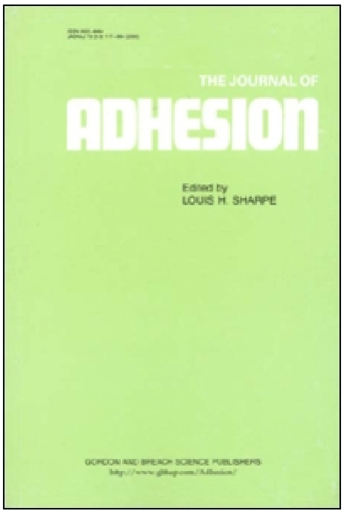

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Local Bending Moment as a Measure of Adhesion: The Cantilever Beam Test

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Local Bending Moment as a Measure of Adhesion: The Cantilever Beam Test

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It was recently proposed (Goussev, O. A., Zeman, K. and Suter, U. W., *J. Adhesion* **56**, 45 (1996)) to characterize the joints between materials directly by the maximum bending moment, $M_{\max}$, borne just prior to delamination (delamination moment). This alternative to the energy-release-rate approach was first introduced for the blister test configuration. Here we extend this idea to a cantilever beam test. We suggest, therefore, to evaluate the bending moment in the cantilever-beam experimental setup with an elastic upper plate through direct measurement of the curvature of the upper plate in the vicinity of the separation line. For the profile measurement and determination of the exact location of the delamination line, the projection-moiré technique was employed. The methodology was tested on measurement of adhesion of an epoxy adhesive to steel. It was shown that the value of the maximum bending moment remains approximately constant during the delamination, indicating that this quantity is a physical characteristic of the joints between materials.

Keywords: Adhesion; adhesion energy; cantilever beam test; delamination moment; local bending moment

1. INTRODUCTION

Cantilever beam tests are widely used for measurement of fracture energy, mainly due to their simplicity. The first application of the cantilever beam test in experimental mechanics was made by Obreimoff in 1930, in testing the crack propagation in mica [1]. The double

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cantilever beam configuration, which is the most commonly used in quantifying the adhesive fracture energy, was introduced into the adhesives industry by Ripling and Mostovoy [2]. A drawback of this test is that the strain energy release rate, which is usually taken as a characteristic of the delamination process, is dependent of the crack length. The use of a correctly-tapered sample [3] or computer-controlled test equipment can, in principle, solve this problem.

On the basis of the cantilever beam analysis, taking into account the effect of the plastic zone at the crack tip, as well as the beam rotation and viscoelastic response of the material, Freiman, Mulville and Mast [4] showed that the application of a constant bending moment to the specimen, rather than the usual constant load, provides a test in which the strain energy release rate is independent of the crack length. Recently, Dillard, Wang and Parvatareddy [5] proposed a new method for testing double cantilever beam specimens. They recommended a rather simple experimental configuration allowing for achieving a nearly constant strain energy release rate.

Nevertheless, dissipative processes, completely omitted from analysis in the above energy approaches, may significantly contribute to the delamination process. It was recently proposed [6] to characterize the joints between the materials for the blister test configuration directly by the experimentally-measured maximum bending moment, $M_{\max}$, borne just prior to delamination. For the peel test, Crocombe and Adams [7] showed that failure occurred at a critical applied bending moment for a particular adherend and adhesive, independent of peel angle. In this paper we extend this idea to the cantilever beam configuration.

2. ANALYZING THE CANTILEVER BEAM TEST

In Figure 1 experimental configuration is shown. The spring steel plate with a thickness of 2 mm (shown in black) is lifted up from the rigid substrate by means of a micrometric screw, S, and a horizontal bar in the z-direction.

Following the approach developed in Ref. [6], we equate the reaction moment at the separation line to the beam's bending moment measured in the vicinity of the separation line.

