Modeling and Design of Biomimetic Adhesives Inspired by Gecko Foot-Hairs

Gaurav J. Shah and Metin Sitti, *Member, IEEE*

Abstract— **This novel research work is motivated by the fascinating climbing ability of geckos. Recent experiments on the attachment mechanism of gecko feet have confirmed that van der Waals forces dominate gecko adhesion. Images of gecko feet have revealed a very intricate hierarchical fiber structures. These fibers are primarily responsible for the important properties of the gecko feet including strong adhesion, easy detachment, rough surface adaptation, self-cleaning, and resistance to wear. This paper introduces a methodology for designing biomimetic dry adhesive pads inspired by the attachment mechanism of gecko feet. The research has enhanced the understanding of gecko adhesive properties and their dependence on the geometry and material properties of gecko feet nano-fibers. We model the fibers as an array of oriented cantilever beams. Mathematical relations between the adhesion properties and fiber properties are studied, and design guidelines are formulated for fabrication of the biomimetic synthetic adhesives.**

Index Terms— **Biomimetic adhesives, Gecko adhesion, Nanotechnology**

I. Introduction

For ages people have been amazed by the climbing ability of geckos. After a century of debate, there is sufficient evidence today to conclude that the intermolecular van der Waals forces dominate gecko adhesion [1]. Efforts are being made to study the properties of gecko-feet and their adhesion to fabricate synthetic biomimetic adhesives. These adhesives will have the same structure as gecko-feet, and thus inherit their adhesion properties. The presented research enhances the understanding of gecko-adhesion and proposes a method for using this knowledge for fabricating synthetic adhesives.

Scanning electron microscope (SEM) images of the foot of a *Tokay* gecko have revealed very intricate fiber structures [2]. Gecko-feet have thousands of keratinous fibers called setae, which are about 30 to 130μm long and 5μm in diameter. Each seta further branches out into hundreds of smaller and thinner fibers. A single foot of the *Tokay* gecko can produce 10N adhesive force per cm^2. The micro- and nano-fibers ensure good contact with smooth as well as rough surfaces and are also responsible for the self-cleaning property of gecko-feet. The hierarchical fiber structure is believed to help in conforming to surfaces with varying degrees of roughness and reducing fiber wear [3].

We present a model for the nano-fibers and use it as a basis to study the dependence of adhesive properties on fiber geometry and material. Mathematical relations between the properties are identified and used to formulate design guidelines for synthetic adhesive design. A design methodology to design gecko-feet based adhesives for various applications has been developed.

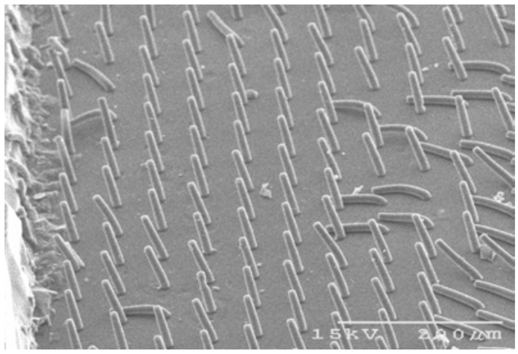

Fig. 1: SEM image of the polymer fibrillar adhesive fabricated at the NanoRobotics Laboratory, CMU

II. Synthetic Adhesive Design

The van der Waals intermolecular forces exist between all materials. The gecko is thus able to stick to a wide variety of surfaces irrespective of the surface material. The nano-fibers provide millions of points of contact increasing the total adhesion. Gecko locomotion is highly efficient due to easy detachment of the fibers by peeling. The nano-fiber geometry is also responsible for good adaptation to rough surfaces and the self cleaning property of the hairs. If nano-scale fibers similar to gecko feet fibers are fabricated on adhesive pads, then these should be able to mimic gecko-adhesion and inherit its properties. Fabrication of the fibers for synthetic pads (Fig. 1) is a design problem with a well defined set of performance requirements and design variables. The important performance requirements for the adhesives are:

- Attachment and detachment forces
- Rough surface adaptation
- Self-cleaning property
- Durability

The fibers need to be designed to achieve the desired properties. We have identified the following design variables

G. J. Shah is with the NanoRobotics Laboratory, Carnegie Mellon University, Pittsburgh, PA 15232 USA (corresponding author, phone: 412-268-8847; fax: 412-268-3348; e-mail: gshah@cmu.edu).

