Biologically inspired wavy surface adhesion

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Abstract

The mechanics of detachment of a rigid solid from an elastic wavy surface has been analyzed in a recent article, in which the axisymmetric case of a sphere and the plane strain case of a cylinder were considered. Due to the qualitative similarities, the discussion was limited to the axisymmetric case only. It was shown that the surface waviness makes the detachment process proceed in alternating stable and unstable segments and each unstable jump dissipates mechanical energy. As a result, the external work and the peak force required to separate a wavy interface are higher than the corresponding values for a flat interface; i.e., waviness causes interface toughening as well as strengthening. In this paper, a systematic experimental investigation is presented which examines the above theoretical analysis, by measuring adhesion between a "rigid" wavy punch and a soft "elastic" material, which here is a block of gelatin. The observed increase in adhesion due to waviness closely agrees with the theoretical predictions within the experimental and material uncertainties. The experiments not only validate the theory, but also demonstrate that adhesion of a soft material can be substantially enhanced by topographic optimization alone, without modifying the surface chemistry.

1. Introduction

Reversible adhesion of a soft material to another surface is known to be influenced by the surface roughness. It is generally thought that surface roughness decreases adhesion because the total decrease in the free energy due to the formation of an adhesive interface is offset by the elastic energy penalty required to deform and bring the two surfaces into complete contact. The evidence for this can be found in the decrease in adhesion between two nominally rough surfaces as roughness increases, which has been demonstrated in several experimental investigations [1-7]. However, when one of the contacting surfaces is soft, there is evidence to the contrary that roughness can actually increase adhesion, as demonstrated by the experiment of Briggs and Briscoe [8] and Fuller and Roberts [9]. In the recent literature, there have been attempts to explain these experimental observations in terms of the increase in the surface area with roughness [10-12]. According to these arguments, as roughness is increased starting from a flat surface, the contribution to the net decrease in the free energy from the increase in the surface area initially dominates the elastic energy penalty. As a result, roughness initially increases apparent adhesion. As roughness is increased further, the elastic energy penalty eventually prevails, resulting in a decrease in the apparent adhesion. By assuming appropriate values for certain parameters, Persson [12] were able to fit his theory with the experimental results of Briggs and Briscoe [8]. However, an inherent assumption in this approach is that the elastic energy stored in deforming the surface is recovered completely during the decohesion process and is used in creating the new surfaces. In other words, decohesion of a rough interface is assumed to be a stable and reversible process.

In a recent article, Guduru [13] analyzed the mechanics of decohesion between a soft elastic material and a wavy rigid sphere (or a cylinder), in which the surface roughness was idealized to be a single wavelength, well defined sinusoid. It was shown that the waviness makes the decohesion process inherently unstable and dissipative. As a result, the stored elastic energy is not completely recovered during decohesion, resulting in interface toughening and strengthening. Thus, surface instabilities which arise due to the interaction between wavy geometry and mechanics of interface adhesion, which has been assumed to be equivalent to linear elastic fracture mechanics, at the scale of individual crest and trough can have a significant effect on the adhesive interaction at a larger scale. The objective of the experimental work presented in this article is to examine the predictions of the wavy surface adhesion theory presented by Guduru [13] and understand its implications for rough surface adhesion. Experiments are conducted in which a gelatin block is indented with a wavy-spherical polycarbonate punch while the force and displacement are measured. The maximum separation force and the force-displacement curves are compared with the analytical predictions.

It should be pointed out that the basic motivation to study the wavy surface adhesion in the present context arises from a need to understand the ability of several insect species to achieve excellent reversible adhesion on surfaces of varying roughness by means of soft pads on their feet. It was demonstrated by Santos et al. [14] through controlled experiments that certain organisms such as echinoderms achieve better adhesion on slightly rough surfaces than on smooth surfaces. A thorough understanding of the mechanics behind such biological adhesion strategies can potentially lead to new surface engineering
strategies to maximize reversible adhesion of a soft material at macroscale by optimizing the surface topography at micron and sub-micron scales.

The article is organized as follows. The next section summarizes the essential theoretical results relevant for defining the objectives of the investigation and designing the experiments. It is followed by a section on experimental setup and procedure and sample preparation. Details of the experimental results are presented next, along with a comparison with the theory and discussion.

