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Emergence of the interplay between hierarchy and contact splitting in biological adhesion highlighted through a hierarchical shear lag model

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Contact unit size reduction is a widely studied mechanism as a means to improve adhesion in natural fibrillar systems, such as those observed in beetles or geckos. However, these animals also display complex structural features in the way the contact is subdivided in a hierarchical manner. Here, we study the influence of hierarchical fibrillar architectures on the load distribution over the contact elements of the adhesive system, and the corresponding delamination behaviour. We present an analytical model to derive the load distribution in a fibrillar system loaded in shear, including hierarchical splitting of contacts, *i.e.* a "hierarchical shear-lag" model that generalizes the well-known shear-lag model used in mechanics. The influence on the detachment process is investigated introducing a numerical procedure that allows the derivation of the maximum delamination force as a function of the considered geometry, including statistical variability of local adhesive energy. Our study suggests that contact splitting generates improved adhesion only in the ideal case of extremely compliant contacts. In real cases, to produce efficient adhesive performance, contact splitting needs to be coupled with hierarchical architectures to counterbalance high load concentrations resulting from contact unit size reduction, generating multiple delamination fronts and helping to avoid detrimental non-uniform load distributions. We show that these results can be summarized in a generalized adhesion scaling scheme for hierarchical structures, proving the beneficial effect of multiple hierarchical levels. The model can thus be used to predict the adhesive performance of hierarchical adhesive structures, as well as the mechanical behaviour of composite materials with hierarchical reinforcements.

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Introduction

Animal contact elements exploiting dry adhesion, such as those found in insects,[1,2] spiders[3,4] or geckos[5,6] share a common strategy to enable optimized attachment to a non-adhesive substrate: contact is achieved through a large number of fibrillar structures that interact with the surface through van der Waals[7] and/or capillary forces.[8] A large variety of behaviours have been observed,[9] but in general the adhesive strength of the contact pads has been found to increase as the size of the terminal elements (*i.e.* spatulae or setae) decreases and their number increases.[1] Indeed, contact models such as that by Johnson, Kendall and Roberts (JKR)[10] predict an unlimited increase in the adhesive strength as the size of the contact tips decreases. This decrease in size also leads to an increase of the total peeling line, *i.e.* the sum of all contact tip widths, which is proportional to the peeling force according to thin-film peeling theories.[11] Additionally, as the size of the animal increases and the dimensions of the contact units are reduced, hierarchical splitting is observed. For example in geckos, the lamellae support so-called setae, which are themselves split into hundreds of spatulae.[6] Similar structures are observed in arachnids.[4] Fibrillar contacts have been shown to be beneficial over non-fibrillar ones in certain ranges of the mechanical parameters.[12] Additionally, the hierarchical arrangement of fibrillar adhesives has been described as a way to increase the work of adhesion,[13] optimize surface adaptability[14] or self-cleaning abilities[15] and to avoid self-bunching,[13] and has been extended not only to the hairy adhesive structures, but also to spider silk anchorages.[16–18] Frictional properties of adhesive systems have also been recently discussed.[5,19,20] Despite these numerous works, important

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