M. Sitti is with the NanoRobotics Laboratory, Carnegie Mellon University, Pittsburgh, PA 15213 USA (e-mail: sitti@cmu.edu).

that will determine the above properties for synthetic adhesives:

- Fiber density
- Fiber orientation
- Fiber material elastic modulus and surface energy
- Fiber geometry (length, diameter, aspect ratio and tip shape)

The aim of the design is then to select the right values for the design variables to achieve desired performance for an application.

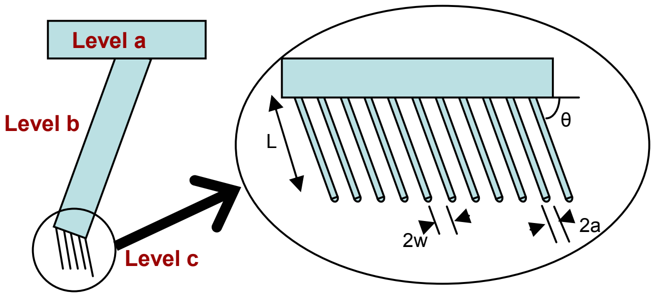

Fig. 2: Multiple levels of compliance in gecko-foot hairs

III. Fiber Model and Adhesion

A. Fiber Compliance

The hierarchal fiber structure provides the gecko with different layers of compliance. These are primarily responsible for good adaptation to rough surfaces. Three levels of compliance that can be easily identified are: a) the lamellae (tissue level macro compliance); b) micro-fibers; and c) nano-fibers (Fig. 2). The different levels of fibers help in adaptation to a wide range of surface roughness. We model for the nano-fibers alone as the model can be easily scaled up for micro-fibers.

We have modeled the nano-fibers as oriented cylindrical cantilever beams with hemispherical tips. This model is a reasonable representation of the gecko-fibers. The real gecko-fibers end in a spatula structure. The assumption of a hemispherical end simplifies the analysis and closely represents synthetic fiber tips. In Fig. 2, L is the length of nano-fibers; θ is the fiber orientation, a is the fiber radius; and $2w$ is the gap between fibers.

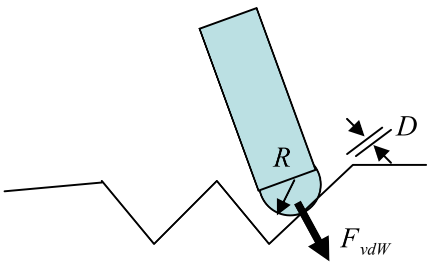

Fig. 3: Fiber adhesion through van der Waals force

B. Single Fiber Adhesion

The fiber adhesion is dominated by the van der Waals forces. For the assumed fiber model, the van der Waals force of adhesion per hair in contact with the surface is given by (Fig. 3):

$$F_{vdW} = \frac{A_{12}R}{6D^2} \quad (1)$$

In Eq. (1), A_{12} is the Hamaker constant between fiber material 1 and surface material 2, R is the radius of the tip, and D is the atomic gap distance. Typical values for A and D are 10^{-19} J and 0.165 nm, respectively. The Hamaker constant can be calculated from [4]:

$$A_{12} \approx \sqrt{A_{11}A_{22}} \quad (2)$$

where A_{11} and A_{22} are the Hamaker constants for the fiber and surface material respectively. The Hamaker constant of a material depends on the surface energy γ of the material [4]:

$$A_{11} = 24\pi\gamma D^2 \quad (3)$$

Measurements of adhesive force on real gecko-feet fibers indicate a van der Waals force of around 200 nN per fiber (200 nm in diameter) [2]. This data indicates that R for 200nm fiber is 0.38 μm. In our analysis, we assume the tip radius R to be linearly proportional to the diameter of the fiber. Though the force per individual fiber is small, the total force is high due to the high density of the fibers. For example, the *Tokay* gecko has 100 million hairs in contact with a cm^2 area of the surface. The total adhesion force per unit area (P_T) depends linearly on the density of fibers (Δ). This force can be calculated by:

$$P_T = F_{vdW} \times \Delta \quad (4)$$

Clearly the fibers need to be packed as densely as possible in synthetic adhesives for higher adhesion.