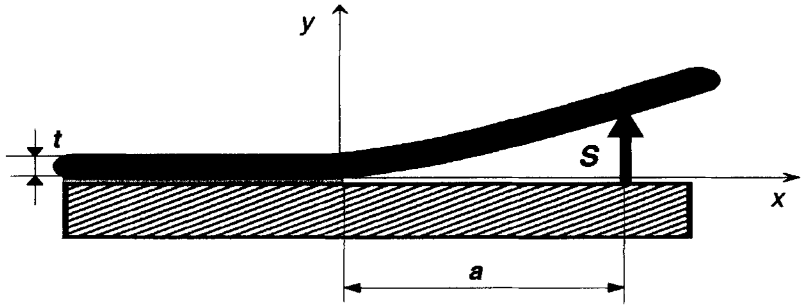

FIGURE 1 Schematic of the cantilever beam test.

For small deflections of a cantilever beam in the y-direction, the bending moment per unit length of a contour is determined by the second derivative (curvature) of the deflection along the normal to the contour [8]:

$$M = D\frac{\partial^2 y}{\partial x^2}\bigg|_{x=0}. \tag{1}$$

D is the flexural rigidity of the upper plate and for a homogeneous, isotropic elastic medium is:

$$D = \frac{Et^3}{12(1-\nu^2)}, \tag{2}$$

where E is Young's modulus, ν Poisson's ratio, and t the thickness of the plate that is being bent.

The plate deflection in the vicinity of the separation line can be approximated by the following series expansion:

$$y = y|_{x=0} + \frac{\partial y}{\partial x}\bigg|_{x=0} x + \frac{1}{2}\frac{\partial^2 y}{\partial x^2}\bigg|_{x=0} x^2 + O(x^3). \tag{3}$$

Because of the clamped boundary conditions:

$$y|_{x=0} = 0 \quad \frac{\partial y}{\partial x}\bigg|_{x=0} = 0, \tag{4}$$

one obtains the following approximation for the y-deflection:

$$y \approx \frac{1}{2}\frac{\partial^2 y}{\partial x^2}\bigg|_{x=0} x^2. \tag{5}$$

If one can measure the profile of the bent plate, then the second derivative at the separation line can be obtained by least-square fitting of the above equation to the measured y-values:

$$\sum_{i,y<t}\left[\frac{1}{2}\frac{\partial^2 y}{\partial x^2}\bigg|_{x=0} x^2 - y_i\right]^2 = \text{minimum}. \tag{6}$$

With the value of the second derivative known and assuming dissipation to be irrelevant, one can readily calculate the adhesion energy [8], W:

$$W = \frac{1}{2}D\left(\frac{\partial^2 y}{\partial x^2}\bigg|_{x=0}\right)^2_{\max} \tag{7}$$

As discussed in Ref. [6], the equations for the bending moment (1) and the adhesion energy (7), together with the flexural rigidity D of Eq. (2), are valid if the neutral surface is situated midway through the plate (following Landau and Lifshitz [8]). If the neutral surface is at the lower surface of the plate, then one has to use another value for the flexural rigidity, namely (following Obreimoff [1]):

$$D_{\mathrm{OB}} = \frac{Et^3}{3(1-\nu^2)}. \tag{8}$$

In fact, it is not clear which of the two representations is more accurate in the vicinity of the separation line. To understand where the neutral surface is actually situated, the Finite Element method can be employed.

3. FINITE ELEMENT ANALYSIS

The setup shown in Figure 1 was studied. We considered only this static configuration, which occurs before delamination, and did not analyze the state of stress in the disbondment zone during crack propagation, which, as was shown by Kaelble [9], is quite complex. Elastic behavior was assumed. Different materials were used for the adherend (steel with $E = 205\,\text{GPa}$ and aluminum with $E = 70\,\text{GPa}$) and adhesive ($E = 3$ and $0.3\,\text{GPa}$). The thickness of the adhesive was varied from 0 to 1 mm. The lower substrate was assumed to be rigid, *i.e.*, the position of the lower nodes were constrained in both directions. Eight-noded quadrilateral plane-strain elements were employed. The finite element analysis was carried out with the MARC software package [10].