2. Summary of Relevant Theoretical Results

In an earlier article [13], the axisymmetric problem of adhesion between an elastic half space and a rigid wavy spherical indenter was considered, as illustrated in Fig. 1. The spacing between the two interacting surfaces is given by

\[ f(r) = \frac{r^2}{2R} + A \left( 1 - \cos \left( \frac{2\pi r}{\lambda} \right) \right) \]  

(1)

Where \( R \) is the radius of the sphere; \( A \) and \( \lambda \) are the amplitude and wavelength of the sinusoidal waviness superposed on the sphere. Note that the sphere is approximated by a paraboloid. If \( E^* \) is the plane strain modulus of the half space and \( \gamma \) is the interface energy per unit area, the applied compressive force \( P \), the contact radius \( a \) and the punch displacement \( h \) were shown to be related as

\[ h(a) = \frac{a^2}{R} + \pi^2 \frac{A}{\lambda} a H_\lambda \left( \frac{2\pi a}{\lambda} \right) - \sqrt{\frac{2\pi a \gamma}{E^*}} \]  

(2)

\[ P(a) = 2E^* \left( \frac{2}{R} + \frac{4\pi^2 A}{\lambda^2} \frac{a^3}{3} + \frac{\pi A a}{2} \right) - \frac{\pi^2 A a^2}{\lambda} H_\lambda \left( \frac{2\pi a}{\lambda} \right) - \sqrt{8\pi E^* \lambda a^2} \]  

(3)

where \( H_\lambda(\cdot) \) is the Struve function of order \( n \) [15]. In the absence of the waviness \( (A = 0) \), the above relations get reduced to the solution to the classical JKR problem, in which the maximum tensile separation force required is given by

\[ P_{JKR} = \frac{3}{2} \pi \gamma R \]  

(4)

By defining the following non-dimensional parameters,

\[ \bar{P}' = \frac{P}{P_{JKR}} \quad \bar{x} = \frac{x}{R} \quad \bar{a} = \frac{a}{R} \quad h = \frac{h}{a} \quad \bar{a} = \frac{A}{R} \quad \gamma' = \frac{2\pi^2 \gamma}{E^* R} \quad \bar{P} = \frac{P}{\gamma R} \]  

(5)

Eq. (2) and (3) can be represented in a non-dimensional form as

\[ \bar{h} = \bar{a}^2 + \pi^2 \bar{a} \bar{H}_\lambda \left( 2\pi \bar{a} \right) - \sqrt{\frac{\gamma' \bar{a}}{\bar{\lambda}}} \]  

(6)

\[ \bar{P}' = \frac{8}{3\gamma' \bar{a}} \left[ \frac{2}{3} \bar{a}^3 \bar{\lambda}^2 + \frac{4}{3} \pi^2 \bar{a}^2 \bar{\lambda}^2 + \frac{\pi^2}{2} \bar{a} \bar{\lambda}^2 \bar{H}_\lambda \left( 2\pi \bar{a} \right) - \pi^2 \bar{a}^2 \bar{\lambda}^2 \bar{H}_\lambda \left( 2\pi \bar{a} \right) \right] - \frac{8}{3} \sqrt{\frac{\bar{a}^3 \bar{\lambda}^2}{\gamma'}} \]  

(7)

A detailed discussion on the nature of the solution given Eq. (6) and (7) is given by Guduru [13]. It was shown that surface waviness introduces corrugations on the JKR solution. As a result, for displacement controlled or load controlled indentation or for any intermediate case, the corrugations make the interface recede in alternating stable and unstable segments; with each unstable jump dissipating mechanical energy. As a result, the external work done to detach the wavy sphere is greater than that for a smooth sphere, leading to interface toughening. Also, the maximum separation force \( P_{max}' \) is greater than \( P_{JKR}' \), resulting in interface strengthening. The interface strength relative to the JKR case can be written as

\[ \frac{P_{max}'}{P_{JKR}'} = \bar{P}_{max}' \left( \bar{x}, \bar{a}, \gamma', \eta \right) \]  

(8)

where

\[ \eta = \frac{a_{max}}{R} \]  

