On the effect of interfacial patterns on energy dissipation in plastically deforming adhesive bonded ductile sheets

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Abstract

Toughening of brittle adhesive joints is a topic of great interest for the fabrication of layered structures. Recent experimental work by the authors indicated that spatially varying interface properties (i.e., patterned interfaces obtained using laser irradiation) could tune energy dissipation in plastically deforming adhesive joints. In this study, we use a cohesive zone approach to ascertain the interplay between fracture process zone size and pattern geometry on the overall work of separation. The analysis is carried out in the context of the elasto-plastic peeling response of adhesive bonded ductile thin sheets. The mating surfaces of the adherents feature alternating strips with strong and weak cohesive properties. Our finite element study shows that a careful choice of pattern length-scales, which requires a small area fraction of surface pre-treatment, allows us to achieve a step-like increase in peel load and absorbed energy in otherwise brittle adhesive joints.

Keywords: adhesive bonding, cohesive model, patterned interface, peel loading

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1. Introduction

Emissions reduction targets established by various governments worldwide, and increasing fuel costs, are leading to the extensive use of structural bonding in high-end structures, especially in automotive and aerospace industries [1, 2]. Classical joining techniques, such as bolting and riveting, add to the total structural weight and require hole drilling, which induces stress concentrations and the need for shimming. The use of adhesives offers several advantages, including a more uniform stress distribution, and increased fatigue life, and better damping of structural vibrations [3].

Extreme lightweight packages are currently pursued by bonding thin ductile metallic adherents [4]. Thus, when the interface features strong adhesion, extensive plastic deformations accompany fracture of the joints [5]. The extent of plastic energy dissipation depends on the magnitude of the closing tractions exerted by the adhesive layer across the interface [6].

Because surface preparation plays a significant role on the magnitude of interfacial tractions and the resulting mechanical behavior, a sustained research effort has been carried out in the area of surface modification strategies [7–9]. It is increasingly apparent that laser irradiation is an effective and highly controllable surface pretreatment for adhesive bonding. Thanks to the ability to guide laser beams using automated positioning systems, it has been used on a large variety of materials, including titanium [10], copper [11], and aluminum alloys [9], as well as composite materials [12, 13].

Previous works on epoxy-bonded sheet metals loaded in peel have shown that laser irradiation enables a significant increase of the joint fracture toughness compared to a baseline sanding treatment [14, 15]. As a consequence, larger forces (and bending moments) were needed to sever the joints, thus enabling extensive plastic deformations in the course of failure. Notice that the determination of fracture tough-
ness requires the contribution of plasticity to be segregated from the work of fracture using a cohesive zone approach in the finite element framework [5, 6, 15].

Although the presence of plasticity confounds the interpretation of test data and complicates the determination of fracture toughness [16], accessing the extrinsic\(^1\) dissipation due to adherents plasticity increases the total work of separation needed to fracture the interface [14, 15]. This last might be several times higher than the intrinsic fracture energy of the adhesive layer, ensuring optimal levels of energy absorption, such as those requested during a crash [17].

Recent works have shown that the use of interface patterning is a suitable strategy to enhance energy dissipation during the debonding of layered materials [18–22]. In the pursued approaches, the energy input needed for fracture was increased by patterning (i) the interface [18–20, 23], (ii) the adhesive layer (through stop-holes) [21], or (iii) the bending stiffness of the substrates [22, 24–26].

We have shown that a patterned interface with spatially varying surface properties represents a viable strategy to control the extent of plastic energy dissipation in otherwise brittle adhesive joints [11]. The patterning strategy, enabled by a pulsed laser beam, was proposed as an alternative to homogeneous surface treatments to reduce manufacturing time and cost. An appraisal was carried out around the effect of pattern geometry and area fraction on the mechanical response of the joints. It was found that an accurate choice of pattern shape and spacing has important consequences on crack propagation. Indeed, by using seemingly small area fraction (i.e., 25%) of the laser-treated interface, a substantial increase of peel load (×7) and work of separation (×4) was achieved with respect to the baseline sanded interface [11]. However, our previous study did not address the interplay between additional essen-

\(^1\)Note that here the term *extrinsic* is used to denote that the energy is due to sources other than those associated to fracture as well as to inelastic deformations within the adhesive layer.
tial variables, such as the fracture process zone size and the pattern length-scales, on the outcome of mechanical tests. Such information may allow the design of interfacial patterns able to increase the peel load and energy dissipation substantially while using a minimum fraction of surface pre-treatment, and with consequent reduction of costs and complexity.