In Figure 2 the e_{xx} strain component (at $x = 0$) of the steel/epoxy system with varying adhesive thickness for a beam of 128 elements is shown. For the meshes of more than 128 elements, the location of the neutral surface is independent of the mesh density. The position of the neutral surface for different systems is shown in Figure 3. One can see that the location of the neutral surface ($e_{xx} \equiv 0$) rapidly approaches the middle of the upper plate with increasing adhesive thickness; at a thickness of about 15 μm the deviation is already less than 4% for the steel/epoxy and less than 15% for the aluminum/epoxy. The results for the other adhesive are similar. This convincingly validates Landau's premise about the location of the neutral surface [8]. (It has to be

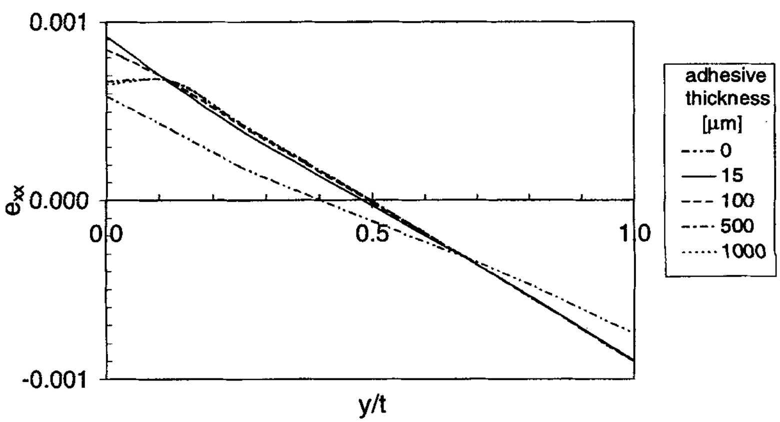

FIGURE 2 e_{xx} strain component for a model of 128 elements for the system steel/epoxy with different adhesive thickness. The neutral surface ($e_{xx} \equiv 0$) is in the vicinity of the middle of the plate ($y/t = 0.5$).

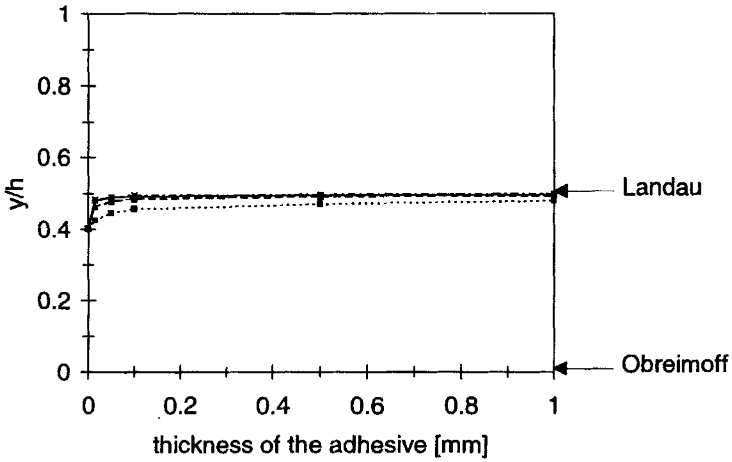

FIGURE 3 The location of the neutral surface for different systems as a function of the adhesive thickness: the solid line (◆) – steel adherend/epoxy adhesive; dotted line (■) – aluminum adherend/epoxy adhesive; dash-dotted line (×) – steel adherend/adhesive with $E = 0.3\,\mathrm{GPa}$; dashed line (▲) – aluminum adherend/adhesive with $E = 0.3\,\mathrm{GPa}$.

pointed out that in many industrial applications the minimal recommended adhesive thickness is 50 μm.)

4. TEST SAMPLES

As a lower plate, steel plates of 10 mm thickness were used. As an upper plate, elastic spring steel plates of 2 mm thickness and 20 mm width were employed. Young's modulus of the spring steel plate measured with a tensile tester was 205.2 ± 0.3 GPa; Poisson's ratio was assumed to be 0.25.

