

The influence of substrate roughness, patterning, curvature, and compliance in peeling problems

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1 curvature and deformability. The approach is validated by comparing its predictions with classical
2 thin film peeling theoretical model results, and then used to predict effects of substrate properties.
3 Results can provide deeper insight in experimentally obtained results and the developed model a
4 useful tool to design and optimize artificial adhesives with tailor made characteristics.

5 **Keywords:**

6 Biological adhesion, thin film peeling, bioinspired adhesives, numerical modelling.

7

1 **1. Introduction**

2 In recent years, there has been growing interest in the study of biological systems displaying
3 architectures that are optimized for specific functions such as structural resilience, protection,
4 locomotion, self-cleaning or self-repair [1] [2] [3]. The observation and mimicry of natural systems
5 has therefore led to the emergence of novel smart strategies to improve artificial system
6 functionalities [4]. This applies to the field of biological adhesion, which also studies the way in
7 which animals like beetles, spiders or geckos achieve optimized adhesion control by means of
8 arrays of tape-like micro- or nano-contacts organized in a hierarchical manner, especially in
9 heavier animals [5]. It has been demonstrated that these contact units can be modelled as
10 delaminating (or “peeling”) thin films, rather than punch-like units [6], and that structures such as
11 gecko, spider or insect pads can be described using models based on this description of the contacts
12 [7] [8]. One of the key features of analytical tape peeling models, such as the Rivlin model [9] or
13 the Kendall model [10], is that the peeling force, i.e. the force necessary to initiate detachment of
14 the adhesive structure, strongly depends on the angle between the applied force and the substrate,
15 i.e. the “peeling angle”. In addition to the observed contact geometries, one of the main arguments
16 for treating animal attachment as ensembles of delaminating tapes is that the angle dependence on
17 the detachment force has been experimentally observed in all species displaying “hairy” contacts,
18 both at micro and macro scale [6]. In addition to the geometry of the tape unit and the peeling
19 angle, the adhesive energy at the interface between the contact units and the substrate contributes
20 to determining the peeling force. This adhesive energy is mainly due to van der Waals interactions
21 [11] and to capillarity [12], but in the cited contact models, all substrate and interface properties
22 are condensed into a single adhesive energy term. For a given loading scenario and tape
23 geometrical/mechanical properties, the adhesive energy varies as a function of the material and the

1 surface profile of the substrate [13] [14]. In turn, the peeling force derived in analytical peeling
2 models is related to the variation of the difference between adhesive energy and total potential
3 energy, which describes the micro scale physics of interface failure.

4 With current progress in mimicking natural adhesives, the understanding of peeling mechanisms
5 and the derivation of adhesion optimization criteria become essential. To design optimal solutions,
6 adequate numerical tools taking account of all mechanical mechanisms are required, and thus
7 reliable models need to be developed. One of the main drawbacks of current models and of
8 Kendall's formulation in particular, is that they do not account for the dependence of the adhesive
9 force on substrate properties, i.e. the substrate is considered perfectly flat, perfectly smooth and
10 infinitely rigid. However, outstanding adhesive properties of animal attachment systems also
11 appear in the presence of variable substrate compliance, roughness, or of structured surfaces [15].
12 These essential features should therefore also be included in models, especially in the case of soft
13 substrate materials.

14 Persson et al. [16] [17] presented a theoretical study on the influence of surface roughness
15 occurring at various size scales on the adhesive properties of biological adhesives, showing that a
16 hierarchical fibrillar structure is essential in guaranteeing sufficient adaptability to the surface.
17 Peng et al. proposed an analytical model to describe the effect of roughness on an elastic nanofilm,
18 linking its adhesion to the "wavelength" of the roughness profile [18]. Huber et al. [19] and Cañas
19 et al. [20] presented experimental studies on the effect of surface roughness on artificial adhesives
20 with spatula- or mushroom-shaped tips, including qualitative analysis of the assumed mechanisms
21 for adhesion enhancement for varying asperity size scales. The issue of roughness as a cause for
22 partial contact was addressed in [21], where the JKR theory was extended to account for energy
23 released during rippling. A review of these and other modelling approaches related to the influence

1 of toughness are provided in [22]. However, in these works, the effect of roughness or surface
2 patterning on adhesive strength is not explicitly correlated to the dimension of the process zone,
3 i.e. the size scale at which stress concentrations occur in peeling processes.

4 In this paper, we adopt a different approach to address the issue of surface roughness and
5 patterning, adding analysis of the influence of substrate curvature and compliance, with the
6 objective of better understanding the role of the substrate on the peeling behaviour of adhesives.

7 We therefore present a novel computational approach to model the so-called process zone of
8 peeling, which is the area where the interface between adhesive and substrate is subject to stresses,
9 leading to failure of adhesive bonds and therefore to detachment. The model is validated with
10 results from classical peeling theories and several aspects of the interface/substrate are discussed.

11

2. Analytical modelling of the process zone

We consider a problem of dry adhesion of a contact unit on a substrate. The mechanics of its detachment, illustrated in *Figure 1.A*, is analogous to the problem of a propagating crack front in an adhesive interface. A classical energetic approach such as Kendall's model [10] provides a macro-scale description of this mechanism, and is the reference model in the study of biological adhesion. The progression of the peeling front becomes energetically favourable, and therefore occurs if:

$$\frac{\partial V}{\partial l_d} - \frac{\partial U_e}{\partial l_d} > \frac{\partial U_s}{\partial l_d} \quad (1)$$

where V is the work associated with the external load applied to the tape, U_e the stored elastic energy in the tape, U_s the surface energy and l_d the detached tape length, which increases as the peeling proceeds. When delamination occurs, the dissipated energy per unit detached surface area, indicated in Linear Elastic Fracture Mechanics (LEFM) as the strain energy release rate [23], equals the adhesive energy G per unit area of the interface:

$$G = \frac{1}{w} \left(\frac{\partial U_s}{\partial l_d} \right) \quad (2)$$

where w is the tape width. According to Kendall's theory, this corresponds to:

$$G = \frac{1}{w} \left(\frac{\partial V}{\partial l_d} - \frac{\partial U_e}{\partial l_d} \right) = \frac{F}{w} (1 - \cos \theta) + \frac{F^2}{2Ebw^2} \quad (3)$$

where F is the applied load at the detached tape end, b the tape thickness, E the tape elastic modulus and θ the angle between the applied load and the substrate (*Figure 1.A*). The critical peeling force F_C therefore becomes:

$$F_c = Ebw \left(\cos \theta - 1 + \sqrt{(1 - \cos \theta)^2 + \frac{2G_c}{Eb}} \right) \quad (4)$$

1

2 Another approach in the study of adhesion and delamination is to determine the loading state of
 3 the interface, assuming a thin adhesive layer bonding the tape and the substrate [24]. In this
 4 formulation, a finite-length region exists in the vicinity of the propagating delamination front,
 5 referred to as the process zone, in which deformations in both the tape and the interface take place
 6 [25]. Considering a simple loading scenario where the applied external load is parallel to the
 7 substrate at $\theta = 0$, the force balance acting on the attached region, according to the shear lag model
 8 [26], can be written as:

$$\frac{d\sigma_T}{dx} = \frac{\tau_I}{b} \quad (5)$$

9 where $d\sigma_T$ is the infinitesimal variation of the tape axial stress over an infinitesimal length dx and
 10 τ_I is the shear stress in the interface layer, which is assumed initially to be a linear function of the
 11 axial displacement within the tape u and the interfacial stiffness K_I (in the tangential direction):

$$\tau_I = K_I u \quad (6)$$

12 Introducing the tape strain $\epsilon_T = du/dx = \sigma_T/E$, after differentiation of Eq. (5), we obtain:

$$\frac{d^2\sigma_T}{dx^2} = \frac{K_I}{bE} \sigma_T \quad (7)$$

13 This equation is solved applying the boundary conditions $\sigma_T(x = 0) = F/(bw)$ and supposing that
 14 the attached length l_a of the tape is sufficiently long for the tape axial stress to tend to zero at its
 15 edge $\sigma_T(x \rightarrow -l_a) = 0$. In this case, we obtain the following distribution of interfacial stress:

$$\tau_I(x) = \frac{F}{w} \sqrt{\frac{K_I}{bE}} \exp\left(\sqrt{\frac{K_I}{bE}} x\right) \quad (8)$$