(9)
In the above equation, $a_{\text{max}}$ is the radius of the rigid punch, as illustrated in Fig. 1. If $a_{\text{max}}$ and $R$ are given and the half space material is chosen, then the last two of the four non-dimensional parameters appearing as arguments in Eq. 8 are determined. A detailed discussion on the dependence of $P'_{\text{JKR}}$ on each of the four non-dimensional arguments was discussed by Guduru [13]. In relation to the current experiments, it can be summarized briefly as follows. $P'_{\text{max}}$ increases monotonically with increase in $A$; decreases monotonically with increase in $\gamma'$; increases monotonically with $\lambda$ initially, but becomes independent of it when $\lambda$ is of the order of 1. The dependence on $\lambda$ is the most interesting; $P'_{\text{max}}$ approaches unity at both limits $\lambda \to 0$ and $\lambda \to \infty$, recovering the JKR case at both extremes. It can be understood as follows. For a fixed value of $A$, as $\lambda \to 0$, the punch shape approaches a smooth sphere, which is simply the JKR geometry. For any finite value of $\eta$, as $\lambda \to \infty$, the punch shape again approaches a sphere, recovering the JKR result. At intermediate values of $\lambda$, $P'_{\text{max}}$ has local maxima; depending on the values chosen for the other three arguments, the maximum value of $P'_{\text{max}}$ can be a “large” number, suggesting substantial interface strengthening due to waviness alone. For further details of the analysis, the reader is referred to Ref. [13]. The objective of the experimental work presented here is to examine the validity of these theoretical results and to demonstrate that interface strengthening can be obtained by topography optimization, without modifying the surface chemistry.

3. Experimental Procedure

3.1 Sample Preparation

The elastic block in the experimental investigation is made of gelatin, which is a soft elastomer and is easy to produce. Although it displays viscoelastic behavior, for the purpose of this study, it is idealized to be an elastic material. Possible differences between the theoretical predictions and experimental results due to the elastomeric nature of the material are discussed later. In order to prepare the gelatin blocks, Granular gelatin (MP Biomedicals, 100 Bloom) is dissolved in water at 60°C, at a ratio of 1:8 by weight. In order to minimize dehydration of gelatin during the experiment, glycerol is added to the solution. The final solution contains 10% wt glycerol, 10%wt gelatin and 80%wt water. The solution is then poured in a mould, which has a flat glass plate on the bottom, and refrigerated at 4°C for 24 hrs. When removed from the mould, a solid gelatin block is obtained, the top surface of which inherits the flatness and the smoothness of the glass plate. The RMS surface roughness of the glass plate and the gelatin block were measured with an atomic force microscope (AFM) and was found to be around 6-9 nm. The size of the gelatin blocks is approximately 10 cm x 10 cm x 5 cm. Since the mechanical properties of gelatin are sensitive to temperature, the blocks are left at room temperature for 4 hours prior to the experiments, in order to reach thermal equilibrium at room temperature. This also allows the condensed water film to evaporate from the gelatin surface.

3.2 Experimental setup
The experimental setup is schematically illustrated in Fig. 2. The gelatin block is placed on top of a transparent tilt stage, which is used to align the gelatin surface normal to the punch axis. Since the applied compressive force and the adhesive force are of the order $0.1 \sim 1$ N, the punch is attached to a high precision miniature load cell (Honeywell Sensotec, load range: ± 10N), which has a force resolution of 10 mN. The load cell is attached to the top crosshead of an electro-mechanical universal testing machine (Instron 5800), which has a displacement resolution of 1 $\mu$m. On the bottom side of the tilt stage, a 45° mirror is used to image the contact area and measure the contact radius during the experiment. Although gelatin is idealized to be an elastic material in this investigation, it is actually a viscoelastic material, the properties of which are sensitive to the loading rate. In order to minimize the loading rate effects, in all experiments the crosshead velocity was kept constant at 3 mm/min. During an experiment, the load cell output signal is amplified and fed to the Instron data acquisition system so that the load and the crosshead displacement are recorded as a function of time at a sampling rate of 5 Hz.

4. Experiments

4.1 Measurement of elastic modulus ($E^*$) and the interface energy ($\gamma$)

The properties of gelatin are sensitive to curing time and temperature. Hence, it is necessary to measure its elastic modulus ($E^*$) and the interface energy with the punch material ($\gamma$) for each batch of experiments separately. This is accomplished by performing a compression and pull-off cycle on the gelatin block with a spherical punch and using the JKR theory [16].