Therefore, in this work, we deploy a finite element modeling approach to ascertain the existing interplay between the fracture process zone size and the length-scales of the pattern on the load-bearing capability of peel loaded adhesively-bonded thin ductile adherents. The pattern is represented by a periodic arrangement of strong/weak interfacial strips, and the decohesion behaviour is simulated using the cohesive zone approach. The modelling accounts for the nonlinearities arising from large displacement and adherents plasticity. The work is organized into two main parts, which address, respectively, the effect of single and multiple bands. The evolution of global response, crack length, and fracture process zone size is presented for various pattern geometries, as well as for different choices of cohesive fracture properties.

2. Modeling approach

2.1. Decohesion behavior of homogeneous and patterned interfaces

A T-joint has been selected as a model material system for our parametric investigation. A schematic that highlights sample geometry in the undeformed and deformed configurations is given in Fig.1(a). The T-joint is a quite versatile test coupon frequently employed in the automotive industry to compare the response of adhesively bonded sheet metals for distinct adhesive or surface preparation techniques [15, 16, 27–29]. The mechanical response depends on adherents and interface properties, which influence the force required for debonding and the shape of the deformed specimen. If the fracture process zone has constant size during debond-
ing, the distance from the line of action of the applied load to the crack front, \textit{i.e.}, distance \(d\) in Fig. 1(a), does not evolve during crack propagation. It follows that \textit{self-similar} (or \textit{steady-state}) debonding occurs and the global load-displacement response resembles the schematic given in Fig. 1(b). The peak load \((P_k)\) is associated with crack initiation, while in the steady-state crack propagation, the applied load levels out at constant value \((P_0)\). Note that an increasing fracture toughness translates into a higher load plateau \((P_1)\), as shown in Fig. 1(b). Among various metrics usually extracted from T-joint tests, we recall the \textit{T-peel strength}, which is given by the steady-state peeling load normalized with the sample width \((P_0/B)\), and the \textit{apparent peel energy}, which is twice the T-peel strength. Recent work suggests that the T-peel strength is, however, the poorest metric at conveying the energy dissipation potential of the joint [16]. As discussed later, we employ a cohesive zone approach to monitor the evolution of peel load, dissipated energy, and fracture process zone size in the course of fracture.

For the parametric investigation, we selected thin copper sheets bonded with a bi-component epoxy adhesive. This material system was already analyzed experimentally in our works discussed earlier [11, 15]. The metallic substrates have thickness \(t=0.5\text{ mm}\), width \(B=15\text{ mm}\), and length of the bonded portion \(L=150\text{ mm}\). The patterning strategy pursued herein is schematically shown in Fig. 1(c). It consists of alternating \textit{weak} (0) and \textit{strong} (1) interfacial strips of length \(b_0\) and \(b_1\), respectively. The current choice allows reducing problem dimensionality with consequent computational cost savings while still allowing to shed light on the most important parameters controlling the debonding process. Pattern period is denoted by \(\lambda\), such that \(\lambda = b_0 + b_1\). As described later, the mechanical properties of the interfaces are based on that reported in [15]. Because of interface patterning, the peeling response varies periodically as the front negotiates the regions with different adhesion properties, as shown schematically in Fig. 1(d).
2.2. Finite element models

Nonlinear finite element simulations were carried out to analyze plane strain quasi-static deformations of the system and the debond initiation and propagation. The finite element model was developed using COMSOL Multiphysics [30]. The material properties, geometrical dimensions, and boundary conditions were determined (unless otherwise noted) from the uniaxial tensile tests and the experimental data obtained in [15]. In the finite element model, the interface between adjacent substrates is described by resorting to a penalty contact formulation combined with a cohesive zone model approach. The contact model mimics a thin adhesive layer that ties the adherents at the interface. The interfacial constitutive behavior is described through a traction-separation relation. In particular, the magnitude of the interfacial tractions evolves with the relative displacement of the adherents following a bilinear relationship, as illustrated previously in Fig. 2(a). Preliminary analyses have shown that the surface-based cohesive behavior has excellent stability and achieves convergence with a relatively fine mesh, which comprised plain-strain eight-nodes square elements with a size smaller than 0.3\( t \) (\( t \) is the thickness of the substrates). The finite element model accounts for large displacement and large rotations. Moreover, the experimentally obtained copper stress-strain curve was provided as input in the FE program, and the tensile behavior was extended to multiaxial stress states assuming isotropic hardening and with the aid of the von Mises yield surface. Therefore the plastic energy dissipated in finite element simulations is a natural outcome of the deformation process.