1 In correspondence with the peeling line at $x = 0$, the interfacial stress is maximum and failure of
 2 the adhesive bond occurs when its elastic energy reaches the critical value:

$$G_c = \frac{F_c^2}{2Eb w^2} = \frac{\tau_{Ic}^2(x=0)}{2K_I} \quad (9)$$

3 This equation also provides the relation between interface stress distribution and detachment force.

4 The critical peeling force in Eq. (9) is in agreement with Kendall's equation in Eq. (4) for $\theta = 0$,

5 showing the consistency of the approach with existing peeling theories. Notice that previous works

6 have investigated the influence of bending stiffness on the peeling behaviour of thin films [27]. In

7 the present paper, we consider this to be negligible, and tape thickness values will be chosen

8 accordingly.

9 When the peeling angle differs from 0, the adhesive bonds experience both tangential and normal

10 loads, whose distributions influence the external force at which the system detaches. The interface

11 is therefore subject to a mixed-mode fracture mechanism with an opening mode (mode-I) and a

12 sliding mode (mode-II). For small peeling angles, the mode-II strain energy release rate G_{II} can be

13 approximated by solving Eq. (7) with the boundary condition $F(x=0) = F \cos \theta$, leading to:

$$G_{II} = \frac{F^2}{2Eb w^2} \cos^2 \theta \quad (10)$$

14 The mode-I strain energy release is estimated injecting Eq. (10) into Eq. (3) with $G = G_I + G_{II}$,

15 leading to:

$$G_I = \frac{F^2}{2Eb w^2} \sin^2 \theta + \frac{F}{w} (1 - \cos \theta) \quad (11)$$

1

2 **3. Numerical model and results**

3 We propose here a numerical model to determine both tangential and normal stress distributions
4 at the interface and to understand how the mechanisms acting within the process zone affect the
5 overall adhesive performance. The tape is thus discretized with a set of truss members of length
6 Δx (the discretization length), undergoing axial load only. A traction vs. separation law, usually
7 referred to as a Cohesive Zone Model (CZM) [28], is introduced for each tape node to model the
8 interface between the tape and the substrate, i.e. a restoring reaction force is generated on the tape
9 nodes as a function of the deformations of the system. The relation between the tape axial stress
10 and strain is taken as linear elastic for simplicity, but geometrical nonlinearities can occur in
11 interfacial stresses due to the nature of the problem. As the applied force and its angle with respect
12 to the substrate increase, deformations, translations and rotations of the tape vary in the process
13 zone, as does the stored elastic energy of the adhesive interface bonds, which are responsible for
14 the macroscopic behaviour of the peeling system. To calculate the mechanical equilibrium after
15 the application of the force, a Newton-Raphson iterative scheme [29] is adopted (details are given
16 in Appendix A). A 2-D model is employed, assuming that the detached and attached tape regions
17 and the applied force are coplanar. The detached part of the tape is not modelled, since the far-
18 field external load can be directly applied in correspondence with the peeling line at $x = 0$. This
19 is because the tape bending stiffness is neglected, so that the detached part of the tape only transfers
20 axial load without influencing the mechanical equilibrium of the process zone. We introduce a
21 linear interfacial traction vs. separation law as:

$$\frac{R}{w\Delta x} = K_I \delta_I \quad (12)$$

1 where R is the nodal reaction force and $\delta_I = \sqrt{u^2 + v^2}$ is the separation of a tape node with respect
2 to its initial position in the plane, with u and v the components of the nodal displacement along x
3 and y . Note that interface bonds experience axial load only (tangential and normal forces are
4 coupled). A schematization of the numerical model is shown in *Figure 1.B*.

5 In the following, tape and interface properties are chosen as: $w = 1$ mm, $b = 0.01$ mm, $K_I = 10$
6 MPa·mm⁻¹, $l_a = 2$ mm, and an external load of $F = 10$ N is applied. The tape Young's modulus is
7 chosen as $E = 100$ MPa since most biological fibrillar adhesives reach values above 1 GPa [17]
8 [22] [30], but recent studies indicate that the modulus decreases towards the tips of the contacts
9 [31]. The corresponding tangential and normal stress distributions, calculated from the
10 displacement field at equilibrium as $\tau_I = K_I u$ and $\sigma_I = K_I v$, as a function of the peeling angle are
11 shown in *Figure 2.A and 2B*. These distributions highlight the fact that the angle dependency is
12 related to stress distributions within the process zone. At $\theta = 0$, the normal stress is zero and the
13 shear stress distribution agrees with the analytical solution in Eq. (8) (shown in red). We note that
14 the normal interfacial stress is more concentrated at the peeling line compared to the shear one,
15 and is mainly responsible for the decrease in the peeling force as the peeling angle is increased. In
16 addition, no compressive normal stress is present ahead of the peeling front, consistently with the
17 fact that with the chosen parameters, the bending stiffness is negligible.

18 In the numerical model, the mode I and mode II strain energy release rates are computed from the
19 displacement field at the most critical adhesive bond (in correspondence with the peeling line) as
20 follows:

$$G_I = \frac{1}{2} K_I v^2 \quad (13)$$

$$G_{II} = \frac{1}{2} K_{II} u^2 \quad (14)$$

1 The dependence of G_I and G_{II} on the peeling angle θ , calculated both analytically and numerically,
2 is shown in *Figure 2.C*. There is a good agreement between analytical and numerical results, but
3 for large peeling angles, rigid body motions of the tape and large adhesive bond deformations
4 within the process zone affect the interfacial stress distribution and lead to a discrepancy between
5 the two.

6 We now introduce a local energy-based failure criterion, i.e. a critical strain energy release rate G_c
7 for the interface bonds, beyond which detachment occurs, as:

$$G_c = \frac{1}{2} K_I \delta_I^2 \quad (15)$$

8 The corresponding peeling force as a function of the peeling angle calculated numerically agrees
9 with the analytical solution of Eq. (3), as shown in *Figure 3* for an adhesive energy $G_c = 0.5$
10 MPa·mm.

