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Adhesive tapes; cohesive laws for a soft layer

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Abstract

For adhesive tapes, the strain before fracture often exceeds 500%. Although the maximum stresses are quite modest the high strains to fracture result in impressive fracture energy. Due to hydrostatic stress the fracture process often starts by nucleation of microscopic cracks inside the layer. The final crack path is usually close to one of the adherends.

Repeated experiments are performed both with DCB-specimens and butt-joints. The used adhesive tape is an acrylic foam tape with a thickness of 1.1 mm and a width of 19 mm. The geometry of the specimen is adapted to the properties of the soft layer. For the DCB-specimen this implies that the length of the specimen is about 1 m. The evaluated cohesive laws from the DCB-specimens give a fracture energy of 2 kN/m and a maximum stress about 0.5 MPa. For the butt-joints, the evaluated cohesive law corresponds well to the results from the DCB-experiments. However, the strain to fracture is slightly smaller. The stress in these specimens is distributed over a larger area and a nucleated crack rapidly crosses the load bearing area and fails the joint prematurely. For both kinds of experiments the evaluated cohesive laws show a small linear part. After this part there is an almost linear strain-hardening phase until fracture.

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Keywords: Pressure-sensitive adhesive (PSA); Adhesive tape; Cohesive law; Double Cantilever Beam (DCB)

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1. Introduction

The use of *pressure-sensitive adhesives* (PSA) or simply *adhesive tapes* has a lot of advantages. From an industrial point of view they are easy to use and provide no or minor health risks for the assembler. From a researcher's perspective, the soft and relatively thick layer also entails some challenges. To experimentally find the mechanical properties of the adhesive is important in order to make accurate numerical simulations. For stiff adhesives it is common to represent the layer by a cohesive law cf. e.g. Stigh et al. (2010). For soft and thick (~1 mm) adhesives the cohesive laws will be influenced by the geometry of the layer, cf. e.g. Biel et al. (2012). Accordingly the geometry of the PSA influences the result since the stress-state is changing with the width. PSA usually have a viscoelastic behavior and the response is time dependent, see e.g. Christensen et al. (1998) and Townsend et al. (2011). Due to the viscoelastic behavior and the time dependence also the curvature of the substrate will influence the cohesive law, see Zhang and Wang (2009). To use PSA in more critical applications there is however a need for detailed experimental knowledge of the mechanical properties.

In this paper the cohesive laws for a PSA is obtained in mode I by use of the *double cantilever beam* (DCB) specimen and the butt-joint specimen. Compared to ordinary peel-experiments, see e.g. Hata et al. (1965), the curvature in both these experiments is small. Cohesive laws are evaluated from both experiments.

The used PSA in this study is a closed cell acrylic foam tape (3M VHB-4611F) with a thickness of, t = 1.1 mm and a width of b = 19 mm. Before applying the tape, the surfaces are cleaned with heptane and acetone. The time between the manufacturing of the specimens and the experiment is more than 100 hours.

Nomenclature

J	Energy release rate (N/m)
J_c	Fracture energy (N/m)
σ	Cohesive stress (N/m^2)
F	Force (N)
θ	Specimen rotation at the loading-point (-)
w	Deformation of the adhesive layer (m)
Δ	Separation of the loading-points (m)
a	Initial unbonded length (m)
b	Width of the adhesive layer (m)
t	Thickness of the adhesive layer (m)
E	Young's modulus of the adherends (N/m^2)
I	Area moment of inertia of the adherends (m^4)

