Proceedings of the International Conference on Applied Mechanical Engineering Research (IC-AMER2019)
NIT Warangal, India – May 02-05, 2019
Paper No. XXX (The number assigned when the papaer is accepted)

Investigating the influence of geometrical and material parameters on peeling behaviour of a gecko spatula

Saipraneeth Gouravaraju, Sachin S. Gautam*
Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati, India 781039

*Corresponding author Email: ssg@iitg.ac.in

Geckos can generate strong attachment forces and at the same time detach swiftly from any surface by employing the hierarchical fibrillar structures on their toe pads. In this paper, a coupled adhesion-friction model in the framework of nonlinear finite element analysis is used to analyze the peeling behaviour of gecko spatulae. It has been found that the material stiffness, adhesion strength, size of the spatula, and adhesion range greatly influence the spatula stresses, pull-off forces, and deformation behaviour.

***Keywords*:** Gecko adhesion, dry friction, nonlinear finite element method, peeling.

1. Introduction

Geckos make use of the hierarchical fibrillar structures on their toe pads to generate strong attachment and rapid locomotion on variety of surfaces [1]. The underside of each digit on the gecko toes has expanded digital scales called scansors, which have rows of lamellae that contain thousands of micro-fibrils called setae. Each seta is about $30 - 100$ µm long and 5 µm in diameters. At their ends these setae further branch into hundreds of nanoscale spatula-like structures, which adhere to substrates through van der Waals interactions [2, 3]. Autumn et al. [2] made first direct measurements of the adhesive force of a single gecko seta. They found that with proper orientation, perpendicular preloading, and a parallel drag on the substrate, a single seta can generate a maximum friction force as high as approx. 200 µN.

There have been many studies, analytical, experimental, as well as numerical to understand the characteristics and design principles of gecko adhesion system [4-6]. Experiments of Huber et al. [7] revealed that when the spatulae are pulled vertically, the maximum pull-off force for a single spatula is close to 10 nN. Tian et al. [8] used a tape model for estimating the adhesion and friction forces between a single spatula and a rigid substrate. Chen et al. [9] analyzed the influence of pre-tension on the peeling force using the Kendall's peeling model. Sauer and Li [10] developed a computational quasi-continua model (called CGCM) for nano-scale adhesion from coarse graining of molecular dynamic simulations of individual atoms and. Based on this quasi-continua model, Sauer and Holl [11], analyzed the spatula adhesion using a detailed three-dimensional (3D) parametric model. They studied the influence of the spatula shape, stiffness and strength and range of adhesion on the pull-off behaviour. Gautam and Sauer [12] proposed a new time integration scheme for solving the dynamic adhesion problems, which they used to study peeling of a gecko spatula. Recently, Mergel et al. [13] developed two new continuum contact models for friction due to adhesion that can capture sliding friction even under tensile normal loads. The first model, "Model DI", assumes that the sliding threshold is independent of the normal distance and is equal to a constant frictional shear strength, which is related to the maximum adhesive traction. In their second model, "Model EA", the sliding traction varies with the normal distance and is dependent of the normal traction.

The gecko adhesive system has evolved over centuries for optimum attachment and detachment on different surfaces in nature. In order to understand the design principles of gecko's fibrillar structure it is essential to study the smallest element in the hierarchy, i.e., spatula. In the present work, the influence of material and geometrical parameters on the peeling behaviour of a gecko spatula is studied to understand the principles behind their optimum design. For this purpose, in this contribution the spatula is modelled as a thin strip and is analyzed using a combination of CGCM of [10] and “Model EA” of [13] in a nonlinear finite element framework.

2. Mathematical Formulation

In this section, the computational contact formulation of the coupled adhesion-friction between spatula and a flat rigid substrate is briefly presented. The weak form governing the deformation of the spatula interacting with the rigid substrate through van der Waals forces in the can be written as

$$\int_{\Omega} \mathrm{grad}\,(\delta\boldsymbol{\varphi}) : \boldsymbol{\sigma}\,\mathrm{d}v - \int_{\partial_c\Omega} \delta\,\boldsymbol{\varphi}\cdot\mathbf{t}_{\mathrm{c}}\,\mathrm{d}a - \delta\Pi_{\mathrm{ext}} = 0, \quad \forall\,\delta\boldsymbol{\varphi} \in \mathcal{V}, \tag{1}$$

where $\mathcal{V}$ represents the kinematically admissible deformation field $\boldsymbol{\varphi}$ space. Here, $\delta\Pi_{\mathrm{ext}}$ denotes the virtual work of the external forces acting on the spatula, $\boldsymbol{\varphi}$ is the motion mapping any arbitrary point $\mathbf{X}$ in the reference configuration Ω_0 of the spatula to the deformed current location $\mathbf{x} \in \Omega$ and is given by $\mathbf{x} = \boldsymbol{\varphi}(\mathbf{X}, t)$.