The cohesive surfaces relate interfacial cohesive tractions \( T_i \) to crack face separations \( w_i \). However, it is common to recast the cohesive model in an equivalent one-dimensional formulation. For the most general case of mixed-mode crack opening, a separation vector norm is used to conveniently define the traction-separation relation, which allows a unique definition of the state of decohesion. In this context,
mixed-mode initiation and propagation criteria determine the onset and final failure of the interface (see [31] for the details). The one-dimensional model is often assumed to be linear before damage onset and also during softening, i.e., bi-linear traction-separation model [31]. Notice that in the case of pure mode I problems, such as that addressed in the present work, there is no mode interaction, and the cohesive model reduces to a relation between the normal traction and the normal separation ($T - w$). In the FE model, the macroscopic constitutive behavior of the adhesive is expressed using the $T - w$ relation [32].

The input properties for the $T-w$ relation are cohesive energy ($\phi$), cohesive strength ($\sigma$) and the initial stiffness ($K$). For simplicity, weak (0) and strong (1) interfaces share similar initial stiffness; however, distinct values of cohesive strength and fracture energy are prescribed along the path of crack propagation, i.e. ($\phi_0, \sigma_0$) and ($\phi_1, \sigma_1$). A schematic of the corresponding traction-separation relations is given in Fig.2(a). Notice that in finite element simulations spatial variation of cohesive properties has been enforced using a summation series, where the generic cohesive property $f(x) = \{\phi(x), \sigma(x)\}$ is defined as:

$$f(x) = \sum_{k=1}^{n} f_0 \{H[(k\lambda - b_1) - x]H[x - (k-1)\lambda]\} + f_1 \{H[k\lambda - x]H[x - (k\lambda - b_1)]\}$$

where $\lambda$ is the pattern period; $H(\cdot)$ is the Heaviside step function; $n$ is the number of strips along the interface; ($f_0, f_1$) are amplitude factors, such that $f_0 = \{\phi_0, \sigma_0\}$ and $f_1 = \{\phi_1, \sigma_1\}$. A schematic of the fluctuation of cohesive strength and fracture energy across the interface is provided in Fig.2(b). For subsequent results discussion, we also define the cohesive strength and fracture energy contrasts, i.e. $\sigma_1/\sigma_0$ and $\phi_1/\phi_0$, which reflect the mismatch in $\phi$ and $\sigma$. The following values have been considered for the analysis, i.e., $\phi_1/\phi_0 = 10$ and 30, $\sigma_1/\sigma_0 = 1$ and 4. Experimental results by the authors suggest that these mismatches in cohesive fracture properties, before and
after surface preparation, can be typically achieved using laser irradiation [15, 33].

2.3. Selected metrics from the peel tests

We now set the stage for results discussion by presenting the main output parameters extracted from the numerical simulations. First of all, note from Fig. 1(b) that $P_1$ and $P_0$ represent the steady-state peel loads achieved for a crack propagating along an homogeneous interface with cohesive properties ($\phi_1, \sigma_1$) and ($\phi_0, \sigma_0$), respectively. For a patterned interface with period $\lambda$, as the crack negotiates the weak and the strong interfacial bands, the peel load oscillates between $P_{\text{min}}$ and $P_{\text{max}}$ (recall the schematics of Fig. 1(d)). We define the effective peel load as the maximum load achieved over a single period of crack growth (i.e., $P_{\text{max}}$), that is the load needed to advance the crack front past a strong interfacial band. As it will be shown later, depending on the precise set of interfacial properties, $P_{\text{max}}$ can be smaller or larger than the steady-state load corresponding to a homogeneous interface ($P_1$).