C. Density Constraint: Non-Matting Condition

The density of fibers is extremely important for high adhesion. However, if the fibers are packed too closely, neighboring fiber will attract each other (Fig. 4). The slender fibers might stick to each other and get entangled. This is known as matting and the fibers need to be spaced far enough to avoid matting.

Consider the fibers stuck as show in Fig. 5. The elastic energy U_E, is stored only in length s of the beam, and is given by [5]:

$$U_E = \frac{6EIw^2}{s^3} \quad \text{where } I = \frac{\pi a^4}{4} \quad (5)$$

Eq. (5) above assumes small beam deflection and is hence only valid above some threshold elastic modulus of the fiber material. Fibers of softer material, required to be placed further apart, will undergo large deflection, and the assumption will be invalid.

The interfacial energy U_S stored in length d of the beam, is given by:

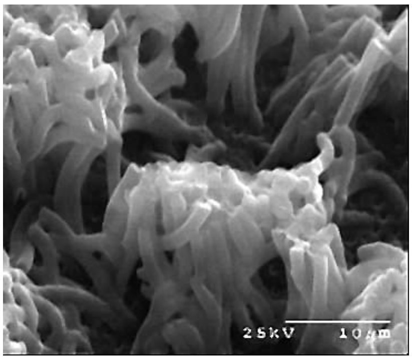

Fig. 4 Densely packed fibers matted together.

$$U_s = -(2\gamma_s)(2b \times d) \tag{6}$$

where $d = L - s$, γ_s is the surface energy of the fiber material, and b is the contact radius (See Fig. 5). From the Johnson-Kendall-Roberts (JKR) theory for cylindrical fibers in contact [6], the relation between the net applied load (P) and contact radius (b) is given by:

$$P = \frac{4E^* b^3}{3a} - (16\pi a^3 \gamma_s E^*)^{1/2} \tag{7}$$

where $E^* = E/2(1-\nu^2)$ and ν is the Poisson's ratio. Since $P = 0$ for the matting condition, we get the contact radius as:

$$b = \left(\frac{9\pi\gamma_s a^2}{E^*}\right)^{1/3} \tag{8}$$

The total energy of the system U_T is the sum of the elastic and interfacial energy.

$$U_T = U_E + U_s = \frac{6EIw^2}{s^3} - (2\gamma_s)(L-s)2b \tag{9}$$

In order that the hairs do not stick to each other, the spring force needs to be more than the adhesion force. The equilibrium length s^*, where the two forces are balanced, can be found by equating the rate of change of total energy with s to zero (to find the minima) [5].

$$\frac{dU_T}{dS} = 0 \Rightarrow s^* = \left(\frac{9EIw^2}{2\gamma_s b}\right)^{1/4} = \left(\frac{9\pi E w^2 a^4}{8\gamma_s b}\right)^{1/4} \tag{10}$$

Shear distortion modifies the detachment condition by a numerical factor [5]. Accounting for the shear distortion, the minimum spacing to avoid matting between the fibers is calculated to be:

$$w > \frac{L^2}{a^2}\sqrt{\frac{32\gamma_s b}{9\pi E}} \tag{11}$$

IV. Total Adhesion Pressure

The total adhesion pressure (P_T) represents the maximum adhesion of the synthetic adhesive per unit area assuming that all the hairs are in contact with a flat substrate. For our fiber model, from (4), P_T for the synthetic adhesives is given by:

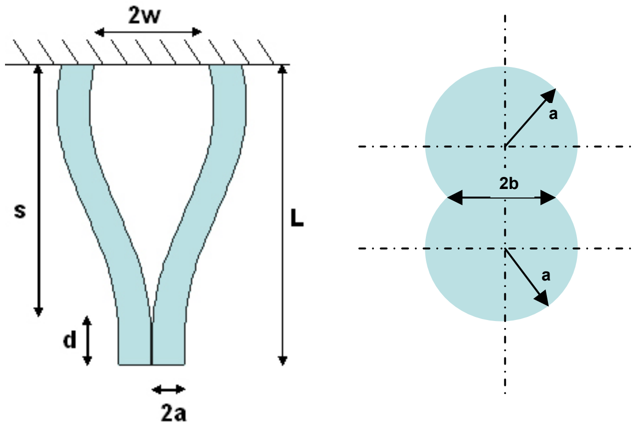

Fig. 5: Matted fiber model to determine minimum spacing between fibers

$$P_T = F_{vdW} \times \Delta = F_{vdW} / 4(w+a)^2 \tag{12}$$

Fig. 6 plots the total adhesive pressure as a function of the fiber radius for several fiber moduli E on a flat surface. The maximum density of the hairs is determined from the matting condition. The aspect ratio ($2a{:}L$) is taken as 1:15, while the surface energy γ_s is taken to be 48.7 mJ/m^2. The van der Waals force (F_{vdW}) is calculated from Eq. (1). The adhering surface is glass with Hamaker constant A_{22} = 7.3x10^{-20} J, and the polymer has a Hamaker constant A_{11} = 1 x10^{-19} J. It is evident from the plot that thinner fibers (up to 100 nm) with high elastic modulus can be packed closely together resulting in very high adhesive pressure. For very thin fibers (a < 100 nm), the force of adhesion per hair is very small resulting in smaller van der Waals force per hair. These two factors result in an adhesion peak around a = 100 nm. It is for the same reason that the gecko fibers are made up of β-keratin (E = 4 GPa [3]), and are 100nm in radius. The synthetic adhesive fiber radius and elastic modulus need to be determined from the required adhesive pressure.

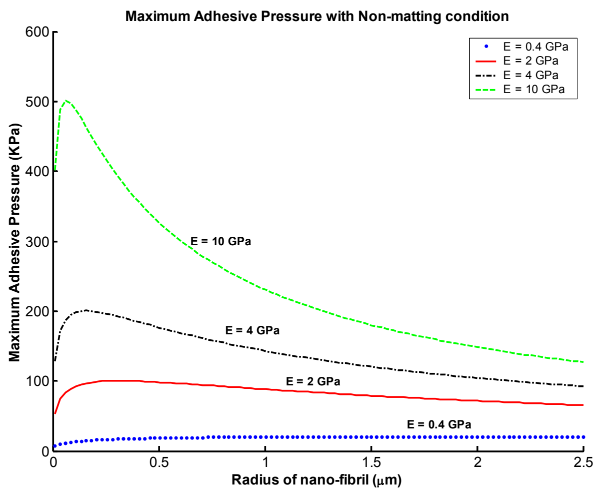

Fig. 6: Maximum adhesive pressure as a function fiber radius using the non-matting condition and van der Waals force model

V. Rough Surface Adaptation

Rough surface adaptation is a very important property of gecko fibers. The micro- and nano-fibers and the soft foot tissue enable the gecko to climb surfaces with widely varying surface roughness. We believe that the gecko soft foot tissue help in adaptation to macro-scale roughness, micro-fibers help in adaptation to micro-scale roughness, while the nano-fibers help in adaptation to nano-scale roughness. The nano-fibers could adapt to micro-scale roughness, however then the nano-fibers would need to be too long leading to matting issues and increased wear. The advantage of a fibrillar adhesive over a solid one can be understood by studying the influence of the fibers on the structural compliance of the adhesive. The high aspect ratio fibers are very compliant in the lateral direction as compared to the axial direction. It can be easily shown that $K_{axial}/K_{lateral} \propto L^2/a^2$, where K_{axial} and $K_{lateral}$ are the axial and lateral stiffness of the cylindrical fiber. The orientation greatly increases the compliance by making the lateral stiffness component dominant in the normal (to surface) direction. The compliant fiber structure helps the adhesive to adapt to rough surfaces and also reduces the preload for good contact. There are two important criteria that determine the influence of oriented fibers in increasing rough surface adaptation: a) Preload to make good contact, and b) Adhesion pressure. We use large beam deflection theory to study fiber deflection due to preload and adhesive forces.

