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Analysis of the three-dimensional delamination behavior of stretchable electronics applications

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Abstract. Stretchable electronics offer potential application areas in biological implants interacting with human tissue, while also facilitating increased design freedom in electronics. A key requirement on these products is the ability to withstand large deformations during usage without losing their integrity. Experimental observations show that delamination between the metal conductor lines and the stretchable substrate may eventually lead to short circuits while also the delaminated area could result in cohesive failure of the metal lines. Interestingly, peel tests show that the rubber is severely lifted at the delamination front caused by its high compliance. To quantify the interface in terms of cohesive zone properties, these parameters are varied such that the experimental and numerical peel-force curve and rubber-lift geometry at the delamination front match. The thus obtained interface properties are used to simulate the delamination behavior of actual three-dimensional stretchable electronics samples loaded in tension.

Introduction
In stretchable electronics applications small rigid semiconductor islands can be interconnected with thin metal conductor lines, see Fig.1(a). To achieve stretchability of the thin metal conductor lines, these can be deposited on flat substrates using planar patterning technologies and seek for 2D deformability, e.g. by designing spring-like conducting lines as is shown in Fig.1(b). The structural integrity of the stretchable electronic circuits is one of the major concerns for stretchable electronics applications: (i) cohesive fracture in the stretchable lines will lead to failure, because the electrical function will be lost. This topic has been addressed by Li et al [1] and Gonzalez et al [2]. In their works, it is shown that a serpentine shape of the metal conductor permits large deformation of the substrate and results in small strains in the metal; (ii) adhesive fracture between the metal lines and the stretchable substrate is also of concern as the position of the delaminated conducting line is unsure and may lead to shorts, and the delaminated region may be a source of cohesive fracture and thus electrical failure of the stretchable device. This has motivated the development of a three-dimensional numerical model that can describe delamination using cohesive zone elements within a finite element framework. In order to estimate the interface properties, 90° peel-tests are performed. Next, a numerical model of the peel-test is developed in which cohesive zone elements are applied to describe the peeling process. In order to arrive at a unique set of interface properties, not only the global peel-force but also the local geometry near the delamination front will be used as validation parameters. Finally, the delamination behavior of a serpentine-shaped three-dimensional sample is simulated by using the thus determined interface properties.

Figure 1: (a) Rigid islands with brittle components in a compliant matrix connected with stretchable lines (from www.stella-project.de); (b) spring-like conducting lines (taken from [3]); (c) undesired delamination of metal lines from elastomer substrates leading to possible shorts (picture provided by IMEC)
Peel-test experiments

To characterize the interface properties, a 90° peel-test is used. Here, the force is measured as a function of the clamp displacement and during peeling the force is more or less constant: the peel force. A more detailed treatise of film peeling can be found in [4] and references therein. The peel-test samples are manufactured at IMEC and consist of a rubber (Sylgard 186, PDMS) substrate with a copper (electrodeposited, grade TW-YE, Circuit Foil) film. The rubber thickness varies from 1.0 up to 1.5 mm, while the thickness of the copper film is 17 ± 0.5 μm. The bottom plane of the rubber is glued on a metal plate that is mounted in the set-up. In order to monitor the local geometry near the delamination front for the quantitative validation purposes of the present work, the camera set-up shown in Fig.2(a) is added to the peel-test set-up.

In Fig.2(b) the measured force-displacement curves are shown for several samples. The averaged steady state peel-force \( P_f \) per unit width, which is in general a complex function of geometry, the constitutive properties of the film and substrate, and the interfacial cohesive properties [5], is shown as a dashed straight horizontal line in the figure. This value is used to calculate the adhesion energy or work of separation \( \Gamma \) according to \( \Gamma = P_f \), when assuming that the peeling angle remains approximately 90° during testing. From the measurements, the average adhesion energy is 1343 ± 51 J/m² (standard deviation).

For validation purposes, three geometry parameters are defined from the local deformation images, see Fig.2(c): the width of the lifted rubber \( w \), the height of the lifted rubber \( h \), and the radius of the copper foil \( R \). The averaged values over 15 measurements of different samples and steady-state stages during peeling are given in the inserted table in Fig.2(c).

Figure 2: (a) Peel-test set-up with camera; (b) Measured (solid lines) and averaged (dashed gray lines) force-displacement curves; (c) Local deformation of rubber and copper near the delamination front

Peel-test model

The peel-test is simulated using a 2D plane strain finite element model which is shown schematically (not to scale) in Fig.3(a). First results of this model have been reported in [6]. At the bottom plane of the substrate all degrees of freedom are fixed, corresponding to the experiment where the bottom side of the sample is glued rigidly to the test setup. The peeling of the copper film is simulated by prescribing \( U_y = 10 \) mm. The geometry is discretized using a sufficient amount of finite elements that account for geometrical and material non-linearities, such that a unique, converged solution is obtained upon mesh refinement. The material parameters of copper and rubber are experimentally determined and reported in [7].