In order to readily assess how the size of the process zone evolves when the crack front traverses the interface, the scalar damage variable $D$ has been tracked down in the numerical simulations (see the appendix for further details on $D$). The damage variable controls interfacial degradation, such that $D = 0$ represents the undamaged state and $D = 1$ the complete failure, see Fig. 2(c). The crack tip is identified by the trailing edge of the fracture process zone ($D = 1$), while the cohesive crack tip represents the leading edge ($D = 0$). The distance between these points represents the current process zone size ($\ell$), as shown in Fig. 2(c). Notice that $\ell$ is thus an output variable obtained from the finite element simulations, whose evolution has been monitored through a post-processing stage carried out using MATLAB [34]. Because of the periodic arrangement of weak/strong strips in front of the growing crack, the size of the process zone evolves during crack propagation, and the rate of crack growth varies as a function of the applied displacement. A plot that schematically shows
the evolution of $\ell$ during a peeling test is given in Fig. 2(d). In our analysis, for the purpose of data presentation and results discussion, $\ell$ represents the size of the process zone achieved when the crack tip ($D=1$) firstly breaks into the strong band. (i.e., process zone fully embedded within the strong strip).

3. Results and discussion

3.1. Effect of a single strong strip across a brittle interface

A brittle interface featuring a single strong strip has been initially investigated to address the effect of the length-scale ($b_1$) on the mechanical behavior of the joint. The following contrasts have been considered: $\phi_1/\phi_0 = 10$ and $\sigma_1/\sigma_0 = 4$. Because cohesive properties do not vary for this set of simulations, the size of the fracture process zone is basically constant, while the length-scale $b_1$ is varied in a range. The top part of Fig. 3(a) shows the evolution of peel load as a function of applied displacement. The bottom part displays the range of the applied opening displacement $\delta$ at which the fracture process zone is traversing the strong band. The peel load ($P$) and the extension ($2\delta$) are normalized with respect to the steady-state peel force of the homogeneous weak interface ($P_0$) and the thickness of the metal sheet ($t$), respectively. The results, presented as a function of $\ell/b_1$, highlight the interplay between the chosen $b_1$ and $\ell$. In general, the effective peel load, $P_{\text{max}}$, and the overall energy dissipation (i.e., area below the $P-\delta$ curve), increase substantially as $\ell/b_1$ decreases. The enhancements are coming at the expense of the extra plastic work occurring in the adherents. Plastic deformations are indeed affected by the root rotation, i.e., the angle at the root of the crack. Seminal work by Kim and Aravas [34] has indeed demonstrated that the elasto-plastic peeling force is mostly contributed by the macro-scale plastic deformations of the adherents.

On the one hand, it is interesting to note that if $b_1$ is larger than the process zone
size, there is a substantial enhancement of the overall dissipated energy (i.e., area enclosed by the curve). Moreover, the effective peel load can exceed that of a homogeneous strong interface. This point will be discussed further later. On the other hand, when the process zone has a size comparable with that of the strong strip (i.e., $\ell/b_1=1$), the above enhancements are essentially muted. Figure 3(b) reports the load-displacement responses and evolutions of process zone for two selected cases, that is $\ell/b_1=0.2$ and 1. The comparison allows to draw an important observation.

First of all, when the cohesive crack tip breaks into the strong band, the cohesive tractions increase. Our simulations indicated that the angle at the root of the crack increases as well, and so does the peel load and plastic dissipation. Once the process zone is fully embedded within the strong band, if $\ell$ and $b_1$ are comparable, any subsequent increment of crack growth causes the cohesive crack tip to break into the weak band, thus decreasing the cohesive tractions. Shortly after, the joint reaches a non-equilibrium configuration, and the crack snaps through the boundary between the strong and the weak band. As a consequence, the peel load drops, and so does the absorbed energy in the process. However, if $\ell/b_1<1$, then a fully developed process zone within the strong strip enables a sustained increase in load and energy dissipation until it reaches the weak band. Therefore, the results suggest that for maximum enhancement of peel load and energy dissipation, the interplay between the length-scale of the strong strip and fracture process zone size plays a significant role.

The mechanics of crack propagation is further assessed in Fig. 4(a). The peel load and the distance $d$, as shown in Fig. 1(a), are compared with the evolution of the process zone. Two values of the toughness contrast are presented to study the corresponding effect on the mechanical response. The grey area in the plot represents the strong interfacial band.

If one focuses on $\phi_1/\phi_0 = 10$, it is observed that when the crack front approaches
the boundary between the weak and the strong strips (point I), crack propagation is delayed. A further increase in the applied displacement increases the peel load, until the crack tip breaks into the strong band (point II). After that, crack growth increases non-linearly with the opening displacement, and the applied load increases and reaches a peak (II \to III). Then the crack steadily grows until the end of the strong strip (point IV). At that point, an instability occurs, and the load drops (V) because the crack snaps through the weak region.