Each plate was first cleaned with acetone, then dried under controlled conditions of 23°C and 50% relative humidity for one hour, and after this covered by a 15 μm epoxy (Araldite 2011) layer. Both plates were kept in vacuum (about 100 Torr) for 10 minutes to remove blisters (bubbles) in the adhesive and then placed together under a weight of 1 kg for one week, under controlled conditions. The initial value of a (see Fig. 1) was 50 mm.

5. EXPERIMENTAL SETUP

For the profile measurements, the projection moiré technique was employed [11]. This technique enables quantitative measurement of the shape of an object. The experimental setup for the profile measurements is shown in Figure 4. A light source projects a shadow of a linear grating, G_1, onto the surface under examination. A camera, placed behind another similar grating, G_2, records moiré fringes arising from the superposition of the distorted projected grating, G_1, with the undistorted one, G_2. The information about the shape of the object's surface is contained in these fringes. Both gratings have the same line density of 20 lines per mm. The pattern of the flat sample was used for calibration of projection moiré measurements [12]. We employed a projection moiré system (NEWPORT 1000) with a vertical resolution of approximately 10 μm and a horizontal resolution of 250 μm.

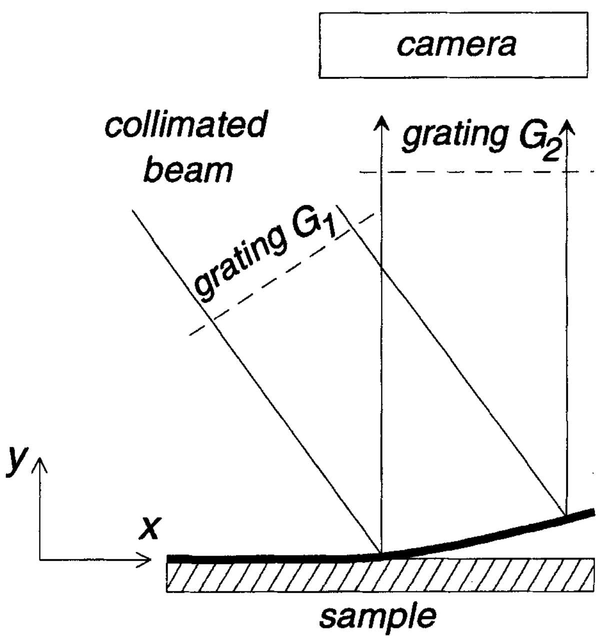

FIGURE 4 Setup for projected Moiré. A collimated beam projects the grating, G_1, onto a sample.

The free end of the spring steel plate was lifted up with the help of a micrometric screw, and the profile was measured. The plate was lifted up once more, and the measurements were repeated. It is worth emphasizing explicitly that delamination occurs at every individual lifting step every time yielding an estimate of the maximum bending moment. Therefore, one can considerably improve the accuracy by averaging the individual values of the bending moment.

The delamination occurred always between the adhesive and the lower plate.

6. RESULTS

A typical picture of a moiré pattern of a bent steel plate is shown in Figure 5. The distance between two adjacent white stripes is about 0.5 mm. Stripes of different color are used to improve the visual contrast of the picture during the post processing.

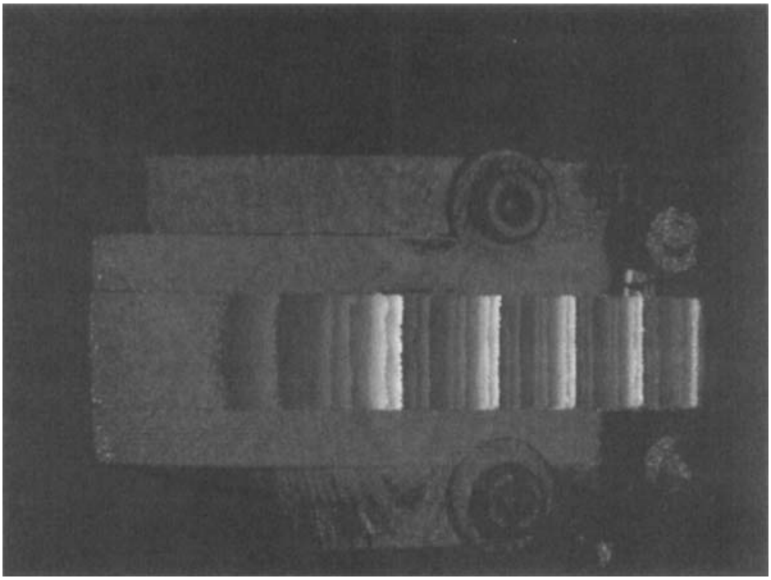

FIGURE 5 Moiré interference fringe. The spring steel plate is lifted off the substrate at the right of the picture by 2.5 mm. (See Color Plate I).