11 In nature, a wide variety of types of bonding between the tape-like contacts and the substrate has
12 been observed in biological systems. The van der Waals interaction responsible for the adhesion
13 of Geckos, the capillarity forces in insect attachment or glue-coated spider silks all have specific
14 interactions with the substrate. The traction-separation law is therefore expected to depend on the
15 type of interaction. In the case of a nonlinear force vs. separation relation of the interface bonds,
16 the peeling force is not affected by the type of nonlinearity as long as the total energy dissipated
17 by a specific bond during loading is invariant. This means that although the model has been
18 developed for dry adhesion, wet adhesion can also be simulated, provided an appropriate adhesive

1 term can be formulated. We thus consider different traction-separation laws (Reaction force R vs.
 2 elongation δ_I) in the model:

- 3 • Linear elastic:

$$\frac{R}{w\Delta x} = \begin{cases} K_I \delta_I & \text{for } \delta_I < \delta_I^* \\ 0 & \text{for } \delta_I > \delta_I^* \end{cases} \quad (16)$$

- 4 • Perfectly elasto- plastic:

$$\frac{R}{w\Delta x} = \begin{cases} K_I \delta_I & \text{for } \delta_I < \delta_I^* \\ K_I \delta_I^* & \text{for } \delta_I > \delta_I^* \\ 0 & \text{for } \delta_I > \delta_I^{**} \end{cases} \quad (17)$$

- 5 • Exponential:

$$\frac{R}{w\Delta x} = \frac{R^*}{w\Delta x} \frac{\delta_I}{\delta_I^*} \exp\left(1 - \frac{\delta_I}{\delta_I^*}\right) \quad (18)$$

6 The input parameters for each of these laws must satisfy the following condition:

$$\int_0^\infty \frac{R}{w\Delta x} d\delta_I = G_c \quad (19)$$

7 When the peeling force is reached, the load distribution at the interface $\frac{R}{w\Delta x}$ vs x changes
 8 considerably as a function of the chosen traction-separation law, as shown in *Figure 4.A* (for $\theta =$
 9 $\pi/8$ and $G_c = 0.5 \text{ MPa}\cdot\text{mm}$).

10 The applied force versus force application point displacement η obtained for a peeling test, i.e.
 11 when the system is loaded until complete detachment of the tape, is shown in *Figure 4.B* for an
 12 exponential traction-separation law and $\theta = \pi/8$, highlighting an “elasto-plastic” behaviour.
 13 When the applied load is below the peeling force (points a and b), the elastic energy in the interface
 14 increases as it deforms. Next, the crack front propagates at constant peeling force (point c) over

1 the attached length of the tape. A small drop of the peeling force is observed (point *d*) when the
2 crack front reaches the end of the attached region, before complete detachment. This is because
3 the remaining attached part is not long enough for the axial load in the tape, and consequently the
4 interface load, to tend to zero (*Figure 4.C*).

5 **4. Influence of substrate geometrical features**

6 We now study the influence of several characteristics of the substrate on the peeling force using
7 the previously introduced numerical model. For simplicity, the linear-traction-separation law is
8 employed for the interface in simulations, together with the local energy-based delamination
9 criterion.

10 *4.1. Substrate roughness and patterning*

11 An imperfect contact between the tape and the substrate, as a result of surface roughness, can be
12 introduced by statistically assigning a variable adhesive energy G_C^* to each adhesive bond. These
13 energy values are extracted randomly from a uniform distribution $G_C^* = 2 \cdot U(0, G_C)$, and from a
14 normal distribution $G_C^* = \mathcal{N}(G_C, G_C/10)$ with $G_C = 1$ MPa.mm. The first of the two is considered
15 since it allows to evaluate the effect of a large scatter in adhesive energy values. The second of the
16 two is closer to the surface roughness distribution found in real materials. The simulation is
17 performed for $\theta = 0$ and $\theta = \pi/4$. The corresponding force-displacement plot of the force
18 application point η is shown in *Figure 5.A*. The general behaviour of the system is similar to that
19 for a smooth substrate shown in *Figure 4.B*. The two plots refer to different traction-separation
20 laws, but this does not influence the overall behaviour, provided the integral in Eq. (19) is the
21 same. The peeling force appears to be approximately constant in spite of the high variability in the
22 local failure energies. It is interesting to note that the obtained peeling forces are $F_c(\theta = 0) \cong$
23 10 N and $F_c(\theta = \pi/4) \cong 7.41$ N, which are approximately those predicted by Eq. (4) considering

1 the mean value $G_c = 0.5 \text{ MPa} \cdot \text{mm}$. The time variation of the load distribution is shown in *Figure*
2 *5.B* in the case of a uniform distribution at $\theta = 0$, and helps gain a better understanding of the
3 peeling force results. In the early stages of loading of the system, some local detachment events
4 occur ahead of the crack front, in correspondence with the weakest adhesive bonds, and the load
5 is then distributed on the surviving ones, driving the peeling force.

6 Another important effect related to the substrate morphological properties is the possible presence
7 of entire regions where contact is absent, such as in the case of patterned surfaces. To investigate
8 this, we simulated numerically the case of a periodic pattern schematically shown in *Figure 6.A*,
9 by alternating regions without and with bonding between the tape and the substrate, respectively
10 of length α and β . The results of the simulations for $\theta = \pi/8$ and varying α and β values are
11 shown in *Figure 6.B*. Here, the maximum peeling force for the considered structure is normalized
12 with respect to the one predicted by Eq. (4) i.e. for full contact over the entire substrate. When the
13 length of the attached region α reaches the theoretical process zone length, the normalized force
14 tends to 1, which means that the pattern does not affect the process zone distribution. As β
15 decreases, the maximum peeling force is reduced due to an increase in the load concentration
16 within the process zone. The size of the gaps within the attached region also affects the peeling
17 force. As the length α increases, the detachment force decreases for a fixed β . Simulations show
18 that patterned substrate surfaces are detrimental to the peeling force, especially when the size of
19 gaps in the interface is large with respect to the process zone length. *Figure 6.C* shows that the
20 peeling force is not constant during a peeling test on a patterned substrate. As the first attached
21 length ahead from the peeling front is reduced, the peeling force tends to decrease until the
22 detachment front encounters a detached region. Then, the force increases again as the crack is
23 stopped and the tape undergoes elastic deformation until the next attached length starts to peel-off.

1 The difference between minimum and maximum detachment force in this case increases as the
2 unbounded lengths α are increased.

3 *4.2. Substrate curvature*

4 In [14], the ability of the gecko's lamellar system to adapt to wavy surfaces was studied.
5 Specifically the influence of substrates characterized by a sinusoidal profile on the shear adhesion
6 strength was considered. Depending on the amplitude and the wavelength of the considered surface
7 profile, the hierarchical adhesive pad of gecko performs a full or a partial contact with the substrate.
8 When partial contact is achieved, the problem is similar to that discussed in the previous section,
9 but when tape-like structures of lamellae conform to the curvature of the surface, the process zone
10 load distribution differs from the flat surface case. A radius of curvature for convex and concave
11 surfaces can be simply introduced in the present model by setting the initial coordinates of the tape
12 nodes along an arc of a circle rather than a line. The peeling angle in this case is the angle between
13 the applied external load and the tangent to the substrate surface at the peeling line, and the
14 adhesive energy is set to constant on all points of the model. When the length of the process zone
15 is small with respect to the radius of curvature of the surface (in our case approximately 1mm),
16 this effect is negligible, but as it decreases and becomes of comparable size, the peeling force is
17 affected. *Figure 7* shows the peeling force, normalized with respect to the peeling force on a flat
18 substrate with the same parameters, as a function of the radius of curvature. For convex surfaces,
19 the peeling force increases as the curvature radius decreases, and the opposite happens for concave
20 surfaces. Additionally, the peeling angle changes as the detachment proceeds and the peeling force
21 is not constant during propagation of the peeling front, contrary to the case for a flat surface. This
22 is illustrated in *Figure 7.C*, where the force tends to increase for convex surfaces, and decrease for
23 concave surfaces. When the contacts are split, the adhesive strength is the result of simultaneous

1 delamination of multiple tapes [25], as is the case for animal hairy attachments, and the decrease
2 in local angles at different hierarchical scales could help in optimizing the total peeling force.