The punch profile can be described as $y = r^2 / 2R$, where $y$ and $r$ are the coordinates illustrated in Fig. 1. For all punches used in this investigation, $R$ was chosen to be 0.229 m. This choice is somewhat arbitrary and is governed by the magnitude of the corresponding pull-off force $P_{JKR}$ and its measurability in relation to the sensitivity of the load cell. The diameter of the punch is 59.9 mm ($a_{max} = 29.95$ mm). A load – displacement curve for the indentation is shown in Fig. 3, which includes a hold period of 60 s at the maximum displacement in order to allow load relaxation. A small drop in load during the relaxation can be seen in Fig. 3, which is indicative of the viscoelastic nature of the material. In order to minimize the rate effects, the loading and unloading rates were kept constant at 3 mm/min in all experiments. Note the pull-in and pull-off instabilities in the load-displacement curves, which are predicted by the JKR adhesion theory. A significant deviation from the classical JKR theory is that the loading and the unloading curves do not coincide with each other, primarily due to adhesion hysteresis [17-20]. The interface energy $\gamma$ during unloading for loading is then obtained by fitting Eq. 10 to the unloading data, the elastic modulus $E^*$ is extracted.

Figure 2. Schematic illustration of the experimental setup to indent a gelatin block with a wavy indenter and measure the adhesion force.

Figure 3. A load-displacement curve corresponding to the indentation of a spherical punch on a gelatin block.

Figure 4. Applied force vs. contact radius (P vs. a) during a loading-unloading cycle of a paraboloidal punch indenting the gelatin block. By fitting Eq. 10 to the unloading data, the elastic modulus $E^*$ is extracted. $\gamma$ for loading is then obtained by fitting Eq. 10 to the loading plot and using the value of $E^*$ extracted from the unloading plot.
is inferred from the pull-off force $P_{\text{JKR}}$, maximum separation force, which from the JKR theory is give by Eq. (4). Note that this result is independent of the elastic modulus of the material. The elastic modulus ($E^*$) is measured by fitting the JKR relation between the applied load $P$ and the contact radius $a$

$$P = \frac{4 E^* a^3}{3 R} - \sqrt{\frac{8 \pi \gamma E^* a^3}{R}}$$

with the experimental data. The contact radius $a$ is measured from the sequence of images recorded by the camera illustrated in Fig. 2 during the loading – unloading cycle, which images the contact interface. A sample image of the contact zone is shown in Fig. 5, in which the contact area has a different contrast from the non-contact area. A plot of the $P$ vs. $a$ is shown in Fig. 4, in which the squares and the triangles represent experimental data for the loading and unloading segments of the cycle respectively.

During the loading segment, following the initial pull-in, the contact radius increases monotonically with the load. During the hold period, the load relaxes (Fig. 3) and the contact radius increases slightly. When unloading begins, the contact radius does not begin to decrease immediately. Due to adhesion hysteresis, it remains constant until the load drops substantially before the separation process begins. Knowing the value of $\gamma$ from the pull-off load, Eq. (10) is used to extract the best fit value for the elastic modulus $E^*$ from the unloading data. The extracted value of $E^*$ and the best fit curve are shown in Fig. 4. Using this value of $E^*$, Eq. (10) is then used to fit the loading data points to extract the value of $\gamma$ for the loading segment. Notice the large difference in the interface energy during the loading and unloading segments, i.e. adhesion hysteresis, which is a well known phenomenon at elastomer interfaces [17-20]. For all wavy surface experiments in this investigation, the relevant interface energy is that corresponding to unloading.

### 4.2 Design and fabrication of the punch

As discussed in section 2, the objective of this investigation is to examine the implications of Eq. 8. Once the punch profile radius $R$, punch size $a_{\text{max}}$ and the elastic material (gelatin) are chosen, two of the non-dimensional arguments, $\gamma'$ and $\eta$, in Eq. 8 are determined. The other two arguments in Eq. 8, $\overline{A}$ ($= A/\lambda$) and $\overline{\lambda}$ ($= \lambda/R$), are geometric parameters which describe the waviness. The strategy followed here is to choose two specific values for $\overline{A}$ and examine the dependence of $P'_{\text{max}}$ in Eq. 8 on $\overline{\lambda}$ for each value of $\overline{A}$. Using the measured properties of gelatin, the analytical curves for $P'_{\text{max}}$ vs. $\overline{\lambda}$ are shown in Fig. 7, for $\overline{A} = 0.025$ and 0.05. Experiments are designed to examine these two curves at nine specific values of $\overline{\lambda}$ indicated by the dotted lines on Fig. 5. The values of $R$ and $a_{\text{max}}$ are kept same as those for the spherical punch used to determine the material properties. A total of eighteen polycarbonate punches were fabricated, one for each pair of $\overline{\lambda}$ and $\overline{A}$. The profile of each punch is determined from Eq. 1. The elastic modulus of polycarbonate is approximately 1 GPa and that of gelatin is about 17 kPa. Thus, polycarbonate can be considered to be "rigid" compared to gelatin. A summary of all geometric and material parameters for all punches and experiments is shown in Table 1.

