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Hierarchical multiple peeling simulations

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F. Bosia,[a] S. Colella,[a] V. Mattoli,[b] B. Mazzolai[b] and N. M. Pugno*[cde]

The phenomenon of the exceptional dry adhesion achieved by some natural biological materials has been widely investigated in recent years. In particular, the analysis of the terminal elements of gecko pads and their specific structure and topology has led to the development of bioinspired synthetic fibrillar adhesives, including mushroom-shaped tips. To model the expected adhesion and detachment behaviour of multiple contacts, only recently the last author has derived a theory of multiple peeling, extending the pioneering energy-based single peeling theory of Kendall, including large deformations and pre-stretching. In this contribution, we study the problem of the adhesion of single and multiple contacts using finite element analysis, with the aim of studying complex peeling geometries. Both non-hierarchical tape-like and hierarchical geometries are considered, and the adhesive properties are compared, showing a marked improvement in the latter case. Results are promising and the numerical approach can be exploited in future attempts to determine optimal configurations and improve the adhesion of artificial bioinspired structures.

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Introduction

One of the most intriguing and widely studied phenomena in recent years in the field of biomaterials, is that of natural adhesives, due to their exceptional ability to adhere to various types of surfaces.[1] In some cases, this is simply due to so-called "dry adhesion", which depends on van der Waals and possibly capillary forces, and is not mediated by the release of chemical substances.[2,3] Gecko adhesion is particularly remarkable, since adhesion strengths of up to 1 MPa are achieved, corresponding to adhesive forces about ten times the animal's body weight.[4–6] Furthermore, this strong adhesion is combined with easy detachment, thanks to the variation of attachment angle, and self-cleaning.[7] These properties are closely associated to the hierarchical structure of the gecko pads, which split up into micrometre-sized setae and sub-micrometre-sized spatulae (Fig. 1a).[8,9] The same type of architecture is found in other insects that rely on strong adhesion, such as flies or spiders.[1] Interestingly, the size of terminal contacts in the different organisms has been found to be inversely proportional to the their mass.[2] In other terms, the number of terminal contacts increases with insect or animal mass, up to billions of contacts in the case of a single gecko pad. Various attempts have been made to imitate the gecko pad structure to fabricate artificial adhesives, typically using mushroom-shaped micrometric terminal elements manufactured using polymeric materials,[10–13] although hierarchical architectures remain to be efficiently implemented. Climber robots have also been designed, exploiting these bioinspired adhesive films.[14,15] The mushroom-shaped elements in artificial adhesives replicate the 2D profile of gecko spatulae,[16,17] and the detachment mechanism of both is reminiscent of the peeling process of a tape-like film from a substrate.[18]

In previous work, Pugno addressed the problem of multiple peeling[17] of a tape from a substrate, and then compared it to the case of conical peeling,[19] generalizing the single peeling theory by Kendall[20] and finding an optimal peeling angle, which is a function of tape rigidity and surface energy, at which adhesion is maximised.[5] Also, it was shown that it is possible to consider a multiple peeling problem as a superposition of single peeling ones.[17] The theory of multiple peeling can be extremely useful in the modelization of adhesion problems in nature, and has been numerically validated, *e.g.* in the case of spider web anchorages[21] (*e.g.* see Fig. 1b). However, in the case of such complex, hierarchical architectures, a numerical approach can be more appropriate.[22] The objective of this paper is thus to numerically calculate the predictions of multiple peeling theory using a finite element approach, and explore the effectiveness of hierarchical adhesive structures, in view of their exploitation in bioinspired structures.

[a]*Department of Physics and Nanostructured Interfaces and Surfaces Interdepartmental Centre, Università di Torino, Via P. Giuria 1, 10125, Torino, Italy. E-mail: federico.bosia@unito.it; Fax: +39 0116707200; Tel: +39 0116707889*

[b]*Center for Micro-BioRobotics, Istituto Italiano di Tecnologia, Viale Rinaldo Piaggio 34, 56025 Pontedera, Italy*

[c]*Laboratory of Bio-Inspired & Graphene Nanomechanics, Department of Civil, Environmental and Mechanical Engineering, Università di Trento, via Mesiano, 77, I-38123 Trento, Italy. E-mail: nicola.pugno@unitn.it; Fax: +39 0461282599; Tel: +39 0461282525*

[d]*Center for Materials and Microsystems, Fondazione Bruno Kessler, Via Sommarive 18, I-38123 Povo (Trento), Italy*

[e]*School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, UK*