Interestingly, the observed peak load (Point III) is higher than the steady-state peel load of the corresponding homogeneous interface. This effect can be explained by examining the deformed configuration of the joint, which is depicted in the snapshots reported in Fig. 4(b). In particular, as soon as the crack front approaches the strong strip (Point I), crack propagation is delayed, and most of the load is going into bending of the sample arms. These last are progressively straightened approximately into a 90° shape (Point III). At this point, the joint has reached the maximum root rotation, thus requiring a higher peel load because of the enhanced plastic bending of the peeling arms [11, 34]. This condition is similar to what is commonly observed at crack initiation during mechanical testing of a T-joint with a homogeneous interface.

As a result, the load overshoot increases with the toughness contrast, as shown in Fig. 4(a). Notice that the achievement of the 90° shape configuration is confirmed by the evolution of $d$ with opening displacement, and the fact that the minimum value of $d$ matches the peak load.

The important effect associated with the interplay between length-scale of the heterogeneity on joint mechanical behavior was also observed in recent works [20, 35]. Heide-Jorgensen et al. [20] analyzed a patterned Double Cantilever Beam (DCB) consisting of an array of bonded and un-bonded regions. Interestingly, it was shown that for maximum toughness, the size of the bonded (strong) region should slightly exceed the process zone length. Avellar et al., instead, studied the elastic peeling
response of a flexible plate with heterogeneous stiffness [35]. The authors reported
that the presence of a substantial cohesive zone smoothed out the effect due to stiffness
heterogeneity, suppressing the enhancement of peel force.

The analysis of Figs. 3 and 4 show that the peak load, namely, the effective peel
load \( P_{\text{max}} \), largely varies with the size of the strong strip \( b_1 \). The relation between
these two variables is better shown in Fig. 5, which reports the evolution of \( P_{\text{max}}/P_0 \)
as a function of \( \ell/b_1 \), and for varying \( \phi_1/\phi_0 \). For simplicity, let focus on \( \phi_1/\phi_0=20 \).
As \( b_1 \) increases compared to the size of the process zone, \( P_{\text{max}}/P_0 \) increases, and
can be larger than \( P_1/P_0 \), as discussed earlier. However, if a specific length-scale is
reached, in this case, \( \ell/b_1 \approx 0.3 \), the effective peel load does not increase anymore,
and the response quickly converges to that of a homogeneous interface. Therefore,
the results suggest that substantial enhancement of effective peel force of the brittle
interface can be achieved with a relatively small area fraction of strong strips, whose
size must, however, always exceed the size of the fracture process zone.

3.2. Effect of periodic arrangement of weak/strong interfacial bands

We now assess the effect of multiple strips spaced with a constant period \( \lambda \),
i.e., a patterned interface. Figure 6(a) highlights (thicker curve) a typical steady-
state peeling response associated with one cycle of crack advance past a strong band,
and the corresponding crack propagation behavior. The top and bottom dashed
lines indicate the average steady-state loads corresponding to homogeneous weak
and strong interfaces. The fluctuation of the remote applied peel load reflects the
occurrence of crack \textit{initiation}, \textit{propagation} and \textit{arrest} (i.e., crack trapping). Note
that the period of the global responses \( \lambda_m \), which is the distance between two
consecutive peak or valley points, was essentially equal to twice the corresponding
nominal period of the pattern \( \lambda \). The excellent agreement suggests the attainment
of a global steady-state peeling regime in which the opening displacement is globally
Front pinning is reflected by the rising portion of the peeling response in which two distinct slopes can be identified and which are separated at point II. These slopes are associated with initial front pinning (I \rightarrow II) and subsequent crack penetration (II \rightarrow III) within the tougher band, as shown in the bottom part of Figure 6(a). Once that the remote applied load reaches a peak, the load is subjected to an abrupt drop such that \( \frac{d\delta}{dP} \approx 0 \), and the crack front snaps within the subsequent weak region (III \rightarrow IV). In the proposed interfacial arrangement, the fracture energy landscape is highly discretized, and regions of high and low toughness are separated by a step change. As a consequence, during propagation, the crack snaps through the boundary from high to low toughness, and the sudden release of strain energy results in unstable crack propagation. However, because of the displacement-controlled boundary conditions, the displacement is prevented to snap-back to zero. In addition, fast crack propagation within the weak strip is arrested when the front reaches the subsequent strong band, and the process repeats itself cyclically.