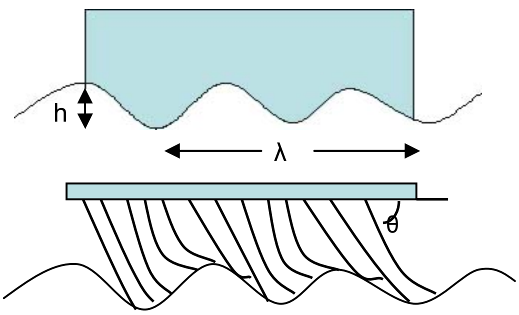

Fig. 7: Rough surface adaptation through fibrillar structure

A. Preload

During preload, the adhesive pad is pushed against the surface, and the fibers make contact. Consider a rough surface profile given by $f(x) = h\sin^2(\pi x/\lambda)$, where λ is the wavelength of the roughness, and h is the amplitude. Then the remote compressive stress σ to achieve intimate contact for a solid adhesive block is [7]:

$$\sigma = \frac{\pi E h}{2(1-\nu^2)\lambda} \tag{13}$$

For a solid block of gecko-feet material (E = 4 GPa) the preload required for good contact for h = 100nm and λ = 100µm, is 7.4 MPa (See Fig. 7). If the solid block is replaced by synthetic adhesive with oriented hairs (30º), a = 100 nm, L = 300 µm, E = 4 GPa, and γ_s = 48.67 mJ/m^2 the required preload for the same roughness profile is only 3.3 KPa. Eq. (13) provides intuition in determining factors affecting the rough surface adaptation of artificial fibers. The adaptation to the rough surface depends primarily on the elasticity E. As expected, structures with softer material show better conformance to rough surfaces. The gecko fibers are made of rigid material in order to avoid matting and enhance self-cleaning. In order to achieve good contact in spite of the high modulus of elasticity, gecko-feet use a hierarchy of oriented fibers of progressively smaller diameters.

The influence of orientation θ on preload is made clear from Fig. 8. Smaller orientation results in lower preload, implying better rough surface adaptability. The effect of orientation on preload is more pronounced at higher roughness amplitudes. The hair orientation can be selected based on the maximum preload for synthetic adhesives.

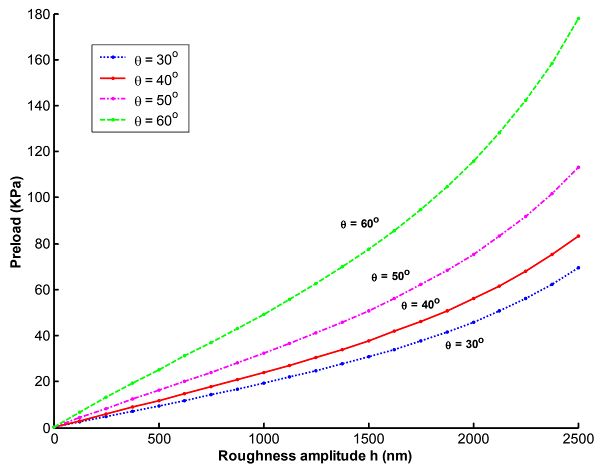

Fig. 8: Preload for good contact as determined from the surface roughness and fiber orientation

B. Adhesion Pressure

Once the fibers have made good contact with the surface during preload, the preload can be relieved. The adhesion pressure can then be calculated as the maximum force the adhesive can hold against before any of the fibers pull-off the surface. This adhesion pressure depends on the surface roughness as fibers attached to rougher surfaces stretch more and pull-off easily. We consider only the van der Waals force of adhesion and neglect the deflection along the axis of the fiber (as the lateral stiffness is much lower than the axial stiffness).

Fig. 9 and Fig. 10 plot the adhesion force before pull-off as a function of surface roughness amplitude (h) for different fiber orientations (θ) and elastic moduli (E) respectively. The plots are obtained for fiber with a=100 nm, L = 3µm, γ_s=48.7 mJ/m^2, and roughness wavelength λ = 100 µm. In Fig. 9, E is fixed at 4 GPa, while in Fig. 10, θ is fixed at 30º. Fig. 9 shows a pronounced effect of fiber orientation on adhesion force. Lower orientation implies that the hair can deflect more before pull-off, leading to better adhesion. Fig. 10 indicates an increasing adhesion force with elastic modulus. This result seems counter intuitive, but can be accounted for by the greater hair density achievable for stiff fibers. We can conclude from the plot that the effect of higher E is minimal in reducing rough surface adaptability, but the allowed high density results in higher adhesion. Thus, synthetic adhesives must be fabricated from stiff polymers.