The weak form in Eq. (1) is characterized by the following two material parameters [10]

$$\gamma_{\mathrm{W}} = \frac{E}{\left(\frac{A_{\mathrm{H}}}{2\pi^2\, r_0^3}\right)}, \quad \gamma_{\mathrm{L}} = \frac{R_0}{r_0}, \tag{2}$$

where E is the reference Young’s modulus chosen for the system, A_{H} denotes Hamaker’s constant, and r_0 is the local length scale used to define the original Lennard-Jones potential.

The second parameter in Eq. (2), γ_{L}, is the ratio of the global length scale R_0 used to normalize the geometry and the local length scale r_0. From the definitions, it can be seen that, γ_{W} characterizes the stiffness with respect to the strength of adhesion, whereas γ_{L} characterizes the overall size of the geometry with respect to the range of adhesion.

3. Spatula Model

The spatula is modelled as a thin two-dimensional strip, similar to many studies in the literature [8, 9]. As such, the words “strip" and “spatula" are used interchangeably in the following.

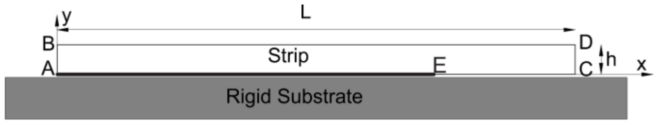

Fig. 1. A deformable strip on a flat rigid substrate.

The dimensions of the strip are $L \times h$, with the length $L = 200R_0$, and height $h = 10R_0$ where $R_0 = 1\,$nm is introduced for normalization (see Figure 1). Adhesion is assumed to be present only along 75% of the bottom surface of the strip (“AE" in Figure 1). The material of the strip is taken to be an isotropic non-linear Neo-Hookean material with Young’s modulus $E = 2$ GPa and Poisson’s ratio $\nu = 0.2$ with $r_0 = 0.4$ nm and $A_{\mathrm{H}} = 10^{-19}$ J. This results in the default values $\gamma_{\mathrm{W}} = 25.266$ and $\gamma_{\mathrm{L}} = 2.50$. The friction coefficient is taken as $\mu_s = 0.3$ to reflect the experimental data on gecko/gecko setae friction on glass surfaces [2]. Plane strain conditions are considered in all simulations. The strip is discretized into 240×12 finite elements along the x and and y directions.

The strip, initially lying flat on the rigid substrate in its equilibrium position is peeled off from from the substrate first by applying an external rotation angle θ to the right end of the strip (CD) while the left end of the strip (AB) is constrained in the x-direction and the point $x = 0, y = 0$ is constrained in both x and y directions. Then, in the second step, after achieving the desired rotation angle on the right end $\theta = \theta_{\mathrm{sh}}$, a displacement $\overline{u}$ is applied to the right end of the strip (CD) at an angle which is denoted as peeling angle θ_{p}. No constraints are applied on the left end (AB) in this second step.

Fig. 2. Peeling by applied displacement.

4. Results and Discussions

As discussed in section 2, the behaviour of the current model is characterized by material parameters γ_{W} and γ_{L}. Hence, changes in these parameters change the adhesion behaviour of the spatula. Variations in γ_{W} correspond to variations in either the material stiffness or the strength of adhesion. Similarly, variations in γ_{L} represent variations in either the spatula size or range of adhesion. These material parameters are varied here by a factor of 1.5 similar to the study of Sauer and Holl [11].