3

4 **5. Influence of substrate deformation**

5 In the case of soft materials, substrate deformation can also affect the way the load is distributed
6 in peeling tests. The inclusion of substrate deformation in the calculation of the peeling force is a
7 complex problem, since implementing an elastic half-plane in the simulation with a sufficient
8 precision, i.e. a sufficiently small discretization length, would lead to a very large number of
9 degrees of freedom. Instead, we propose to introduce an elastic foundation of stiffness K_G in both
10 normal and tangential directions for the substrate nodes. The interface is therefore introduced in
11 the numerical model as a set of interface and substrate bonds arranged in series. The local failure
12 criterion is still applied to the interface bonds when the system is loaded, in the hypothesis that no
13 failure events take place within the substrate. *Figure 8* shows, for a uniform adhesive energy, the
14 peeling force as a function of the ratio between the interface and the substrate stiffness. A more
15 compliant substrate generates a higher peeling force, which tends to the theoretical value of Eq.
16 (4) as the substrate becomes stiffer. This increase is the result of two positive mechanisms: first,
17 the distribution of the load in the interface becomes wider, which reduces the load concentration
18 in the vicinity of the peeling line; second, as a result of the substrate deformation, the local peeling
19 angle, i.e. the angle between the applied external load and the deformed surface of the substrate
20 decreases. This mechanism is also favourable for an increase in the detachment force. A limit of
21 this gain lies in the fact that the attached length of the tape might not be long enough to indefinitely
22 extend the width of the distribution. In this case, the peeling force increase is limited.

1 Notice that these results are in contrast with experimental observations in [32], but as the authors
2 themselves point out therein, the measurements are largely affected by other characteristics of the
3 adopted soft substrates, such as surface chemistry, capillary adhesion, friction, etc., all of which
4 are not assumed to vary in our model.

5

6 **6. Discussion**

7 We have modelled different geometrical and elastic features of the substrate surface profile in
8 order to describe the adhesive behaviour of real materials, where roughness can be observed at
9 different scale levels. We have shown that when the size scale of asperities is small compared to
10 the process zone, their effect on the peeling properties of the tape is limited. We treated this case
11 by considering the roughness as a statistical distribution on the adhesive bond energy to failure,
12 since this implies that the attached length of the film is large with respect to the substrate roughness
13 pattern, and found that the detachment force is close to the one obtained theoretically taking the
14 average of the distribution. As the size of asperities becomes larger with respect to the attached
15 length of the film, the detached areas become comparable to the process zone, and a decrease in
16 the detachment force is observed. This is consistent with theoretical [17] and experimental [33]
17 [20] [22] data, in which the predicted/measured detachment force for a rough surface is
18 considerably affected by partial bonding and the pull-off force decreases monotonically with
19 increasing surface roughness. Above a certain roughness size scale, partial bonding is no longer
20 an issue, as the tape can conform to the surface pattern. In agreement with theoretical results from
21 [18], there is some variation in the detachment force depending on the type of curved substrate on
22 which the tape must adhere. Simulations show that this is the result of the local perturbation in the
23 process zone due to the change of peeling angle in the zone ahead of the detachment front. As

1 delamination proceeds, the detachment force is no longer constant, rather it increases or decreases
2 depending on the criticality of the new distribution emerging from the varying angle of the attached
3 length. The latter observation is consistent with the increase in detachment force obtained
4 experimentally above a certain roughness in [19], since a non-negligible fraction of tape-like
5 contacts is likely to be subjected to a smaller peeling angle as delamination proceeds, and therefore
6 a larger peeling force during simultaneous detachment. All of these results are modified by non-
7 negligible substrate compliance, which we show to be advantageous to adhesive properties in the
8 case of a uniform surface. Further dedicated experimental tests to validate these numerical results
9 would be desirable in the future.

10

11 **7. Conclusions**

12 In conclusion, we have developed a numerical model to simulate the peeling of adhesive tape-like
13 structures that is focused on the adhesive interface between tape and substrate. The numerical
14 procedure has been validated with classical thin film peeling theoretical model, and further studies
15 on the interface and substrate properties have been proposed. It was shown that modelling the
16 interfacial zone where the adhesive bonds are loaded, referred to as the “process zone” allows to
17 capture some effects not predicted by the theoretical model, such as an imperfect bonding, the
18 geometry of the substrate surface or substrate deformations within the process zone. The presented
19 model and simulation contribute in providing a better understanding of the mechanisms and
20 possible optimization of adhesive structures.

21

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7 (www.hpc.polito.it).

8

9 **Appendix**

10 Further details regarding the implementation of the numerical model are provided below. For the
11 tape elements linking two nodes i and j of the model, mechanical equilibrium is implemented using
12 co-rotational truss formulation [34]. The material and geometric local stiffness matrices are given
13 by:

$$\mathbf{K}_{\text{Tm}} = \frac{Ebw}{\Delta x} \begin{bmatrix} n_1^2 & n_1 n_2 & -n_1^2 & -n_1 n_2 \\ n_1 n_2 & n_2^2 & -n_1 n_2 & -n_2^2 \\ -n_1^2 & -n_1 n_2 & n_1^2 & n_1 n_2 \\ -n_1 n_2 & -n_2^2 & n_1 n_2 & n_2^2 \end{bmatrix} \quad (20)$$

$$\mathbf{K}_{\text{Tm}} = \frac{Ebw}{\Delta x} \frac{\delta_T}{\Delta x + \delta_T} \begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 1 & 0 & -1 \\ -1 & 0 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix} \quad (21)$$

14

15 where E is the elastic modulus of a tape element, b its thickness, w its width, Δx its length
16 (corresponding to the discretization length), δ_T its elongation and n_1 and n_2 the components of the
17 (deformed) tape element direction vector in 2-D space, i.e.

1

$$n_1 = \frac{x_j + u_j - x_i - u_i}{\Delta x + \delta_T} \quad (22)$$

$$n_2 = \frac{y_j + v_j - y_i - v_i}{\Delta x + \delta_T} \quad (23)$$

2

3 where $\mathbf{x} = [x \ y]$ is the coordinate vector of a node and $\mathbf{u} = [u \ v]$ its displacement after
4 deformation. Its contribution to the internal force vector is:

5

$$\mathbf{Q}_{Ti} = \frac{Ebw}{\Delta x} \delta_T \begin{bmatrix} n_1 \\ n_2 \\ -n_1 \\ -n_2 \end{bmatrix} \quad (24)$$

6

7 On the other hand, the interface bonds act on one node each (i). For a linear elastic traction-
8 separation law, the contribution of an interface bond to the stiffness matrix is given by:

9

$$\mathbf{K}_I = K_I w \Delta x \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (25)$$

10

11 where k_I is the stiffness of an interface bond. Its contribution to the internal force vector thus
12 becomes:

13

$$\mathbf{Q}_{Ii} = K_I w \Delta x \delta_I \begin{bmatrix} u_i \\ v_i \end{bmatrix} \quad (26)$$

1

2 The external force vector \mathbf{Q}_e contains the components of the external load acting on the system.

3 Once all contributions are assembled into the linear system, mechanical equilibrium is obtained by

4 updating the nodal displacement according to the following iterative scheme:

5

$$\mathbf{u} + (\mathbf{K}_{Tm} + \mathbf{K}_{Tg} + \mathbf{K}_I)^{-1}(\mathbf{Q}_e - \mathbf{Q}_{Ti} - \mathbf{Q}_{Ii}) \rightarrow \mathbf{u} \quad (27)$$

