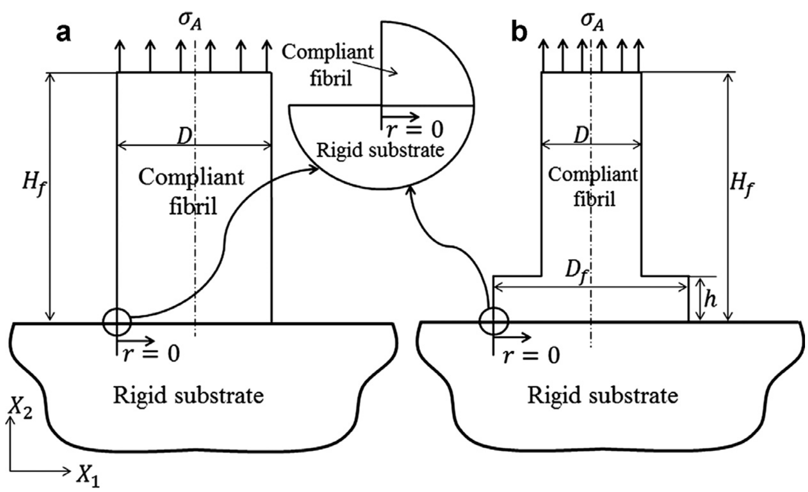

Fig. 1. Schematics of (a) a straight punch shaped fibril without a mushroom cap and (b) a fibril with a mushroom cap, both adhered to a rigid substrate.

Kim and Sitti, 2006). Adhesion also depends on other phenomena such as structural instability due to fibril buckling when they are compressed axially (Paretkar et al., 2013), misalignment of the adhering surfaces (Micciché et al., 2014), surface roughness (Canas et al., 2012; Huber et al., 2007; Persson and Gorb, 2003; Persson and Tosatti, 2001) and backing layer thickness (Kim et al., 2007; Long et al., 2008). In most of the experiments exploring the adhesion of such patterned surfaces, compliant fibrils are pressed against a stiff spherical substrate and adhesive strength is measured during subsequent tensile loading. The fabrication and experimental exploration of such synthetic adhesives at the micrometre and nanometre scale are well established in the laboratory setting, and different parameters such as structure aspect ratio, fibril size and cap shape are well investigated. However, there is still a lack of theoretical models required for a better understanding of the adhesive interactions. The purpose of the present paper is to fill some of the gaps.

There have been on-going efforts by several researchers in the past years to understand the details of gecko adhesion through the development of various analytical models (Gao et al., 2005; Glassmaker et al., 2004; Glassmaker et al., 2005; Hui et al., 2004; Yao and Gao, 2006) and numerical simulations (Aksak et al., 2011; Aksak et al., 2014; Carbone and Pierro, 2012; Khaderi et al., 2014; Spuskanyuk et al., 2008). Spuskanyuk et al. (Spuskanyuk et al., 2008) addressed the influence of shape on adhesion and detailed the reason why mushroom fibrils show better performance than simple punch shapes. Aksak et al., 2011, demonstrated the influence of mushroom aspect ratio on adhesion, and Aksak et al., 2014 used a Dugdale cohesive zone model for mushroom like fibrils to predict the optimal shape for adhesion. They found that adhesion depends on the edge angle and the ratio of stalk radius to the outer fibril radius. Carbone and Pierro, 2012 have calculated the dependence of adhesive performance on the mushroom cap geometry and suggested an optimal shape for adhesion. Khaderi et al., 2014 provided a detailed analysis of the corner stress singularity at the edge of the fibril, its influence on the stress intensity factor for a small interface detachment near that edge, and the resulting influence on the detachment strength for a single compliant flat bottomed cylindrical fibril attached to a compliant or a rigid substrate.

In this work, we consider the corner stress singularity at the edge of a perfectly bonded compliant mushroom fibril on a rigid substrate where sliding of the fibril relative to the substrate is forbidden. In particular, we investigate how the mushroom cap geometry, including its thickness and diameter, influences the adhesive strength. We follow the approach introduced by Akisanya and Fleck, 1997 to describe the corner stress singularity to explore the mechanics of detachment of 2D and 3D fibrils, thus extending the work of Khaderi et al., 2014 to mushroom caps. To evaluate the parameters of the corner stress singularity, we use finite element analysis, utilizing the commercial finite element software Abaqus (ABAQUS 6.11 Documentation, 2011), to solve for the stresses, strains and deformations in compliant fibrils adhered to a rigid substrate as shown in Fig. 1.

2. Analytical solution for the corner singularity

We consider a compliant fibril adhered to a rigid substrate without any interfacial crack. The fibril is treated as an incompressible, isotropic elastic solid, and the edge of the fibril always meets the substrate at right angles. The fibril material is forbidden to slide on the substrate at the interface between them. The boundary condition on the compliant material at the interface with the substrate is therefore one where the displacement is zero. When a tensile load is applied to the fibril as shown in Fig. 1, there will be a stress singularity at the fibril edge where it touches the substrate (Akisanya and Fleck, 1997). We treat both a straight punch fibril without (Fig. 1(a)) and with a mushroom cap (Fig. 1(b)). In the current paper we focus on this corner stress singularity to determine its strength and amplitude for the fibrils (straight punch and mushroom shape) shown in Fig. 1. Studies have been performed both for plane strain (2D) and axisymmetric cylindrical (3D) geometries. In addition, we provide a few results for a variation on the shape shown in Fig. 1.

We adopt the method of Akisanya and Fleck, (1997) and Khaderi et al., (2014). The most singular terms in the asymptotic normal ($\boldsymbol{\sigma}_{22}$) and shear ($\boldsymbol{\sigma}_{12}$) stress components along the interface between a compliant fibril and a rigid substrate (Khaderi et al., 2014) are

$$\sigma_{22} = H_1 r^{-0.406} \quad (1)$$

$$\sigma_{12} = 0.505\ H_1 r^{-0.406} \quad (2)$$

where r is the distance from the fibril edge, and the directions X_1 and X_2 are shown in Fig. 1. The amplitude H_1 can be written in terms of the applied stress and one relevant dimension of the fibril. We choose the average stress σ_I on the interface between the fibril and the substrate as the measure of the applied stress and the width or diameter D_f, of the mushroom flange as the relevant dimension and obtain

$$H_1 = \sigma_I D_f^{0.406} \tilde{a} \quad (3)$$