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Investigations on the energy balance in TDCB tests

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ABSTRACT

The Tapered Double Cantilever Beam (TDCB) test is an established method to determine the critical strain energy release rate of adhesives in mode I. Provided that the adherends stay elastic, that the adhesive layer is not too flexible and that inertia effects can be neglected, the experiment allows to identify the work required by the adhesive layer per area of crack growth. The evaluation according to the standard does not permit to distinguish between different sources of dissipation in the adhesive layer or at the adhesive-adherend interfaces, though. This paper proposes two approaches to gain a more detailed understanding of the dissipation in mode I crack growth of adhesive layers.

The first investigation method uses detailed finite element simulations of the TDCB test based on an elastic–plastic adhesive material model derived from tests on bulk specimens. The simulation is used to distinguish between the work required for the plastic deformation of the entire adhesive layer and the work consumed by the crack and the adhesive in its vicinity. The dependence of this distribution of work on the adhesive layer thickness is studied. The second approach adds a temperature measurement by an infrared camera to the TDCB test. This measurement allows observation of the thermo-elastic effect in the adhesive layer and of the heat generation at the crack. Finally, the results of the two approaches are employed to estimate the energy balance in the TDCB test. The application to a ductile epoxy adhesive shows the feasibility of the proposed methods.

1. Introduction

Fracture mechanical tests are an established tool to characterize adhesives and to provide parameters for numerical modeling of fracture processes in adhesive joints [1]. The tapered double cantilever beam (TDCB) test is a standard test to determine the critical strain energy release rate for mode I crack growth of adhesives [2–4]. The specimen is designed so that the specimen compliance is a linear function of the crack length, if the effect of the adhesive layer compliance can be neglected. Consequently, the crack grows at a constant force during the test provided that the crack growth is stable and occurs at a constant energy release rate. This critical strain energy release rate G_{Ic} can be evaluated from the square of the force according to the Irwin–Kies equation.

The critical energy release rate evaluated from the test is the ratio of the external work performed on the specimen minus the elastic energy of the adherends to the area of crack growth. This work may contain the work required to create the crack itself as well as work for inelastic deformation and damage in the entire adhesive layer. The evaluation of force–displacement curves of the test allows not to distinguish between the work required for different processes, but just provides the total G_{Ic}.

The contributions of plastic dissipation and the "intrinsic" work of fracture to the total work were already analyzed in the 1990s by numerical simulation. Those early works did not specifically regard adhesive joints. Tvergaard and Hutchinson [5] modeled crack growth at an interface between an elastic and an elastic–plastic solid using a cohesive zone model (CZM) at the interface. Assuming a mode independent CZM they showed that a mode dependence of the fracture toughness is caused by different amounts of plastic deformation outside the fracture process zone. A related approach assumed a small plasticity-free region close to the crack [6,7].

An application of the approach to an interfacial crack in an adhesive joint between semi-circular, elastic adherends was presented by Chowdury and Narasimhan [8]. The Drucker–Prager model for the plasticity of the adhesive layer was combined with a trapezoidal traction–separation law at the interface. Madhusudhana and Narisham [9] simulated compact tension shear tests with a crack in the center of the adhesive layer for different loading angles and adhesive layer thickness.

A distinction between the intrinsic work of fracture on one side and the plastic dissipation and stored elastic energy in the adhesive layer on the other side was the aim of a work of Pardoen et al. [10] simulating wedge-peel tests. They combined a trapezoidal

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traction-separation law for the fracture process zone with von Mises plasticity in the adhesive layer. Using this approach, Martiny et al. [11] were able to model different configurations of the wedge-peel test of the adhesive Dow Betamate 73455 using a single set of model parameters. In particular, the dependence of the fracture toughness on the adhesive layer thickness (between 0.1 and 1 mm) could be explained by the contributions of adhesive plasticity and locked-in elastic energy while the fracture energy of the CZM was considered constant.

Next, Martiny et al. applied the same approach to TDCB tests of the adhesive Bondmaster ESP 110 which is tougher than the Betamate 73455 [12]. In this case it was not possible to simulate the tests of different adhesive layer thickness using a constant set of CZM parameters. Because of the difficulty to determine CZM parameters depending on stress triaxiality uniquely, Martiny et al. suggested to use a crack instead of the CZM. They employed a critical stress at a distance criterion to govern the crack growth.

After the submission of the current paper, Jokinen et al. published simulations of double cantilever beam (DCB) tests using an elastic – ideally plastic material model to describe the adhesive layer and the virtual crack closure technique (VCCT) to model the propagation of a crack [13]. They identified the critical energy release rate of the crack growth law iteratively by fitting the simulated force–displacement curve experimental data. The method exhibited computational challenges, and a dependence of the results on stabilization, fracture tolerance and time increment was observed.