6

7 The 2-norm of the residual $\|\mathbf{Q}_e - \mathbf{Q}_{Ti} - \mathbf{Q}_{Ii}\|$ is used as convergence criterion.

8

9

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10

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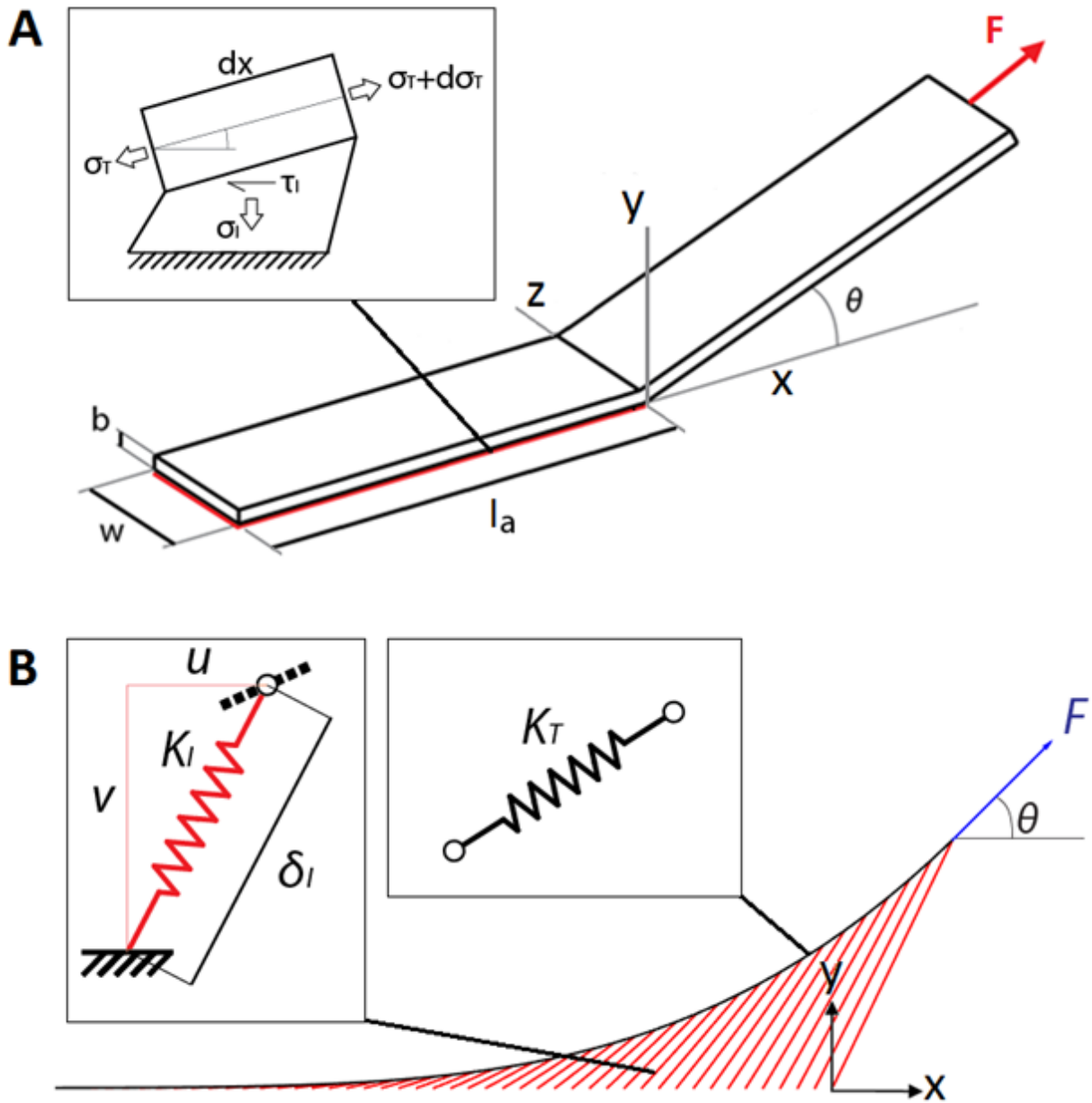
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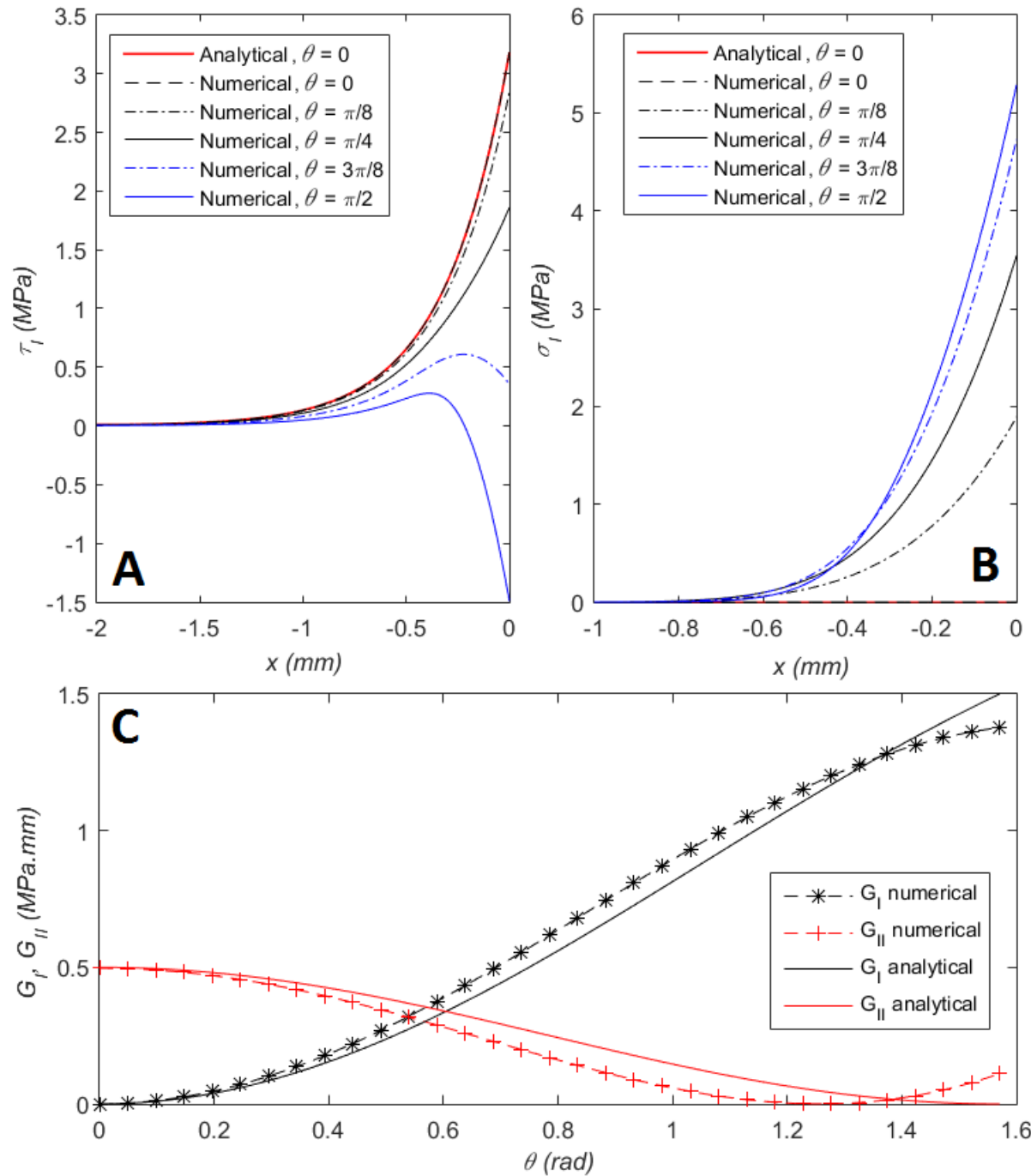
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2 *Figure 1 : A. Schematic representation of the geometry of the considered tape peeling problem*
 3 *and (inset) of the stresses acting on an elementary unit of the interface. B. Corresponding*
 4 *discretization in the numerical model using interface and tape spring elements of stiffnesses K_I*
 5 *and K_T , respectively.*

