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Numerical implementation of multiple peeling theory and its application to spider web anchorages

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Adhesion of spider web anchorages has been studied in recent years, including the specific functionalities achieved through different architectures. To better understand the delamination mechanisms of these and other biological or artificial fibrillar adhesives, and how their adhesion can be optimized, we develop a novel numerical model to simulate the multiple peeling of structures with arbitrary branching and adhesion angles, including complex architectures. The numerical model is based on a recently developed multiple peeling theory, which extends the energy-based single peeling theory of Kendall, and can be applied to arbitrarily complex structures. In particular, we numerically show that a multiple peeling problem can be treated as the superposition of single peeling configurations even for complex structures. Finally, we apply the developed numerical approach to study spider web anchorages, showing how their function is achieved through optimal geometrical configurations.

1. Introduction

Natural adhesives have captured considerable interest in recent years owing to their outstanding mechanical properties [1]. Well-known examples are gecko or insect adhesion [2,3], or spider web attachments [4], in which geometry, structure and material properties are essential in defining functionality. Gecko adhesion, which is based on van der Waals forces, achieves strengths of up to 1 MPa through the contact of billions of spatulae for each foot pad [5,6]. As in other cases of natural adhesives, the key to strong adhesion seems to lie in their hierarchical structure, which allows good adaptation to the surface and repeated contact splitting to increase the total peeling line without self-bunching [7,8]. The observation of these natural structures has inspired the design and realization of artificial dry adhesives (i.e. based on van der Waals forces) that guarantee simultaneous strong adhesion and smart, easy release, usually realized in polymers by means of 'mushroom-shaped' terminal elements tens of micrometres in size [9–13]. These structures, like gecko or insect terminal elements (spatulae), are tapered in shape [7], so that their detachment from the surface is reminiscent of the peeling of a tape from a substrate. Multiple peeling theory (MPT) [14] has recently been introduced by Pugno, and applied to cases of interest such as the delamination of a V-shaped elastic tape from a substrate, or to spider web anchorages [14,15].

The theory is a generalization of the well-known single peeling theory by Kendall [16] and predicts a critical value of the pull-off force corresponding to a limiting peeling angle which is reached as the delamination advances. Both the pull-off force and limiting angle only depend on the geometry of the tape, its elastic modulus and the interfacial energy. In [14], an assumption ('ansatz') is

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