The snapshots of the deformed configuration of the sample were extracted at locations I-IV and are given in Fig. 6(b). It is observed that when the crack is at point I, the process zone is almost entirely within the weak band, while the leading edge breaks within the strong one. At this point, the local curvature of the delaminating sheets, at the crack front, is small. Subsequent crack growth within the strong strip induces an increase in adherents bending, and the load increases till it reaches a peak corresponding to point III. As discussed earlier, once the leading edge of the process zone breaks into the weak band, any further increment of applied displacement induces a sudden load drop, because the crack snaps through. Fast propagation then occurs till the front meets the subsequent strong band. Therefore, the observed peeling response is solely associated with the geometrical aspect of crack growth, as also observed in [11, 37].
The mechanism of crack growth suggests that the evolution of peel load depends not only on the amount of plastic energy dissipated but also on the distance between consecutive bands. Therefore, a variation of the length-scale of the strong strip and/or pattern period should largely modify the amplitude of load fluctuation ($\Delta P$). Thus an analysis around $b_1$ and $\lambda$ is presented next. The aim is to understand how these variables should be chosen in order to maximize the peel load as well as dissipated energy ($U$), while keeping minimum area fraction of the strong interface. The effect of the length-scale $b_1$ on $\Delta P$ has been firstly assessed, and the results are reported in Fig. 7(a). For these simulations the period has been set such that $\lambda/B = 1$, while $\phi_1/\phi_0=10$ and $\sigma_1/\sigma_0=4$. The load-displacement plots reported in Fig. 7(a) show that, for increasing values of $b_1/B$, both minimum and maximum loads increase. The amplitude $\Delta P$ will progressively decrease and eventually will tend to zero as the response achieves that of a homogenous interface. This is best illustrated in Fig. 7(b), which shows the evolution of $\Delta P$ as a function of $b_1$. The results show that, for given contrasts, there is a value of $b_1$ that provides a peak in $\Delta P$. Increasing further $b_1$, it would induce a decrease in load fluctuations, and in the limit that $b_1/B \rightarrow 1$, the results would turn back to the classical scenario of uniform strong interface (while for $b_1/B \rightarrow 0$ to the baseline sanded interface). Since the objective of the proposed patterning strategy is to enable an increase of peel load and energy dissipation with minimum area fraction of treated surface, it follows that further increases of $b_1$ beyond the peak points in Fig. 7(b) is neither needed nor useful to the purpose.

Moreover, the results show that the patterning strategy can also significantly increase the dissipated energy ($U$). In particular, Fig. 8 reports the evolution of dissipated energy $U$ over one period of crack propagation as a function of $b_1/B$. Notice that $U_0$ is the energy needed to sever a joint with an homogeneous weak interface, see Fig. 1(b). Also, for the case under investigation, since $\lambda/B=1$, the amount of dissipated energy achieved for $b_1/B = 1$ corresponds to that of a homogeneous
strong interface ($U_1$), see Fig. 1(b). Clearly, $U$ increases with $b_1$, which is somewhat expected since the area fraction of the strong strips increases. Now, if one focuses on a value of $b_1$ that maximizes the peel load, e.g., $b_1/B=0.2$, it can be observed that the work of separation ($U$) displays a remarkable seven-fold increase with respect to the brittle baseline interface ($U_0$).

The effect of variable $\lambda$ on the outcome of numerical simulations is presented next. We aim to resolve to which extent $\Delta P$ is affected by $\lambda$. The results, which are reported in Fig. 9, show that $\Delta P$ increases with $\lambda$ at a rate that slightly depends on $\phi_1/\phi_0$. It is noted that small values of $\lambda$ would reduce load fluctuations while increasing the overall area fraction of the strong interface. For increasing values of $\lambda$, $\Delta P$ increases and reaches a plateau, which implies that there are no gains by increasing the spacing between the bands. In the limit that $\lambda/B \to \infty$, the results would match those obtained when the interface features a single strong band.