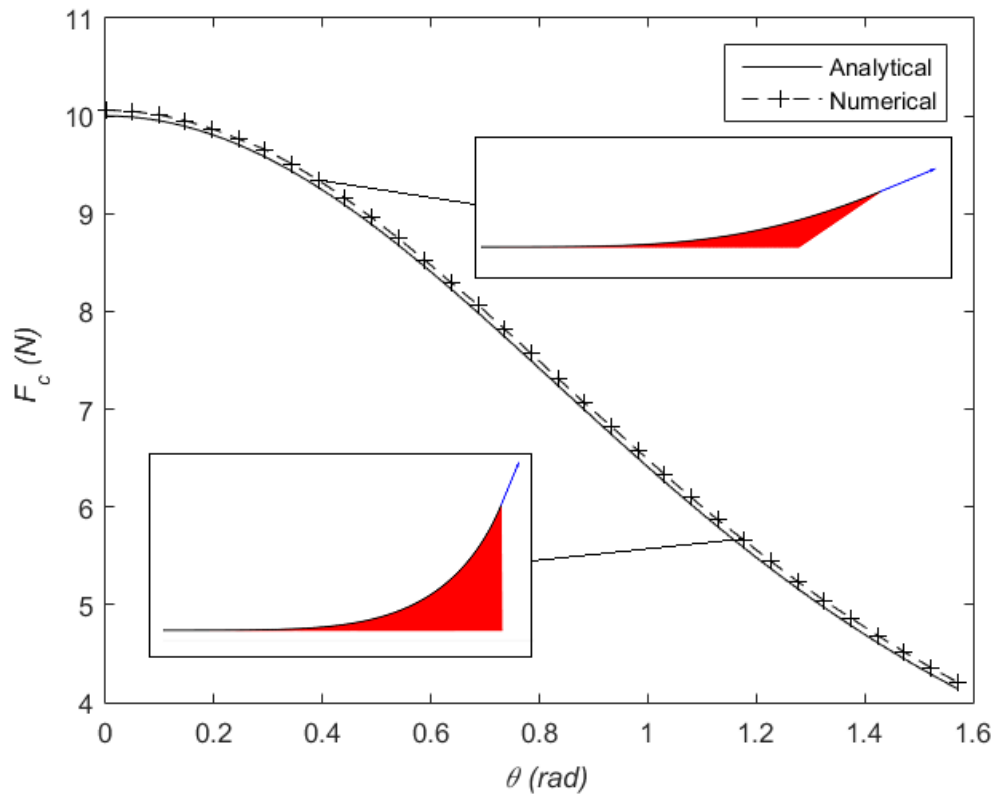
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2 *Figure 2 : A. Shear and B. Normal stress distributions at the interface along the process zone for*
 3 *different peeling angles. C. Mode I and mode II strain energy release rate as a function of the*
 4 *peeling angle.*

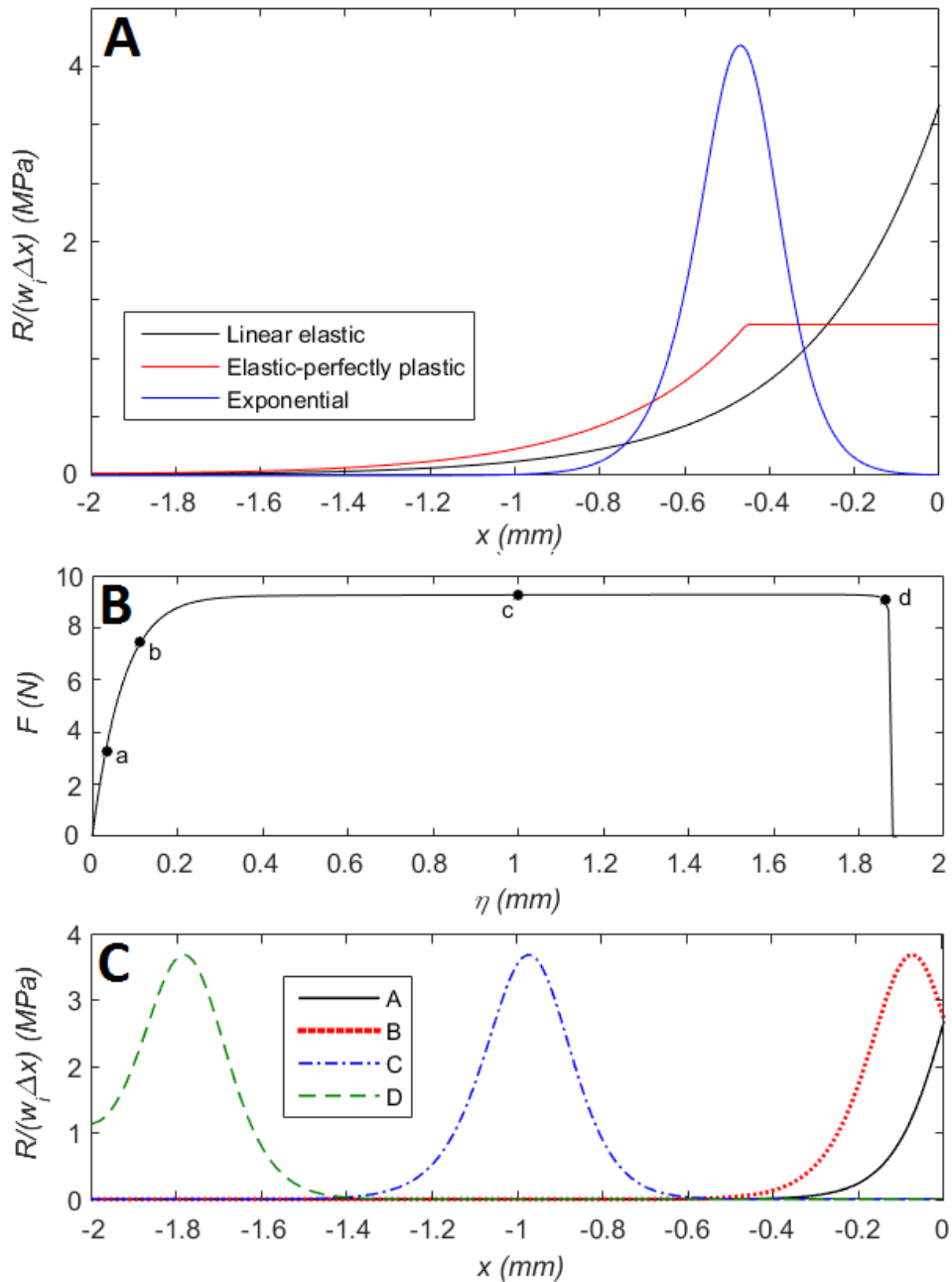
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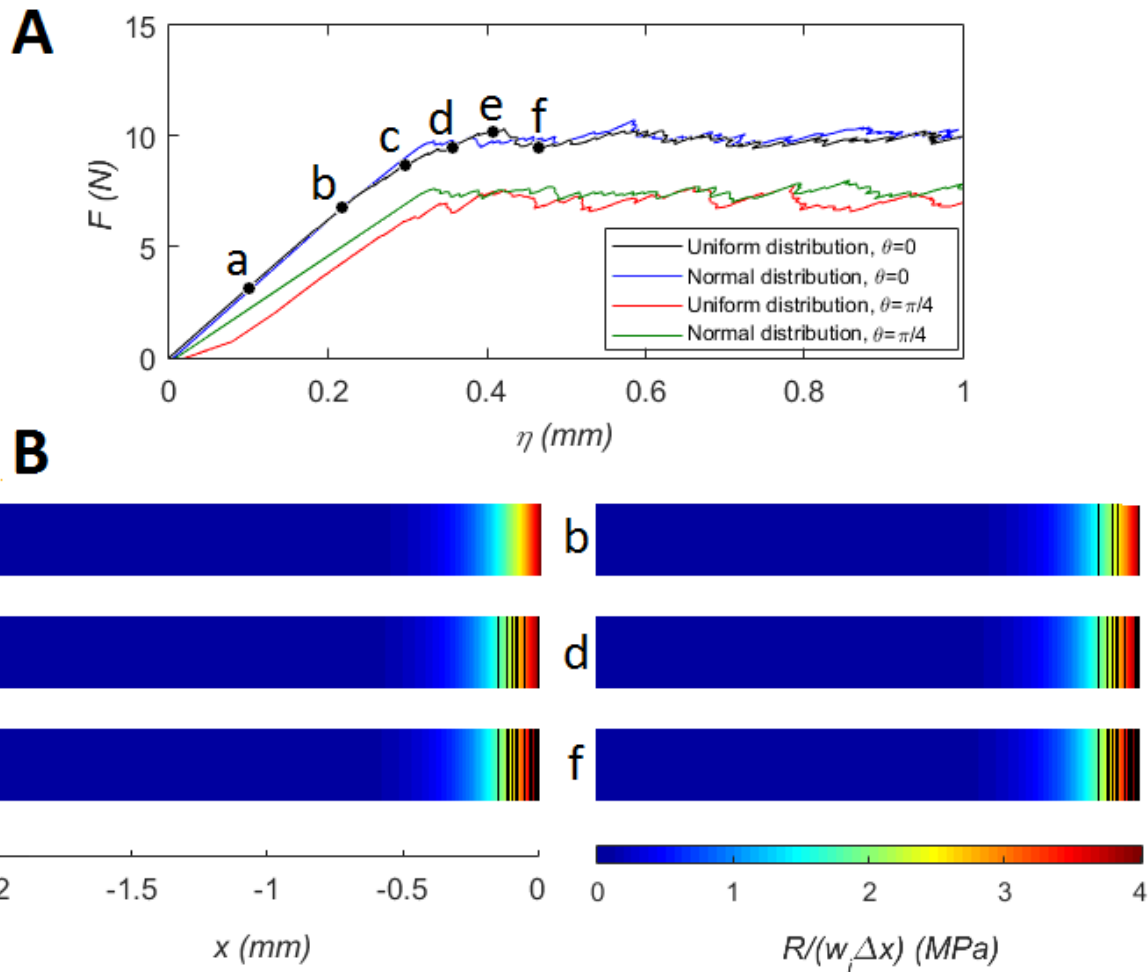
3 *Figure 3 : Peeling force vs. peeling angle with the present numerical model and the theoretical*