<table>
<thead>
<tr>
<th>$A/\overline{\lambda}$</th>
<th>$a_{\text{max}}$ (mm)</th>
<th>$E^*$ (kPa)</th>
<th>$\gamma$ (N/m)</th>
<th>$R$ (m)</th>
<th>$\gamma'$</th>
<th>$\eta$</th>
<th>$\overline{\lambda}/R$</th>
</tr>
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<tr>
<td>0.025</td>
<td>29.95</td>
<td>16.5</td>
<td>0.22</td>
<td>0.229</td>
<td>$3.66 \times 10^{-4}$</td>
<td>0.131</td>
<td>0.04, 0.06, 0.08, 0.1, 0.12, 0.14, 0.16, 0.18, 0.2</td>
</tr>
<tr>
<td>0.05</td>
<td>29.95</td>
<td>17.0</td>
<td>0.21</td>
<td>0.229</td>
<td>$3.4 \times 10^{-4}$</td>
<td>0.131</td>
<td>0.04, 0.06, 0.08, 0.1, 0.12, 0.14, 0.16, 0.18, 0.2</td>
</tr>
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</table>

Table 1. Summary of all the experimental parameters. A total of 18 polycarbonate punches were machined, each with a separate profile as determined from the parameters above. The experiments were conducted in two batches, one for each $A/\overline{\lambda}$. $E^*$ and $\gamma$ shown are the modulus of gelatin and the interface energy respectively for each batch of experiments.
Each of the eighteen punches were machined on a CNC lathe to have the profile obtained from the parameters shown in Table 1. A photograph of one of them is shown in Fig. 6. Since the wavy profiles are locally concave, during loading, the contact area become multiply connected when the central contact zone is surrounded by an annular contact area corresponding to the next peak, trapping a layer of air in between. Since the theory assumes a simply connected contact area, it is necessary to remove this trapped air as much as possible. To accomplish this, a series of small holes (0.5mm in diameter) were drilled in the punch along the circumference of each trough as shown in Fig 6 (also illustrated in Fig. 1). Although the holes help remove the trapped air and allow complete contact, they also act stress as concentration sites for crack initiation during separation, which is not accounted for in the theory. As a result, the holes can be expected to lower peak separation force in the experiments compared to the theoretical predictions. Being a machined surface, the punch surface is not particularly smooth. Its peak to peak roughness is of the order of 4\( \mu \)m. This roughness is expected to play a role in determining the value of the measured value of the interface energy \( \gamma \) uniformly in all experiments. However, it is far removed from the length scale of the sinusoidal waviness introduced and hence it is reasonable to assume that it does not play a role in the phenomenon being examined here. The spherical punch to which comparisons are made has the same short wavelength roughness.