Figure 9 allows to identify the value that should be given to the period in order to have several strong strips across the interface (i.e., to have more obstacles across the crack propagation path), and that would required minimum surface treatment. Indeed, the best compromise is to pick-up the period corresponding to the onset of the plateau region shown in Fig. 9. Notice, however, that although this choice would bring some benefits on the maximum peel load, additional analyses not reported herein, have shown that it also halves the dissipated energy. Therefore, the combined results reported in Figs. 7(a) and 9 show the importance of selecting proper scale ($b_1$) and spacing ($\lambda$) of the strong strips to maximize peel load, enhance energy dissipation while maintaining a reduced area fraction of treated surface.
4. Concluding remarks

A computational analysis was carried out to ascertain the effect of interfacial patterns on the work of separation in brittle adhesive joints. The study focused on a simple patterning strategy, consisting of alternating weak and strong interfacial strips, in the context of elasto-plastic peeling of thin adhesively bonded sheet metals. Modeling of the decohesion process was accomplished using cohesive zone models in the finite element setting, and spatial variation of cohesive properties was enforced using an analytical description based on a summation series. The effects of single and multiple strong strip layouts on the toughening of brittle interfaces were assessed in detail.

The results have shown that the interplay between fracture process zone size ($\ell$) and the size of the strong strip ($b_1$) mostly control the crack propagation behavior. If $\ell$ is sufficiently smaller than $b_1$, a substantial increase in peel load and energy dissipation can be achieved. Indeed, when the process zone is entirely within a strong band, cohesive tractions increase, and so does the angle at the root of the crack. Because of that, the peel load and dissipated energy due to plastic bending largely increase. However, if $\ell/b_1 \approx 1$, the above enhancements are essentially muted. Indeed, once the entire process zone is within the strong band, any subsequent small increment in applied displacement, and crack growth, causes the cohesive crack tip to break into the weak band. Because the associated decrease of cohesive tractions induces the joint to be in a non-equilibrium configuration, shortly after, the crack snaps through, with a consequent drop of peel load and energy dissipation. Moreover, when the size of the strong strip is sufficiently large, the enhancement of the peel load can overcome the steady-state peel load of the corresponding homogeneous (strong) interface. Simulations have shown that this is an effect associated with the deformed configuration of the peeling arms, which attains maximum root rotation ($\approx 90^\circ$ angle
at the crack front), with a consequent increase in plastic bending and peeling load.

The results obtained when multiple strong strips are placed across the interface indicated the peeling load also depends on the pattern period. In particular, a characteristic value was found that allows to enhance the peel load, which results in an even smaller overall fraction of interfaces with strong cohesive fracture properties. However, the enhancement of peel load is, in this case, accompanied by a significant decrease in the work of separation, though still larger than that of the brittle baseline interface. The results suggest that the use of the proposed patterning strategy provides a significant increase in energy absorption in brittle adhesive joints, with a potential reduction of manufacturing time and costs. An important issue to address for future studies concerns the analysis of the proposed approach for materials with different substrates thickness and material properties.

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4. Evolution of peel load for a crack traversing a strong band. (a) Peel load and crack front position as a function of the opening displacement for distinct values of toughness contrasts. The evolution of the distance $d$ from the cohesive crack tip to the line of action of the applied load is also shown (for $\phi_1/\phi_0=10$) (b) Snapshots of the deformed configurations of the joint at various stage of crack growth ($\phi_1/\phi_0=10$).  
5. Effective peel load $P_{max}/P_0$ as a function of $\ell/b_1$ for varying $\phi_1/\phi_0$.  

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Steady-state peeling response of a T-joint with patterned interface. (a) The plot shows the $P - \delta$ curve. The highlighted portion indicates the typical load fluctuation observed when the crack traverses a single strip within the pattern. The period of the observed fluctuations, $\lambda_m$, is about twice compared to the period of the pattern, $\lambda$. (b) Corresponding snapshots of the deformed configuration.

(a) Load-displacement plots for $\lambda/B=1$ and varying $b_1/B$. (b) Amplitude of load fluctuations as a function of $b_1/B$ for varying contrasts of cohesive strength and fracture energy. The insert shows the process zone size determined as described in Section 2.3.

Normalized work of separation as a function of $b_1/B$ and interfacial properties.

Effect of varying pattern wavelength, $\lambda$, for given values of $b_1/B$. 