4 *result, Inset: interface deformation states at two different peeling angles.*



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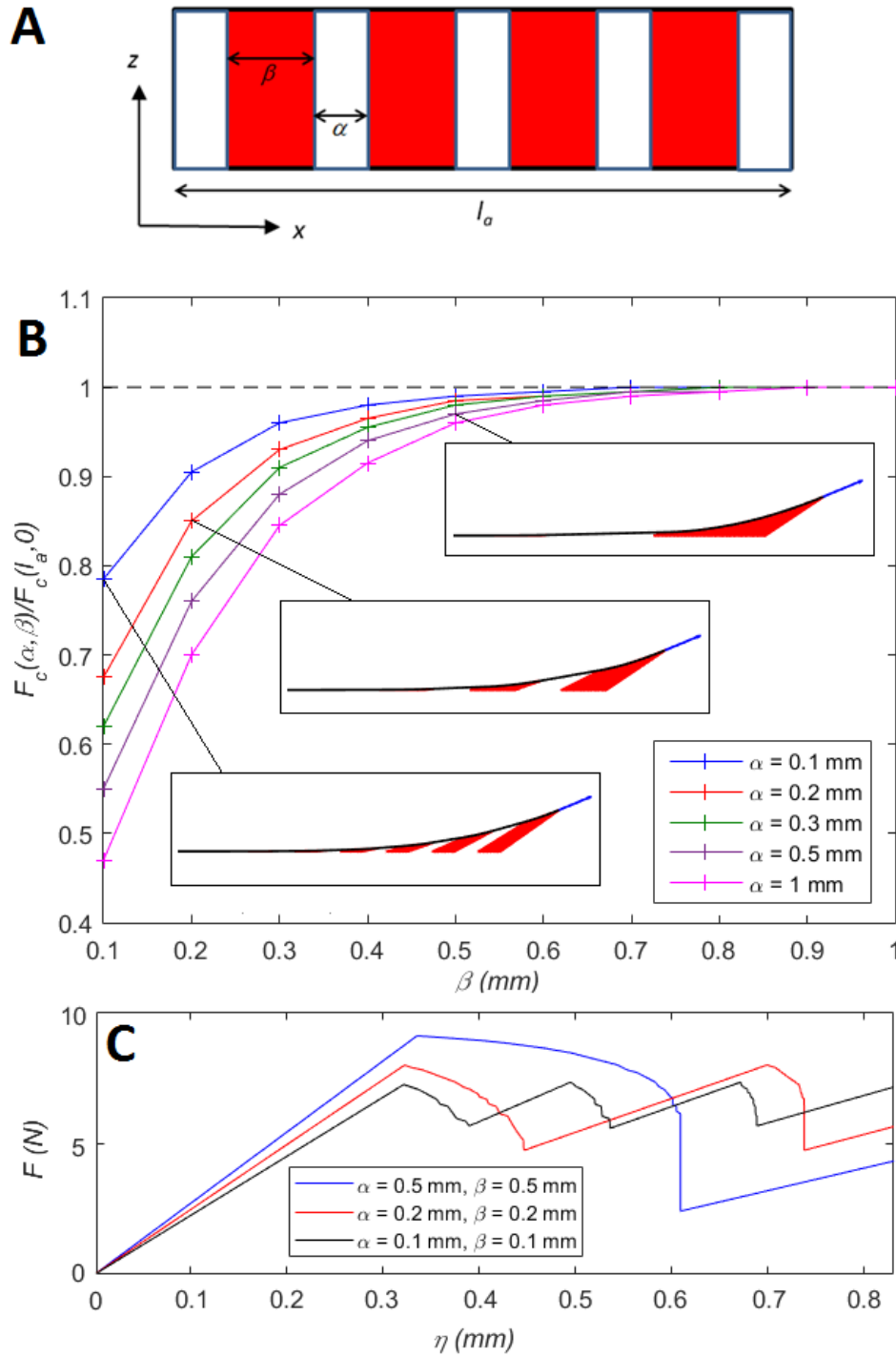
2 *Figure 4 : A. Interface bond axial stress along the process zone for different traction-separation*
 3 *laws when the peeling force is reached (for $\theta = \pi/8$). B. Resulting force-displacement*
 4 *relationship in the peeling test for an exponential traction-separation law. C. Propagation of the*
 5 *peeling front corresponding to points a, b, c, d, visualized using the interface bond axial stress*
 6 *distribution.*



1

2 *Figure 5 : Force F vs. displacement η during peeling of a tape from a substrate with nonzero*
 3 *surface roughness for two different peeling angles and roughness distributions (compare to Fig.*
 4 *4B for a smooth surface). B. Corresponding propagation of the peeling front in the early stages of*
 5 *detachment at points a to f along the F vs. η curve. The color scale represents the interfacial load*
 6 *distributions. The areas where local detachments occur are represented in black.*

