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Mixed-mode I + III tests on hyperelastic adhesive joints at prescribed mode-mixity

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ABSTRACT

This paper presents a novel test-setup for fracture mechanical investigations on adhesive joints under mixed-mode I + III loading. The test has been developed to be adequate especially in case of non-linear elastic fracture. The new test shall be named Mixed-Mode-Controlled Double Cantilever Beam (MC-DCB) test and is controlled by prescribing during the entire experiment a mode-mix ratio, which is defined by the ratio of contributions to the J-integral from single modes, namely J_I and J_{III}. Those contributions are calculated during the test by an analytical approach. That kind of test control holds for the entire period of crack propagation and is valid even in case of strong non-linear material behavior. The proposed test setup seems to be an innovative enhancement compared to classical mixed-mode tests, which are commonly based on linear-elastic fracture mechanics (LEFM).

The experimental work is performed on the hyperelastic adhesive SikaFlex 521-UV™.

1. Introduction

The increasing usage of structural adhesive joints in many industrial applications requires experimental procedures, which are capable to characterize adhesives and adhesive joints with respect to their intended field of application. As example, the fracture behavior of adhesive joints is of large interest in automotive industries, since the energy dissipation of an adhesive joint can influence the crash behavior of a whole car structure significantly. For that reason, many researchers focused on aspects like cohesive zone modeling (CZM) [1,2] of such joints, taking into account effects of rate-dependency, adhesive layer thickness or the kind of loading on the energy release rate (ERR). A lot of experimental effort has been undertaken to develop new test setups to overcome new challenges from new industrial applications and from new kinds of adhesives [3].

Classical fracture mechanics distinguish between three crack opening or fracture modes as illustrated by Fig. 1, which are well-known as mode I (peel), mode II (in-plane shear) and mode III (out-of-plane shear). A combination of those loading conditions is named mixed-mode loading. Several test setups are established or have been recently developed to investigate the fracture behavior under such mixed-mode loading, mainly focusing on a combination of modes I and II: The Mixed-Mode-Bending (MMB) test is a well-established and standardized test on fiber reinforced composites [4]. Jumel et al. [5] applied the MMB-test for investigations of brittle adhesive, a relationship of peel and shear cohesive stresses could be extracted from experimental data in their work as well. Stamoulis et al. [6] used the MMB test successfully on an elastic-plastic adhesive. Costa et al. [7,8] developed an apparatus to investigate different mode-mixities with a MMB test and presented experimental results for three different kinds of adhesive. Since the mode-mixity changes with crack length in their test setup, the results in ERR depend on an equivalent crack length. Nevertheless, fracture envelopes are given, which indicate a strong dependency of critical ERR on mode-mixity for all of the investigated epoxy adhesives. Lundsgaard-Larsen et al. [9] proposed a modification of the Double-Cantilever Beam (DCB) test by loading the specimen instead of forces with uneven bending moments (DCB-UBM). Furthermore, a CZM for composite materials has been directly derived from test results. Another similar test setup, the Mixed-Mode DCB (MCB) test, is presented by Högberg and Stigh [10,11]. It should be emphasized that it is in general not possible to derive the contributions to the ERR from the single modes in case of mixed-mode I + II. Such derivation is possible as long as the assumptions from LEFM are valid, since a superposition of load cases is permitted in case of LEFM only. However, LEFM has been successfully applied by the mentioned authors, even in case of elastic-plastic epoxy adhesives. Walander et al. [12] designed a Controlled Mixed-Mode Bending (CMMB) test and tried to control the test to constant mode-mixity, which was defined by a ratio of components of the crack opening displacement (COD). By that definition of mode-mixity, it was not possible to keep the mode-mix ratio constant after the start of crack propagation, since the COD has been measured at the location of the initial crack tip.