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6. Appendix

The cohesive model was defined in the framework of damage mechanics by introducing a damage criterion to control degradation of the interfacial stiffness and ensure irreversibility of the energy dissipated during the fracture process. The softening behavior is represented through a scalar damage parameter, namely \( D \), which operates on the potential energy per unit surface \( (\Psi) \) of the system as follows [38]:

\[
\Psi [w, D] = \frac{1}{2} (1 - D) w_i \delta_{ij} K w_j, \tag{2}
\]

where \( K \) is the stiffness of the model before the damage onset, which should resemble the initial stiffness of the adhesive. A rule of thumb is to set it equal to the Young modulus of the adhesive scaled by its thickness. In turn, the cohesive interaction across the interface is obtained as follows:

\[
T_i (w_i) = \frac{\partial \Psi}{\partial w_i} = (1 - D) \delta_{ij} K w_j + \ldots \tag{3}
\]

where \( i=1,2,3 \) denotes shearing (1,2) and normal (3) opening displacements. But in the case of pure mode I problems, such as in the present work, mode interactions are not active, and the CZ model reduces to a traction separation relation between the normal traction component and the normal separation component, such that:

\[
T(w) = \frac{K w_i (w_f - w)}{w_f - w_i} \tag{4}
\]

where, \( w_i \) and \( w_f \) are the opening displacements at crack initiation and the final opening displacement which corresponds to zero traction in the cohesive zone. Notice that for simplicity, the subscript 3 has been removed since from now the reference to pure mode I conditions is implied. Combining previous equations, the scalar damage variable \( (D) \) can be expressed as follows:

\[
D(w) = \frac{w_f (w - w_i)}{w (w_f - w_i)}. \tag{5}
\]
Fig. 1. (a) Schematics of the undeformed and deformed configurations of T-joint. (b) $P-\delta$ responses corresponding to steady-state peeling regime. (c) A patterned bonded interface characterized by strong ($b_1$) and weak ($b_0$) interfaces ($\lambda=b_1+b_0$ represents the pattern period). (d) Schematic global load $P-\delta$ response for a patterned interface.
Fig. 2. Bi-linear cohesive models which mimic the properties of strong and weak interfaces; (b) spatial distribution of cohesive fracture properties along the bonded interface; (c) schematic of the fracture process zone, whose length is given as \( \ell = x_{D=1} - x_{D=0} \), with \( D \) being the damage variable. (d) Schematic of the analysis plot used to investigate the evolution of \( \ell \) along the patterned interfaces.
Fig. 3. Analysis of $P - \delta$ curves for an interface featuring a single strong strip with length-scale $b_1$. (a) Peeling responses as a function of $\ell/b_1$. The bottom part of the plot shows the ranges of $\delta$ which correspond to crack propagation within the strong strip. (b) Detailed analysis around the interplay of $\ell$ and $b_1$ on the load-displacement response and crack propagation.
Fig. 4. Evolution of peel load for a crack traversing a strong band. (a) Peel load and crack front position as a function of the opening displacement for distinct values of toughness contrasts. The evolution of the distance $d$ from the cohesive crack tip to the line of action of the applied load is also shown (for $\phi_1/\phi_0=10$). (b) Snapshots of the deformed configurations of the joint at various stages of crack growth ($\phi_1/\phi_0=10$).
Fig. 5. Effective peel load $P_{\text{max}}/P_0$ as a function of $\ell/b_1$ for varying $\phi_1/\phi_0$. 

\[ \sigma_1/\sigma_0 = 4 \]
Fig. 6. Steady-state peeling response of a T-joint with patterned interface. (a) The plot shows the $P - \delta$ curve. The highlighted portion indicates the typical load fluctuation observed when the crack traverses a single strip within the pattern. The period of the observed fluctuations, $\lambda_m$, is about twice compared to the period of the pattern, $\lambda$. (b) Corresponding snapshots of the deformed configuration.
Fig. 7. (a) Load-displacement plots for $\lambda/B = 1$ and varying $b_1/B$. (b) Amplitude of load fluctuations as a function of $b_1/B$ for varying contrasts of cohesive strength and fracture energy. The insert shows the process zone size determined as described in Section 2.3.
Fig. 8. Normalized work of separation as a function of $b_1/B$ and interfacial properties.
Fig. 9. Effect of varying pattern wavelength, $\lambda$, for given values of $b_1/B$. 

\[ \frac{\Delta P / P_{\text{ave}}}{\lambda / B} \]

- Red: $\sigma_1 / \sigma_0 = 30$
- Blue: $\sigma_1 / \sigma_0 = 10$
- Green: $\sigma_1 / \sigma_0 = 4$

$\lambda \to \infty$
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

[Signature]