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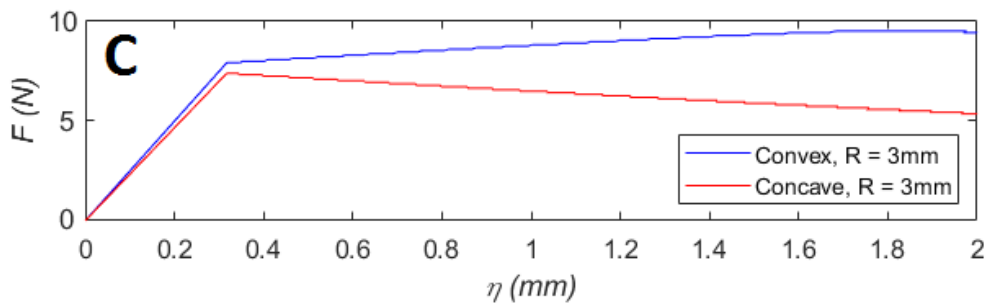
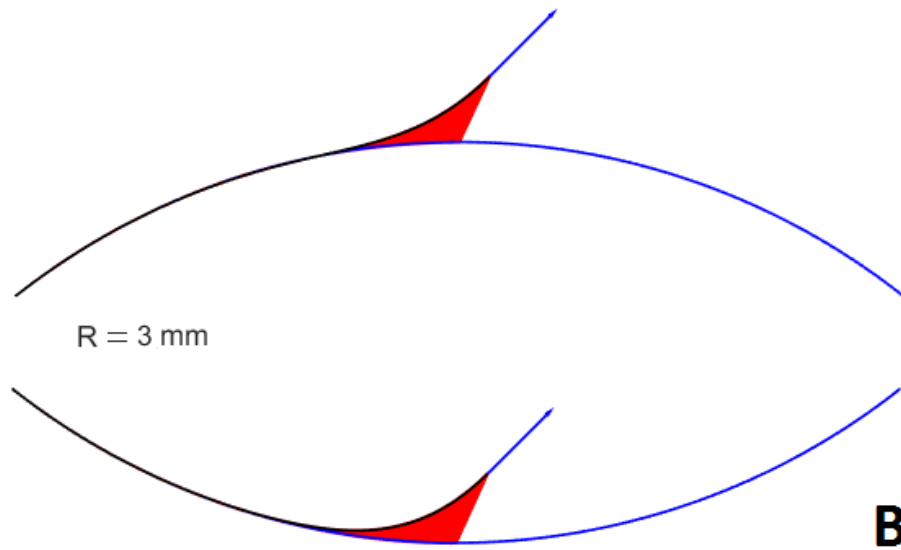
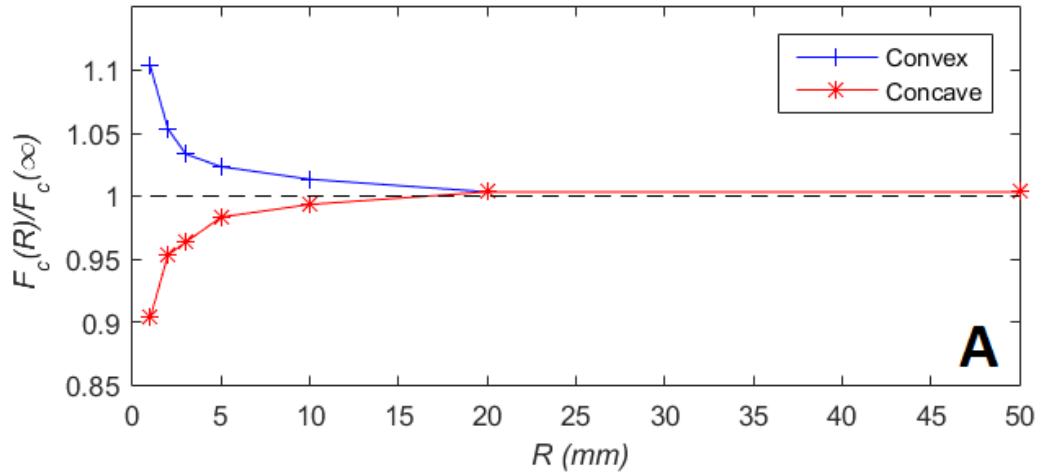


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2 *Figure 6 : A. Schematic of the periodic patterned surface with alternating non-contacting lengths*

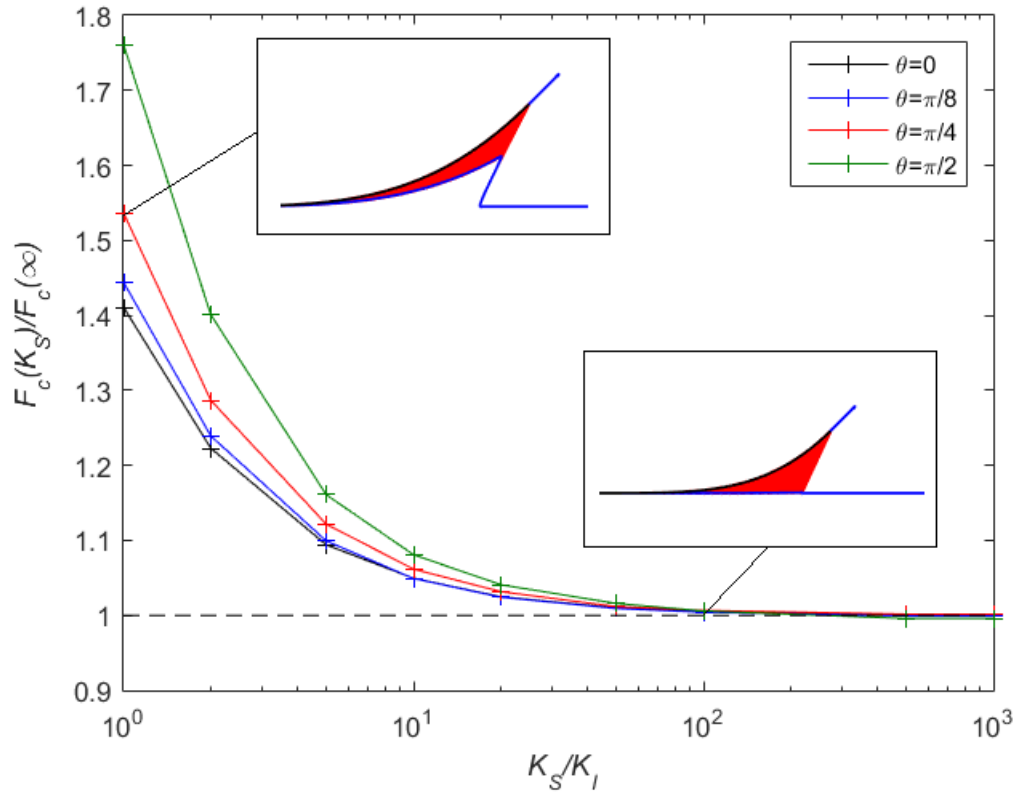
3 *α and lengths in contact β . B. Normalized peeling force vs. β for various α values. Inset:*

- 1 *corresponding deformation states. C. Corresponding force F vs. displacement η during peeling*
- 2 *test.*



1

2 *Figure 7 : A. Normalized peeling force as a function of the radius of curvature of the substrate for*
 3 *concave and convex surfaces. B. Corresponding deformation states. C. Corresponding force F vs.*
 4 *displacement η during peeling test.*



1

2 *Figure 8 : Normalized peeling force as a function of the substrate compliance for various peeling*

3 *angles. Inset: deformation states for various deformed substrate.*

4