2. DCB-experiments

The geometry of the specimen is shown in Fig. 1a. The specimen is mainly used to experimentally determine the fracture energy using linear elastic fracture mechanics. By use of the J-integral approach it is however also possible to determine the cohesive law for the layer. In this case the energy release rate has to be measured until a crack starts to propagate. Several methods exist to determine the energy release rate. By measurement of force and load point rotation see Stigh (1988) and Nilsson (2006),

$$J = \frac{2F\sin\theta}{b} \tag{1}$$

or by measurement of force and load point displacement, see Tamuzs (2001),

$$J = \frac{F^2}{EIb}\left(\frac{3EI\Delta}{2F}\right)^{2/3} \tag{2}$$

When a crack starts to propagate the energy release rate equals the fracture energy, J_c. Similar methods can be used for DCB-specimens with applied bending moment, see Sou et al. (1992) and Sørensen and Jacobsen (2003). To obtain the cohesive relation, the energy release rate has to be differentiated with respect to the deformation of the adhesive layer, w, see e.g. Andersson and Biel (2006),

$$\sigma = \frac{dJ}{dw} \tag{3}$$

The specimens are oriented vertically during the experiment. The used tensile test machinery (Swetest 100-168) is electro-mechanical and the experiment is performed with a constant loading rate of 30 μm/s which results in a tape deformation rate of about 10 μm/s. The rotation at the loading point is measured with an incremental shaft encoder that provides $2 \cdot 10^5$ pulses per revolution. The load is measured with a load cell with a maximum capacity of 500 N. The deformation of the layer is measured with two LVDTs; one on each side of the specimen, see Fig. 1b.

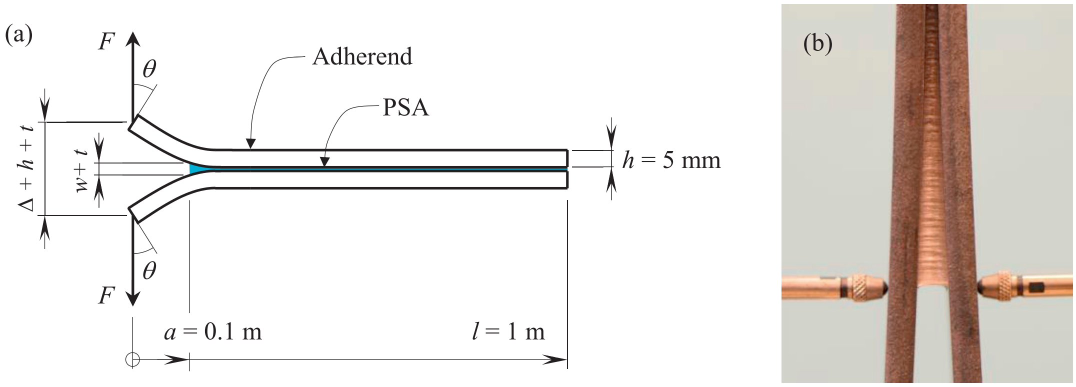

Fig. 1. (a) Geometry of the DCB-specimen; (b) Position of the LVDTs at the start of the layer.

3. Butt-joint experiments

The cohesive law is determined directly from the force and separation. The specimens are oriented horizontally during the experiment. The used tensile test machinery (Instron 8002) is servo hydraulic and the experiment is performed with a constant displacement rate of 10 μm/s, i.e. the deformation rate is the same as in the DCB-experiments. The load is measured with a load cell with a maximum capacity of 1 kN and the deformation of the layer with an LVDT. The geometry of the specimen and the experimental setup are shown in Fig. 2.

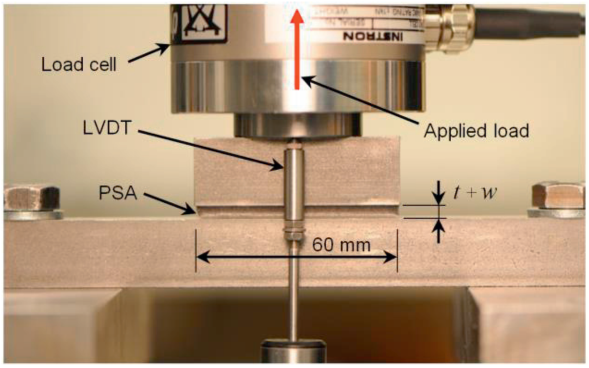

Fig. 2. Butt-joint specimen with a deformation of about $w = 3$ mm.