VI. Self-Cleaning

It is known that the gecko feet clean themselves and do not get dirty. Dirt can greatly reduce adhesion and thus the self-cleaning property is very important. The reusability of gecko-based adhesives will result from their self-cleaning behavior. The self-cleaning phenomena can be explained by the "Lotus Effect". The fibers are responsible for making the adhesives super-hydrophobic. The fibers reduce the fraction of the surface (f) making contact with the water droplets. The droplets cannot make good contact and roll off; carrying the dirt particle with them.

The water contact angle can be used to measure the super-hydrophobicity of synthetic adhesives. For fibrillar adhesives the contact angle can be calculated by using the Wenzel or Cassie equation. Cassie's model accounts for the air trapped below the drop, and is more suitable for high aspect ratio super-hydrophobic materials like the fibrillar adhesives [8]. Cassie's equation gives the contact angle α' for the fibrillar adhesive as:

$$\cos\alpha' = f\cos\alpha + f - 1 \tag{14}$$

where α is the contact angle on a flat surface of the same material, and f is the area fraction covered by the fibers. The equation indicates that fibers make hydrophobic surfaces more hydrophobic and hydrophilic surfaces more hydrophilic. Thus the polymer selected for fiber fabrication needs to be *hydrophobic*. For our synthetic adhesives f is given by:

$$f = \pi a^2 \Big/ 4(a+w)^2 \tag{15}$$

Fig. 11 is a plot of contact angle *(α')* as a function of fiber radius for various materials. The plots are obtained for maximum fiber density determined from the non-matting condition. The aspect ratio ($2a{:}L$) is taken as 1:15, while the surface energy γ_s is taken to be 48.7 mJ/m^2.

The plot indicates that the adhesives can be designed to be super-hydrophobic ($\alpha' > 165^\circ$). However, in order for the adhesives to be hydrophobic the fibers need to have diameter less than 300nm (for $E > 2$GPa). The self-cleaning property provides another reason for the small diameter of the gecko-feet fibers. We have tested some of the fabricated synthetic adhesives for change in contact angle. In spite of the imperfect fabrication, a significant change in contact angle was observed. Snaps in Fig. 12 are for a water droplet on three different surfaces of the same polydimethyl siloxane (PDMS) polymer material: flat PDMS; PDMS fibers with 3µm diameter and 9µm length; PDMS fibers with 5µm diameter and 10µm length. A significant improvement in contact angle

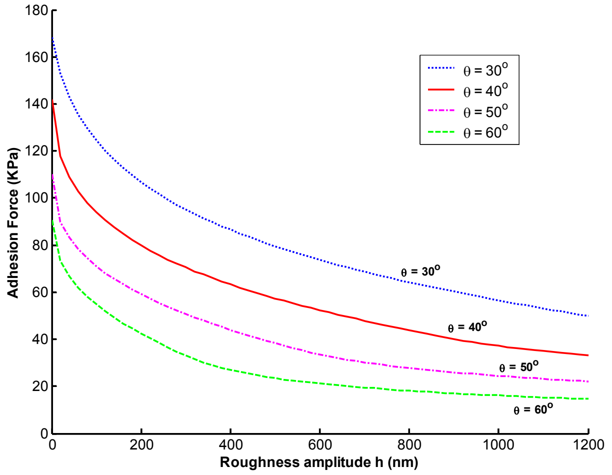

Fig.9: Adhesion force as determined from the surface roughness and fiber orientation

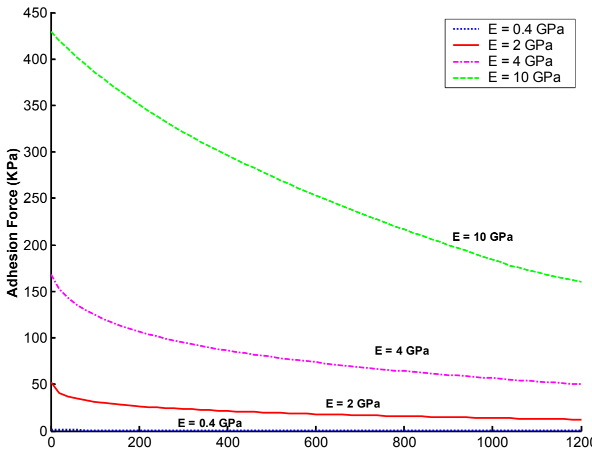

Fig.10: Adhesion force as determined from the surface roughness and fiber elastic modulus