4.3 Results and Discussion

The experimental procedure consists of adjusting the gelatin surface to be normal to the punch plane using the tilt stage and subjecting the former to a loading and unloading cycle, in which displacement rate is 3 mm/min. The alignment is only approximate at best since it is experimentally very difficult to align two planes to be perfectly parallel to each other. However, the results were seen to be relatively insensitive to small deviations from perfect alignment. Each of the eighteen punches was compressed on a new gelatin block. The experiments were divided into two separate batches, one for each \( A/\lambda \). As a result, the measured value of \( E^* \) and \( \gamma' \) are slightly different between the two batches as shown in Table 1. The load-displacement curves for five of the punches are shown in Fig. 7 as solid curves. Also shown on each figure with a dashed line is the theoretical curve for each punch. As discussed by Guduru [13], the theoretical curves are strictly valid during unloading only because the theory assumes a simply connected contact zone; a condition not satisfied during loading. Also shown on each curve are vertical line segments in dash-dot pattern, which show the expected unstable interface crack jump during unloading. These instabilities are discussed in detail by Guduru [13]. The curves are shown only until \( \lambda/R = 0.12 \) because those for higher values are qualitatively similar. Note that in each case shown, the qualitative agreement between the theory and the experiment is very good. Note that in each case, during unloading, the experimental unloading curve follows the theoretical curve, but the instability sets in prematurely and the peak adhesion force (negative values) is slightly smaller than the theoretical prediction in each case. The slope of the experimental curve also matches with that of the theoretical curve prior to the onset of instability. The difference between the theory and the experiment in the peak force can be explained qualitatively as arising from the presence of the air vent holes drilled along each trough, which are not accounted for in the theory. During the separation process, the troughs ahead of the main crack are under tensile stress. However, in the theory based on linear elastic fracture mechanics, the interface can not separate ahead of the main crack as there are no initiation sites.
Figure 7. Load vs. displacement curves for five punches with $A/\lambda = 0.025$. The solid curves are the experimental data; the dashed curves are the theoretical curves; the vertical lines in dash-dot pattern are the theoretical expected paths in displacement controlled experiments. As expected, the loading segment does not match with the theoretical curve because the contact zone is multiply connected during loading.
However, in the experiment, each hole is like a penny shaped crack at the interface, which can be propagated under sufficiently high tensile stress. Thus, the holes weaken the adhesive interface by acting as crack initiation sites ahead of the main crack, accounting for the systematic difference between the experimental observation and the theoretical prediction. Another significant difference between the experiments and the theory is the deviation in the slope of the load-displacement curves as the load increases, although the slopes match at the beginning of compression and just prior to pull-off. This difference is due to the finite size of the gelatin block in the experiment, whereas the theory considers a half space. The load-displacement behavior of a spherical punch against a finite sized block is known to converge slowly to that corresponding to a half space as the size of the block is increased relative to the contact radius. Further, gelatin is an elastomer whereas theory is based on linear elasticity. The stiffness of an elastomer is known to increase substantially with strain, which can also contribute to the observed higher contact stiffness. However, despite such deviations introduced by the finite dimensions and more complex material behavior, the theory captures the salient features of the experiments remarkably well.

The measured values of the peak separation force from all experiments are summarized in Fig. 8. Note that the plot shows at least three data points at each pair of $\frac{A}{\lambda}$ and $\frac{A}{\gamma}$. In many cases the three values are so close to each other that the corresponding symbols overlap and are indistinguishable from each other, demonstrating the repeatability of the results. The experimental measurements not only follow the predicted trends, but also capture the local maxima. Moreover, note that, within the tests conducted, the maximum enhancement in adhesion compared to the JKR case is about 17 (for $A/\lambda = 0.05$), which is solely due to the interaction between the surface geometry and linear elastic fracture mechanics which approximately governs the adhesive interaction. Thus, the current experimental investigation not only validates the theory, but also suggests strategies to engineer surface topography to maximize adhesion. It is conceivable that by choosing a different set of material and geometric parameters, it would be possible to realize even higher adhesive forces. Further, by scaling down the geometric parameters, it should be possible to pattern surfaces at micron or sub-micron scale and realize enhanced macroscopic reversible adhesion for soft elastomers. These issues require further attention and investigation and will be reported elsewhere.

5. Summary

The objective of the experimental work presented here is to examine the theory of wavy surface adhesion presented in an earlier article [13], in which the adhesive interaction between an elastic half space and sphere with superimposed axisymmetric waviness was analyzed. The main feature of the analysis is that the waviness renders the decohesion process inherently unstable, resulting in interface strengthening and toughening. It was proposed that such strengthening could play a role in the attachment ability of certain insect species with soft pads on their feet. The experiments described here validate all features of the analysis and demonstrate that substantial interface strengthening can be realized by topographic optimization alone. The load-displacement curves follow the predicted trends during unloading and capture the unstable segments. The difference between the experiment and the theory in the contact stiffness can be explained by the finite size of the gelatin block and the over-simplified material behavior assumed in the theory. The maximum adhesive force measured in the experiments was slightly lower than the predicted value and the difference is systematic. This difference possibly arises from the presence of the vent holes drilled in the punch, which act as stress concentration sites and initiate the crack prematurely.

Figure 8. Summary of experimental data on adhesion force as a function of wavelength: comparison between the experimental measurements (symbols) and theoretical predictions (solid lines). The top plot corresponds to $A/\lambda = 0.025$ and the bottom plot is for $A/\lambda = 0.05$. Experimental results capture not only the magnitude of the predictions, but also features such as the local maxima.
before the main crack arrives. However, such differences are secondary to the main objective of this article. The close agreement between the theory and the experiments suggests the validity of the analysis, which can be readily extended to multiple scale roughness by appropriate superposition of the basic solution.

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