The current paper suggests two approaches to gain more detailed information about different contributions to the energy balance in the TDCB test. Since the constant force in the TDCB test implies that no further information than G_{Ic} can be obtained from the force–displacement curve, additional measurements are necessary to achieve this aim. The first proposed method follows a computational approach similar to the publications mentioned in the preceding paragraphs. It uses experimental data from tests on adhesive bulk specimens to create a material model. This model is used in finite element simulations which consider crack growth as well as the non-linear material behavior of the adhesive. The results are analyzed to learn how much the dissipation at the crack and in its vicinity and how much the inelastic deformation in the entire adhesive layer contribute to the critical energy release rate, respectively. The modeling method is similar to [12,13] regarding the description of fracture by crack growth instead of using a CZM, but we use a prescribed crack-growth velocity instead of a critical strain energy release rate or of a stress at a distance criterion. Furthermore, the rate-dependence of adhesive plasticity is considered.

The second proposed method increases the data gained from the TDCB test itself. A high speed infrared camera is used to observe the temperature change in the adhesive layer during crack growth. The resolution allows to distinguish between a temperature change in the entire layer, which can mainly be attributed to the thermo-elastic effect, and a local heat generation at the crack.

The results of the simulations and the thermal measurements are combined to make an estimate for the energy balance in the TDCB test. The most important underlying assumptions and open questions concerning their validity are pointed out.

The investigations have been performed using the construction steel S235 for the adherends and a cold-curing to part epoxy adhesive, Dow Betamate 2098. A TDCB specimen geometry according to Fig. 1 with a specimen width of 20 mm and an initial crack length of 80 mm was used.

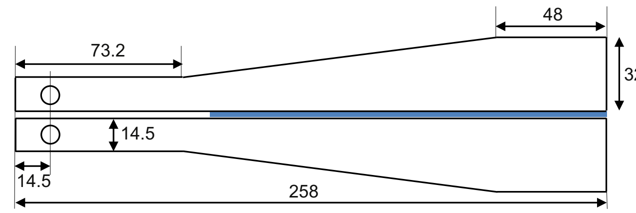

Fig. 1. Geometry of TDCB specimen (dimensions in mm).

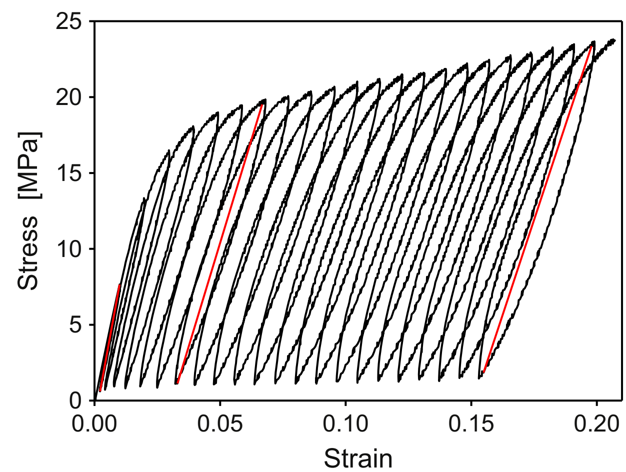

Fig. 2. Stress–strain curve of tensile test with unloadings, Betamate 2098.

2. Estimate of plastic work using finite element simulation

2.1. Tensile tests and material model

In this section additional information from tensile and compressive tests on the adhesive is used to learn about the energy balance in TDCB tests by finite element analysis. Tensile specimens according to DIN EN ISO 527-2 have been manufactured from the adhesive Betamate 2098. The specimens were tested at constant strain rates of 0.005, 0.05 and 0.5 1/s. These rates were chosen according to the strain rates encountered in the simulations of the TDCB tests. Additionally, tensile tests with unloadings were performed (Fig. 2). A complex material behavior is observed: The hysteresis loops as well as the rate dependence of elastic stiffness indicate a visoelastic behavior. The decrease of slope of the hysteresis loops can be described by a damage mechanics model. The strain remaining after the unloadings can be modeled phenomenological using an elastic–plastic model. In the simulation of the TDCB test, the adhesive is loaded as the crack advances closer to the considered material point and unloaded after the crack has passed. For this kind of loading and the aim to estimate the work performed in the deformation of the adhesive layer, an elastic–plastic material model is the best choice, although it is not capable of capturing all properties of the adhesive. The hardening function is defined rate dependent based on the tensile tests performed at different strain rates. A simple von Mises yield function is chosen. While epoxy adhesives often require a yield function depending on the hydrostatic stress, the Betamate 2098 showed only a minor difference (8%) between the yield stress in tension and compression.

The adherends made from steel S235 are considered as linear elastic.