Initiation and propagation of peeling is described using cohesive zone elements [8]. The cohesive tractions are calculated from a so-called traction-separation law (TSL), providing the relation between the separation vector \( t \), which can be decomposed into a normal component \( t_n \) and a shear component \( t_s \), at the interface of the two materials and the traction vector \( \delta \), which can be decomposed into a normal component \( \delta_n \) and a shear component \( \delta_s \). Following Van Hal et al. [9], an exponential Smith-Ferrante TSL is employed:

\[
\tau = \tau_{\text{max}} \left( \frac{\delta}{\delta_c} \right) \exp \left( 1 - \frac{\delta}{\delta_c} \right)
\]

Here, \( \tau \) is the equivalent traction and \( \delta \) the effective separation, defined as \( \delta = \sqrt{\delta_n^2 + \beta^2 \delta_s^2} \). The parameter \( \delta_c \) is the effective displacement at which the maximum traction \( \tau_{\text{max}} \) is reached. The constitutive parameter \( \beta \) defines the ratio between the maximum shear and maximum normal critical tractions. In the simulations, \( \beta = 1 \). It can be shown that the work of separation \( \Gamma \) corresponds to the surface below the traction-separation curve. For more detail, the reader is referred to Van Hal et al. [9].

To determine the cohesive zone properties in an accurate way, the work of separation \( \Gamma \) is varied between 1200 and 1400 J/m², while the interface strength \( \tau_{\text{max}} \) is varied between 0.9 and 4.0 MPa. The resulting force-displacement curve and the predicted geometry at the delamination front are depicted in Fig.3. For the interface toughness, a value of \( \Gamma = 1350 \) J/m² is established. The resulting simulated steady state peel-force
is in good agreement with the experimentally determined value, see Fig.3(b). For completeness, three values of $t_{\text{max}}$ are plotted: 1, 2 and 3 MPa. To determine $t_{\text{max}}$, the local geometry at the delamination front is used. It appears that $t_{\text{max}} = 3$ MPa results in the most accurate values for $h$, $w$ and $R$, see Figs.2(c) and 3(c).

It is remarked that in this approach, all failure phenomena that occur in the peel test, including rubber fracture, are lumped onto the cohesive zone elements, which corresponds to a macroscopic approach.

![Figure 3](image)

**Figure 3:** (a) Schematic of the plane strain peel-test model (not to scale); (b) measured (dashed-gray) and calculated (solid-black, for different $t_{\text{max}}$) force-displacement curve; (c) calculated local geometry at the delamination front, cf. Fig.2(c).

**Application to the three-dimensional structure**

In the previous section, it was shown to be possible to determine the interface toughness and strength parameters when combining peeling information from both global and local scales. The thus obtained interface parameters are now used in the simulation of the delamination behaviour of the structure from Fig.1(a), i.e. the horse-shoe shaped copper line on a PDMS substrate. Corresponding to the top picture of Fig.4(a), the dimensions of the sample are: $R = 0.7$ mm, $\theta = 30^\circ$, and the width of the trace ($w$) 0.1 mm. The thickness of the rubber is 0.5 mm while the height of the sample (the $y$-dimension in the figure) is 10 mm. As tensile loading, horizontal displacements $U_x = \pm 1$ mm are prescribed on the surfaces at the right and left side of the sample, respectively (see Fig.4a). The number of elements in this model 146440. Of course, all results have been checked on mesh convergence.

![Figure 4](image)

**Figure 4:** (a) Schematic of the horseshoe geometry, from [2] (top) and the corresponding three-dimensional model (bottom); (b,c) Top pictures: subsequent deformation stages during tensile loading of the sample; Bottom pictures: evolution of interface damage in the cohesive zone elements during loading. The subsequent stages correspond to (b) 0.50 and (c) 1.00 mm elongation, respectively.
Several deformation stages are shown in the top pictures of Fig.4(b,c). Observe that the thin lines indicate the location of the copper film when no delamination would occur. In the bottom pictures of Fig.4, the damage evolution in the cohesive zone elements is depicted, which is defined as $D(t) = \max(\delta(t)/\delta_c)$, where $\delta(t)$ corresponds to the separation during loading. From the results, it can be observed that delamination of the copper film occurs with the mentioned set of interface parameters. This is confirmed by experimental observations of which the results will be reported in the near future.

**Discussion**

Using a combined experimental and numerical approach, it is shown that the finite element model employing cohesive zone elements quantitatively predicts the peel-force–displacement curve and the local geometry at the delamination front during the peel test. Only when using global and local deformation parameters, a unique set of interface properties could be determined. It appeared that the work of separation $\Gamma$ could be determined from the global force-displacement curve, while the interface strength $t_{\text{max}}$ followed from the local deformation at the crack tip. In this way, all dissipation mechanisms occurring during peeling of the copper are lumped onto the cohesive zone elements, including fracture of the rubber.

In [6] it was argued that the work of separation for this system includes internal dissipation mechanisms in the copper foil. The fact that the steady state peel-force is accurately simulated at the measured total work of separation of 1350 J/m$^2$ when the plastic response of the copper foil is accurately taken into account indicates that plastic dissipation in the copper foil is negligible as a contribution to the work of separation. Furthermore, this rather high value implies that besides delamination between copper and rubber, rubber fracture contributes to the dissipation. Experimental observations confirm this [7]. The three-dimensional results shows that failure between copper and rubber occurs during tensile loading, when using the interface properties as determined from the experimental measurements.

The local geometry at the delamination front (i.e. the way the copper peels from the rubber) shown in Fig.3 suggests that delamination does not occur purely at mode 1 (opening mode), but that also a mode 2 contribution is present (mode-mixity). Both contributions are accounted for in the cohesive zone model by means of an equivalent contribution to the total work of separation [9]. A mode angle dependent work of separation may have to be taken into account for more accurate prediction of delamination phenomena in arbitrary 3D stretchable electronics designs although experimental characterization of this mode dependency is far from trivial.

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**References**