4. Experimental results

Seven DCB-experiments and four butt-joint experiments are performed. The DCB-experiments are evaluated using both eq. (1) and eq. (2). For all the evaluated experiments the difference in energy release rate between these equations is less than 5%. This indicates a good experimental performance since it is in the same range as the accuracy of the methods, cf. Biel and Stigh (2007).

Figure 3a shows the energy release rate for the DCB-experiments. The fracture energy is 2.1 ± 0.3 kN/m. When the crack starts to propagate the fracture energy is decreasing. Figure 3b shows the evaluated cohesive law for the DCB-experiments, by use of eq. (1), and for the butt-joints. The first part of the curve shows a linear part. When the stress has reached a level of about 0.3 MPa cavities inside the PSA start to increase in size and linear hardening of the material is observed. The cavities start to coalesce and form fibrils between the surfaces. Final fracture is usually cohesive and occurs close to one of the adherends. For the DCB-specimens, fracture occurs at a stress of 0.51 ± 0.06 MPa and for the butt-joints at a stress of 0.45 ± 0.05 MPa. For all the experiments the crack propagation occurred abruptly by reducing the stored energy in the PSA. For all experiments the strain at fracture exceeds 500%. For two of the DCB-experiments the stress decreases earlier due to adhesive failure at some part of the specimen.

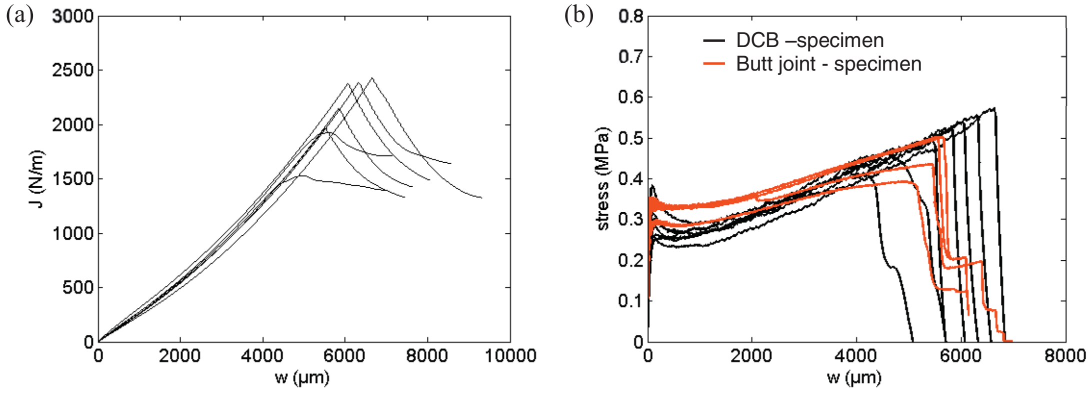

Fig. 3. (a) Energy release rate vs. deformation for DCB-specimens; (b) Cohesive stress vs. deformation for DCB-specimens and butt-joints.

5. Discussion and conclusions

Although the maximum stresses are quite modest, the high strains to fracture results in impressive fracture energy; the measured fracture energy is in the same range as for a structural epoxy adhesive. It is shown that the fracture energy decreases when cracks start to propagate. Thus the energy needed to form a crack is larger than the energy needed for propagation.

Two different geometries have been used. The results from the different methods are quite similar. However, there are some small differences. Generally strain at fracture in the DCB-experiments is larger compared to the butt-joints. In the butt-joints the stress is distributed over a larger area. The crack starts to propagate from one position and then quite rapidly traverses through the main part of the joint. For the DCB-specimens the crack is forced to propagate in one direction. Unfortunately the experiments were stopped shortly after the crack propagation was observed and no fracture energy for the steady state propagating crack was recorded.

Due to the specimen geometry the deformation rate in the DCB-experiments are increasing up to about, $w = 2$ mm. After this point the deformation rate is almost constant, 10 µm/s. For the butt-joint the deformation rate is constant, 10 µm/s during the entire experiment. Since the behavior of the PSA is time dependent this may have an influence in the evaluated results. In the first part of the experiments larger stresses are observed for the butt-joints compared to the DCB-experiments.

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