The upper plate profile, obtained from such a measurement, is shown in Figure 6. Each profile consisted of more than 500 points, providing sufficient accuracy for the calculation of the fitting parameters: the location of the delamination line, the second derivative and the height of the baseline. The points with deflections less than the plate thickness (*i.e.*, 2 mm) (more than 400 points) were taken for the calculation of the second derivative. The observed excellent fit of the theoretical elastic plate shape (Eq. (5)) and the experimental deflections convincingly validates the use of the plate theory [8] for this setup.

As we have already mentioned, a number of individual estimates for the critical bending moment can be obtained from one sample, because the delamination does not occur at once but rather in a sequence of individual steps. Figure 7 illustrates the scatter of the results obtained with two samples studied. For the calculation Eqs. (1) and (7) together with a flexural rigidity of Eq. (2) were employed. After a few initial measurements the value of the bending moment seems to remain approximately constant during the delamination, indicating that this quantity is a physical characteristic of the delamination process. The average over the plateau values (measurement numbers 4–16) gives

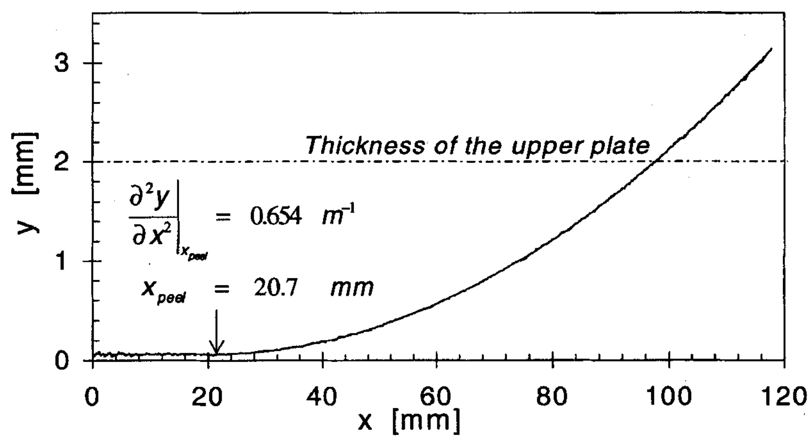

FIGURE 6 Comparison of the experimental (the dotted line) and theoretical (the solid line) results. The height of the screw is 2.5 mm. Eq. (5) was employed to fit the points below the plate thickness (the dash-dotted line).

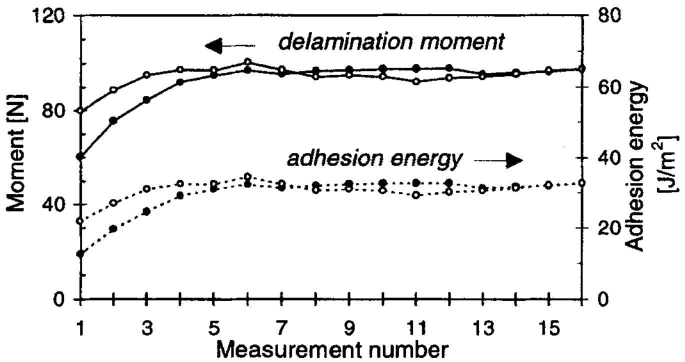

FIGURE 7 Delamination moment (solid lines) and adhesion energy (dotted lines). The two samples (empty and full circles) employed give two independent curves of delamination moment and adhesion energy.