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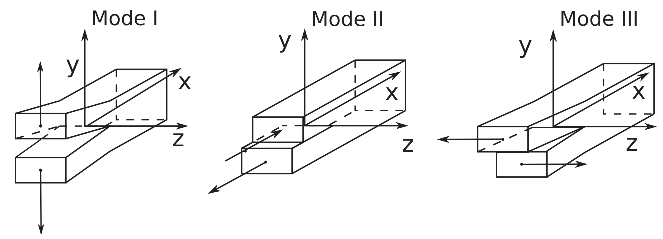

Fig. 1. Illustration of the three classical fracture modes.

The superposition of single mode contributions fails in case of mixed-mode I + II, since peel and in-plane shear loads influence each other as soon as they occur simultaneously. Switching now the focus to mixed-mode I + III, that limitation does not exist anymore and the contributions of mode I (in-plane loads) and mode III (out-of-plane loads) can be easily derived individually also in case of strong non-linear material behavior. Consequently, investigations on mixed-mode I + III seem to be very promising when expecting such non-linear material behavior as in case of thick, hyperelastic adhesive layers. In contrast to mixed mode I + II, only very few publications can be found on mixed-mode I + III. Chai [13,14] proposed a DCB test loaded in mode III as well as a superposition of that test with mode I. In that work a rather brittle adhesive has been studied with methods based on LEFM. However, there exist similarities to the work presented here. In difference to Chai, the proposed MC-DCB test is based on *J*-integral approaches and holds even in case of non-linear elastic fracture. Furthermore, the MC-DCB test is controlled by prescribing a mode-mixity defined in terms of ERR, which represents a further development of the mentioned work. Furthermore, Chai reported similar ERR in modes II and III, while Parvatareddy and Dillard [15] made a different observation for a different adhesive. An overview over published work on mixed-mode II + III is given by Vintilescu and Spelt [16]. More recently, Aliha et al. [17] proposed an Edge-Notched Disk Bend (ENDB) test to study the fracture behavior of asphalt, but their test setup cannot be adapted to adhesive joints. Ayatollahi and Saboori [18] investigated notched PMMA specimens in a setup similar to the Arcan test, but their evaluation method was based on LEFM.

The MC-DCB test, which is proposed in the following, is an extension of the recently developed ODCB test [19], which was designed to investigate fracture under pure mode III loading. To apply mixed-mode, the specimen is additionally loaded in mode I. There is no coupling between both modes as long as higher order effects as lateral moments on the clamping are negligible. The evaluation of ERR is then based on the non-linear fracture mechanical (NLFM) approach of the *J*-integral according to Rice [20] and the contributions to the *J*-integral from the single modes can be separated even when having non-linear fracture behavior. Taking that fact into account, the mode-mix ratio, which shall measure the mode-mixity, is defined here by the ratio of the single-mode contributions J_I and J_{III} to the *J*-integral. That definition allows a test control by prescribing a mode-mixity even in case of having a progressing crack tip. It should be noticed that an alternative definition of mode-mixity by a ratio of components of the crack opening displacement vector would fail from the experimental point of view as soon as the crack starts to propagate.

2. Theoretical background

The proposed MC-DCB test setup is an extension of the Out-of-plane-loaded-DCB (ODCB) test [19]. The ODCB test as a pure mode III test is loaded by an external moment only, transversal and axial forces are avoided. The idea of the novel MC-DCB test is to apply on the ODCB specimen an additional mode I loading, which can be superimposed with the mode III loading. In case of mode I and III, superposition is possible even in case of non-linear elastic material behavior, since the particular loading in one mode is not influenced by the other one.