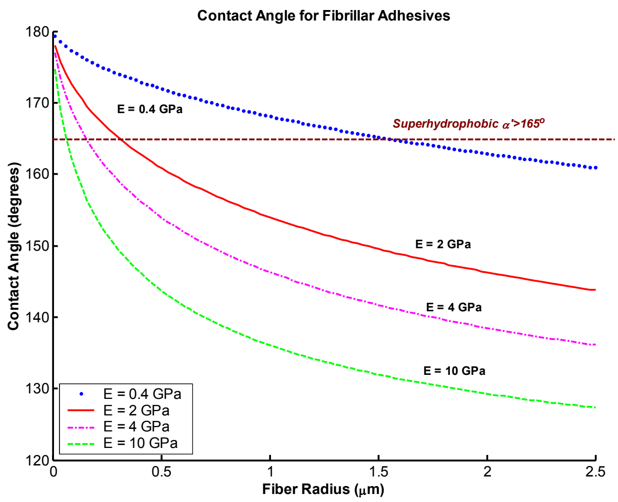

Fig.11: Contact angle for fibrillar adhesive using Cassie's equation

from 106º to 160º was observed for the fibrillar surfaces. The results indicate that designed synthetic adhesives will be super-hydrophobic, and thus self-cleaning, too.

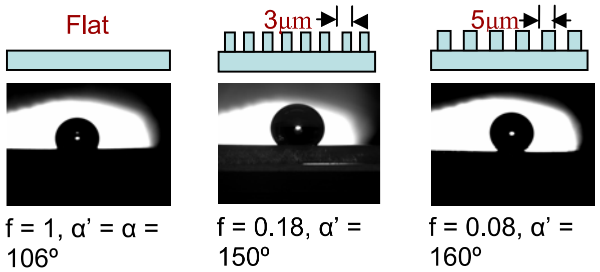

Fig.12: Experimental results from contact angle measurements on PDMS fibrillar adhesives: flat surface (leftmost), 3 µm diameter fibers (middle), and 5 µm diameter fibers (rightmost)

VII. Design Case Study

Consider the design of fibrillar adhesive for a wall climbing robot with the following requirements:

- Adhesion Pressure = 60 KPa
- Roughness amplitude h < 500 nm, and wavelength λ = 100 µm
- Preload Force < 15 KPa
- Water contact Angle α' > 165º

An adhesive pressure of 60 KPa is achievable through fibers 100 nm in radius, 3µm long, oriented at $\theta < 50^o$, with $E \geq 4$ GPa (See Fig. 9). However, to keep the preload force below 15 KPa, we need $\theta \leq 40^o$ (See Fig 8). In order to achieve a contact angle of 165º we require $E \leq 4$ GPa (See Fig.11). Thus a synthetic adhesive with fibers with a = 100nm, L = 3 µm, and θ = 40º needs to be fabricated from material with E = 4 GPa.

VIII. Conclusion

Gecko adhesion is attractive for biomimetic adhesives as it is dominated by the intermolecular van der Waals forces. These forces exist between all surfaces, enabling the gecko to stick to almost any surface. It is well known that the gecko-feet fibers are responsible for the adhesion properties. However, till now, the influence of the fiber properties on gecko adhesion had been a riddle.

Our modeling of the fibers has helped in exploring the influence of fiber properties on adhesive performance. We have validated that the nano-fibers are responsible for strong gecko-adhesion. The influence of nano-fibers on the self-cleaning property and rough surface adaptation was made explicit. Thus the research has enhanced the understanding of the gecko adhesion through fibrillar nanostructure. Design guidelines have been formulated from the identified relations. The proposed design methodology can be applied to design biomimetic fibrillar synthetic adhesives for various applications.

Recent advances in nano-fabrication technology have enabled the artificial fabrication of adhesive pads with biomimetic fibers. Nanofabrication technologies employed include molding [9,10], electron beam lithography [11], and using electro-hydrodynamic instabilities [12]. These techniques allow the synthetic replication of gecko feet nano-fibers with high precision. The developed design methodology along with the nano-fabrication techniques has paved the way for realization of the gecko-feet based biomimetic adhesives and will lead to the fruition of dry adhesive technology.

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