97 ± 1 N and 96 ± 2 N for two samples, respectively. The first 3 points (measurement numbers 1 – 3) were discarded; their low values might be due to non-uniformity of the adhesive layer in the vicinity of the edge at the beginning of the crack. The average values of the adhesion energy calculated *via* Eqs. (7) and (2) are $32 \pm 1\ \mathrm{J/m^2}$ and $31 \pm 1\ \mathrm{J/m^2}$.

7. CANTILEVER BEAM TEST MEASUREMENTS

To allow comparison of this new method with a traditional one, measurements of the fracture energy were performed with a cantilever beam method. Test samples were made as described in Section 4. To monitor the crack tip position, the side of the specimen was painted white with a correction fluid and marked at one-mm intervals. The lower plate was fixed horizontally in a tensile testing machine (Zwick) and the upper plate was lifted with a rate of 0.5 mm/min (see Fig. 1). The crack propagation was observed with a magnifying glass and marks were placed on a load-displacement curve after every 5 mm of crack extension (see Fig. 8).

The strain energy release rate, G, was calculated from the experimental data using the Irwin – Kies relationship [13]:

$$G = \frac{P^2}{2b}\frac{dC}{da}, \tag{9}$$

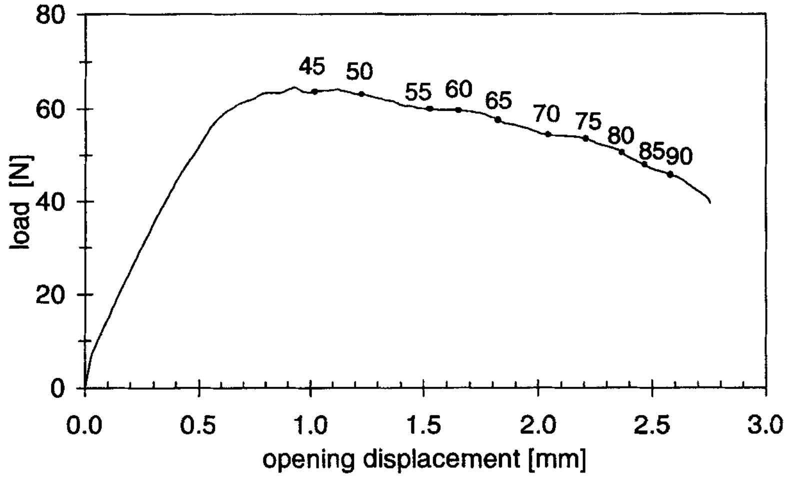

FIGURE 8 The experimental load-displacement curve for the cantilever beam with marks on every 5 mm of the crack propagation. The numbers 45–90 indicate crack lengths. The initial crack length was 40 mm.

where $C = y/P$ is the compliance, P the load, y the deflection, and a the crack length; the critical values of these parameters are taken. b is the width of the upper plate. The derivative dC/da was evaluated by differentiating the polynomial-fitted function $C = f(a)$ [14]. For two samples employed, the values of adhesion energy obtained were $68 \pm 5\,J/m^2$ and $69 \pm 10\,J/m^2$, this being a factor of two larger than those obtained with Eqs. (7) and (2) (see Section 6).

8. CONCLUSIONS

The application of the idea proposed in Ref. [6] for the blister test configuration to the cantilever beam setup showed that for this configuration the bending moment can accurately be deduced from the curvature of an elastic upper plate as it bends away. We should point out explicitly, that our method is based on plate theory, which is correct for the case of elastic behavior of the upper plate in the vicinity of the separation line. The value of the maximum bending moment just before delamination (delamination moment) for the cantilever beam experimental setup was nearly constant during the delamination and, therefore, could be taken as a direct characteristic of the joints between the materials.

We interpret the higher estimated adhesion energy of the cantilever beam experiment as a reflection of the fact that in this test the plastic deformation energy during the complex crack propagation process [9] is included. Our maximum moment estimate tends to avoid this problem. The same tendency was already observed with different blister-test realizations [6].

The projection moiré technique used for the profile measurements allows not only precise measurement of the upper plate profile, but also finding the exact position of the delamination line.

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