First, the pull-off forces, deformations, and stresses are calculated by varying the parameter γ_{W} while keeping γ_{L} constant and vice-versa. Figure 3 depict the deformation of the spatula for a pre-rotated configuration with $\theta_{\mathrm{sh}} = 90°$ and $\overline{u} = 0\,\mathrm{nm}$, and different values of γ_{W} and γ_{L}. It can be observed that for an increase in γ_{W} and a decrease in γ_{L}, the stresses in the spatula decrease. In Figure 3(a) the variation of the resultant pull-off force F_{res} with peeling angle θ is shown for $\gamma_{\mathrm{W}} = 16.867,\ 25.266,\ 37.95$ with constant $\gamma_{\mathrm{L}} = 2.50$. It can be seen that, as γ_{W} increases, the pull-off force decreases. This is due to the fact that by increasing γ_{W} the strength of adhesion decreases. This can also be understood in terms of the material stiffness, i.e., as γ_{W} decreases the stiffness of the material decreases and the spatula more readily adheres to the substrate and more force is required to peel it off from the substrate. This can also be observed from the deformed spatula configurations shown in Figure 3(a) where the pad area of the spatula still-in-contact increases with decrease in γ_{W}.

Second, the variation of the resultant pull-off force with peeling angle θ for $\gamma_{\mathrm{L}} = 1.67,\ 2.50,$ and 3.75 with constant $\gamma_{\mathrm{W}} = 25.266$ is plotted in Figure 4(b). The pull-off force is observed to be increasing with decrease in γ_{L} which corresponds to the increase in the range of adhesion. It can also be understood that as the strip size increases, the pull-off force and stresses decrease. At the same time, it can be observed from the Figure 3(b) that as γ_{L} decreases, the stress inside the spatula increases, which is not desirable. From these results, it can be stated that as γ_{L} and γ_{W} decrease, the pull-off forces increase due to either increase in adhesion strength (or range) or decrease in stiffness (or spatula size). These results can be useful for designing gecko inspired synthetic adhesives. For example, choosing a too large spatula size or a too stiff material – although it reduces the amount of force required to detach at $\theta = 90°$ – it comes at the expense of the friction forces that are generated at low angles during attachment. So, it is essential that when designing a gecko inspired synthetic adhesives, these characteristics of the gecko spatula should be taken into account in choosing the and materials for efficient design.

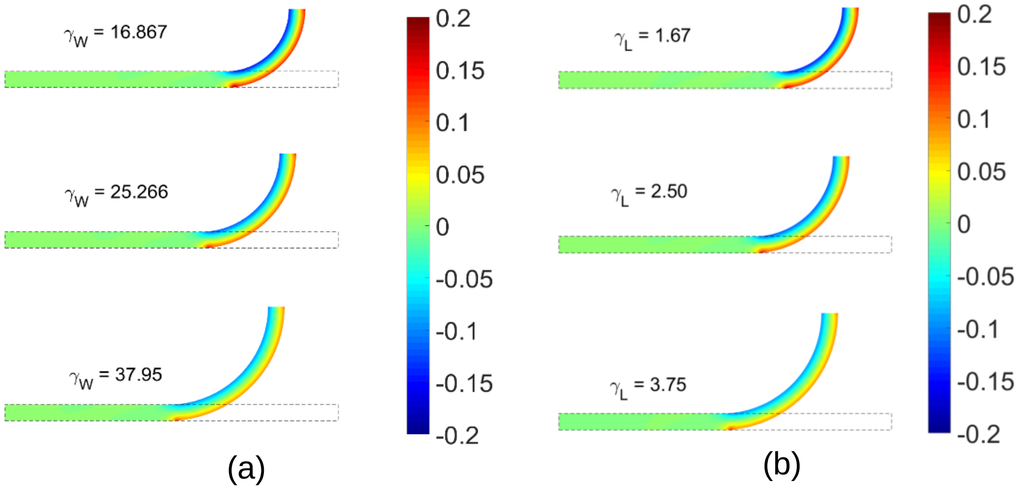

Fig. 3. Deformation and stress for different values of γ_W and $\gamma_L$for initial pre-rotated configuration with $\theta_{sh} = 90°$ and $\overline{u} = 0$ nm. The colorbar shows the normalized stresses $\mathrm{I}_1/E = \mathrm{tr}(\boldsymbol{\sigma})/E$.

