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Investigating the influence of material non-linearity in the fracture properties of ductile adhesives submitted to mixed-mode loading

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ABSTRACT

The influence of the mechanical behaviour of a crash optimized adhesive in its fracture properties at different mode ratios in the plane I/II is discussed. The adhesive under investigation has been previously studied by means of standardized TDCB (Tapered Double Cantilever Beam) and MMB (Mixed Mode Bending) tests. In the current study, these tests were modelled numerically considering first the linear elastic case for the adhesive and secondly its non-linear behaviour using a spectral viscoelastic law. The simulations for the non-linear case have been performed under plane strain and plane stress assumptions. Crack initiation and propagation were simulated using cohesive zone modelling. The non-linearity of the adhesive material had minor effect in its fracture response under mode I loading. However, considerable impact has been observed while moving towards the mode II load case, where the fracture energy was calculated almost constant and equal to the one at mode I.

1. Introduction

The use of adhesively bonded joints in modern industry greatly enlarges the design solutions in the increasing demands for competitive, more environmental friendly and less energy consuming systems. Adhesives are being implemented in several constructions in automotive, marine and/or renewable energy systems. One of the parameters required to identify the strength of adhesive joints is the critical strain energy release rate or fracture toughness G_C, which represents the potential energy released when a crack propagates in a solid medium over a unit area. G_C is considered to be a joint property, and its measurement can be realized using principles based on the fracture mechanics theory [1]. In fracture mechanics, the load state at the end of the crack tip can be decomposed into: the tensile opening mode (Mode I), the in-plane shear mode (Mode II) and the anti-plane shear mode (Mode III). For the general 3-dimensional case, $G_C = G_I + G_{II} + G_{III}$ (the energy release rates for mode I, II and III load cases respectively). It is obvious that under pure mode loading, G_C represents the fracture toughness G_{IC}, G_{IIC} or G_{IIIC}. For the needs of the current research, only the fracture behaviour in the mixed mode I/II plane will be considered.

The knowledge of full fracture envelopes in the mixed mode I/II plane for an adhesive is of great industrial interest. In addition, G_C can also be used as input in cohesive zone models to predict crack propagation [2]. The extensive work

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performed by many research teams has led to the establishment of two standardized tests to measure G_{IC} [3–5]: the DCB (Double Cantilever Beam) and the TDCB (Tapered Double Cantilever Beam). However, this is yet not the case for the other solicitation types in the mixed mode I/II plane. Here, standardized tests mainly developed for fibre reinforced polymer composites have been implemented, such as the MMB (Mixed Mode Bending) test [6]. A literature overview of fracture tests that can be adapted to adhesively bonded structures is given in [7]. Other non-standardized test geometries like the Arcan fixture [8] can also be used [9–11].

The evaluation of all previous tests is mainly based on the LEFM (Linear Elastic Fracture Mechanics) theory, neglecting the plasticity of both the substrates and the adhesive material. This has been found to work well for brittle adhesives [12]. On the contrary, for the case of considerable plasticisation, the LEFM can lead to erroneous results [13,14]. It is therefore that methodologies based on Elastic Plastic Fracture Mechanics (EPFM) have been developed by many research teams [15–20], which make use of the contour integral method [21]. In some of these studies, analytical formulas based on beam theory to calculate the fracture resistance of the adhesive are proposed, which take into account the plasticity of the substrates.

In this paper, the fracture properties of the crash optimized adhesive SikaPower®-498 (which has a strong ductile mechanical behaviour [22]) are examined. This type of adhesive shows a large zone of micro-fibrillation ahead of the crack tip, and methodologies based on LEFM or EPFM [11,23,24] agree that its fracture energy increases considerably when heading towards the mode II load case. The aim of the present work is to evaluate the effect of the non-linear mechanical behaviour of the SikaPower®-498 adhesive in the determination of its fracture energy in the mixed mode I/II plane. A quick review of the results obtained in the previous study [23] using the "classical" methodology based on LEFM is given in Section 2. Section 3 shows the Finite Element (FE) model which was used to identify the energy release rate at the different mode ratios, and explains how damage initiation and propagation were simulated by means of the Cohesive Zone Model (CZM) approach. A comparison between the "classical" method and the FE results is presented in Section 4, where the influence of the non-linearity of the adhesive under investigation in its fracture properties is also discussed.

2. Overview of the experimental procedure and LEFM results

The fracture behaviour of the SikaPower®-498 adhesive was studied in [23] using the TDCB test according to the ISO standard [4] and the MMB test according to the ASTM standard [6]. A schematization of the principles of the two methodologies is given in Fig. 1. All experiments were performed at ambient temperature, at a constant crosshead speed of 0.5 mm/min. The adhesive layer thickness was chosen at 0.5 mm. The initial crack length a_o was set at 70 mm and 35 mm for the TDCB and MMB tests respectively. Concerning the MMB test in particular, loading blocs instead of hinges (shown in Fig. 1b) were used to attach the specimens to the apparatus. Four values of the mode ratio G_{II}/G_C were examined. The MMB apparatus was configured according to the ASTM standard [6] (see Table 1).

The experimental results in [23] were evaluated under linear elasticity assumption for the adhesive and the substrates. The Irwin-Kies equation [25] was used for the TDCB test and the contour integral method [21] for the MMB test. In order to minimize the effect of the plasticity of the adherents on the experimental results, the raw materials of the TDCB and MMB substrates were chosen to have the mechanical properties given in Table 2.

This analysis showed that the evolution of the fracture toughness of the SikaPower®-498 adhesive follows the Benzeggagh-Kenane [26] failure criterion in the mixed-mode I/II plane, which has been identified in [23] as

$$G_C = 2.93 + 8.10\left(\frac{G_{II}}{G_C}\right)^{1.24} \tag{1}$$

According to (1), under pure mode II load: $G_C = G_{IIC} = 11.03$ N/mm, thus increased by a factor almost equal to 4 comparing to G_{IC} which was found equal to 2.93 N/mm. A similar tendency for the fracture energy of the same adhesive under pure mode I and II loads has been also observed by Marzi et al. [24]. The experimental findings of Goglio et al. [27] suggest equivalent behaviour for another type of adhesive under the linear elasticity assumption.

3. Finite element modelling

3.1. Overview of the cohesive model approach

In order to examine the influence of the mechanical behaviour of the SikaPower®-498 adhesive in its fracture properties, both of the previous TDCB and MMB tests were modelled numerically using the Abaqus™ Ver.6.14 software. Progressive damage and failure were simulated by means of the Cohesive Zone Model (CZM) approach [2,28]. The use of the CZM methodology requires first the definition of the crack propagation path. For the model presented here, this path was set in the middle of the adhesive layer thickness and was discretized by a thin layer (1 μm thick) of cohesive elements. This should be a realistic scheme to simulate crack initiation and propagation in the TDCB and MMB tests for the adhesive under investigation according to the overall dimensions of the specimens [23]. More information on how to construct the CZM model according to the overall dimensions of the structure can be found in [29]. In CZM, all inelastic effects due to the presence of the crack are confined to an area called Damage Process Zone (DPZ). Physically, the DPZ corresponds to the area of micro-fibrillation ahead of the crack tip.