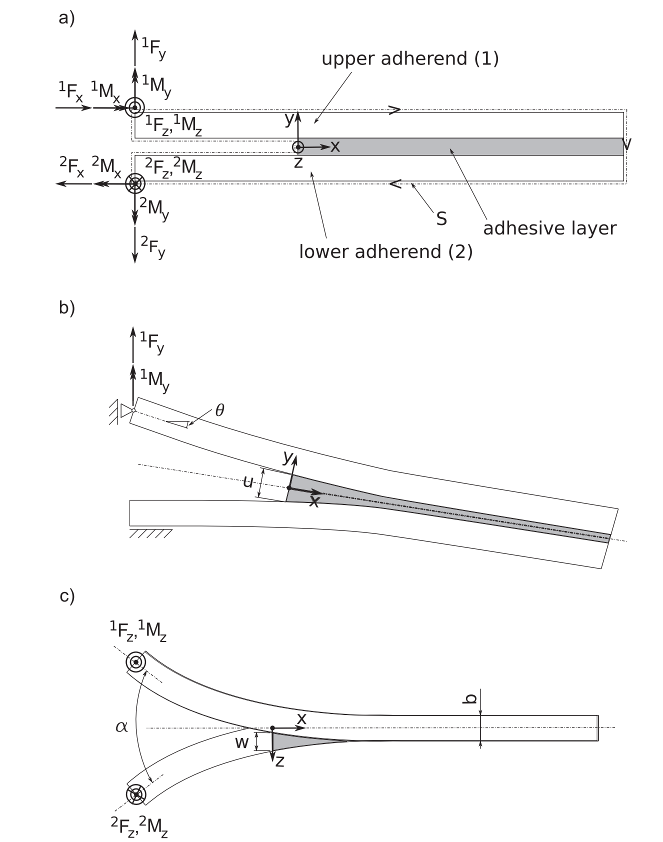

Fig. 2. Sketches of MC-DCB specimen. a) Unloaded state and closed path of *J*-integral. b) Loaded state in lateral-view. c) Loaded state in top-view.

Strictly speaking, the MC-DCB test superimposes a classical DCB and the recently developed ODCB test. The *J*-integral according to Rice [20] is given by

$$J = \int_S \left(W dy - \vec{t} \cdot \frac{\partial \vec{\delta_t}}{\partial x} dS \right), \tag{1}$$

where *S* describes an arbitrary path in counter-clockwise direction containing the crack tip. *W* is the strain energy density, $\vec{t}$ and $\vec{\delta_t}$ denote traction and corresponding displacement vector. The coordinates *x* and *y* are shown in Fig. 2, where *x* is the direction of crack propagation. The contributions to *J* from external loads are in equilibrium with the actual ERR since *J* vanishes along a closed path. When choosing a path *S* around the outer bounds of the specimen as sketched in Fig. 2, only forces and moments caused by the specimen support contribute to the *J*-integral. Precisely, these are one reaction force $\overrightarrow{{}^iF}$ and one reaction moment $\overrightarrow{{}^iM}$ at each of the two support locations, distinguished by index *i*. Then the ERR is obtained by the contributions to *J* from external (reaction) loads, expressed in components *x*, *y* and *z*,

$$J = \frac{1}{b} \sum_{i=1}^{2} \left[{}^iF_x \frac{\partial ({}^i\Delta_x)}{\partial x} + {}^iF_y \frac{\partial ({}^i\Delta_y)}{\partial x} + {}^iF_z \frac{\partial ({}^i\Delta_z)}{\partial x} + {}^iM_x \frac{1}{2} \left(\frac{\partial^2 ({}^i\Delta_z)}{\partial x \partial y} + \frac{\partial^2 ({}^i\Delta_y)}{\partial x \partial z} \right) + {}^iM_y \frac{\partial^2 ({}^i\Delta_z)}{\partial x^2} + {}^iM_z \frac{\partial^2 ({}^i\Delta_y)}{\partial x^2} \right]. \tag{2}$$

Herein, *b* is the width of the adhesive layer and $\overrightarrow{{}^i\Delta}$ is the displacement vector of the *i*-th support location.

In the proposed test-setup, the specimen support is realized in a way that four components of force and one component of moment vanish to zero,

$${}^1F_x = {}^1F_z = {}^2F_x = {}^2F_z = 0 \; and \; {}^1M_z = 0. \tag{3}$$