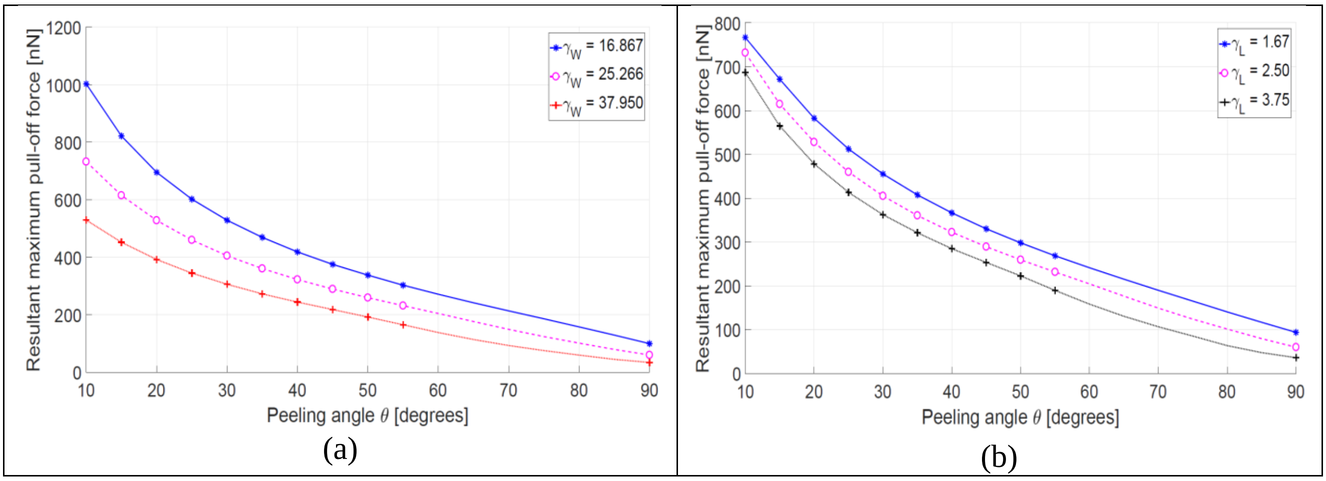

Fig. 4. Evolution of the resultant maximum pull-off force with peeling angle θ for different values of γ_W and γ_L.

5. Conclusions

The influence of stiffness, adhesion range, strength, and spatula size has been analysed by varying the material parameters γ_W and γ_L . It is found that as L and W decrease, the pull-off forces increase due to either an increase in adhesion strength (or range) or decrease in the stiffness (or spatula size).

Acknowledgements

Authors are are grateful to the SERB, DST for supporting this research under project SR/FTP/ETA-0008/2014. Authors would also like to thank Prof. Roger A. Sauer at AICES, RWTH Aachen University for his valuable comments.

References

1. Ruibal, R. and Ernst, V. J. Morphol. 117, pp. 271-293 (1965).
2. Autumn, K., Liang, Y.A., Hsieh, S.T., Zesch, W., Chan, W.P., Kenny, T.W., Fearing, R., and Full, R.J. Nature. 405, pp. 681-684 (2000).
3. Autumn, K., Sitti, M., Liang, Y.A., Peattie, A.M., Hansen, W.R., Sponberg, S., Kenny, T.W., Fearing, R., Israelachvili, J.N., and Full, R.J. Proc. Natl. Acad. Sci. 99, pp. 12252-12256 (2002).
4. Jagota, A. and Hui, C.Y. Mater. Sci. Eng. R Reports. 72, pp. 253-292 (2011).
5. Hu, S., Lopez, S., Niewiarowski, P.H., and Xia, Z. J. R. Soc. Interface 9, pp. 2781-2790 (2012).
6. Kasar, A.K., Ramachandran, R., and Menezes, P.L. J. Bio- Tribo-Corrosion 4, pp. 1-17 (2018).
7. Huber, G., Gorb, S.N., Spolenak, R., and Arzt, E. Biol. Lett. 1, pp. 2-4 (2005).
8. Tian, Y., Pesika, N., Zeng, H., Rosenberg, K., Zhao, B., McGuiggan, P., Autumn, K., and Israelachvili, J. Proc. Natl. Acad. Sci. 103, pp. 19320-19325 (2006).
9. Chen, B., Wu, P., and Gao, H. J. R. Soc. Interface 6, pp. 529-537 (2009).
10. Sauer, R.A. and Li, S. Int. J. Numer. Methods Eng. 71, pp. 931-962 (2007).
11. Sauer, R.A. and Holl, M. Comput. Methods Biomech. Biomed. Engin. 16, 577-591 (2013).
12. Gautam, S.S. and Sauer, R.A. Int. J. Comput. Methods 11, 1350104 (2014).
13. Mergel, J.C., Sahli, R., Scheibert, J., and Sauer, R.A. J. Adhes. 00, pp. 1-33 (2018).