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Instrumented end notched flexure – Crack propagation and process zone monitoring Part II: Data reduction and experimental

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ABSTRACT

A mode II instrumented end notched flexure three point bending (ENF) adhesion test is described. The adhesive joint consists of two aluminium alloy (AW7075-T6) plates bonded with a structural epoxy adhesive (Hysol® EA 9395™). Strain gauges are attached to the outer surface (backface) of the substrates in the lengthwise direction to measure local surface strain during crack propagation. Simultaneously, load/displacement measurements are performed. Two cases were investigated. The first was static: the joint was loaded below the crack propagation threshold. In the second, applied load above the threshold led to crack propagation. The former test confirmed the predicted load transfer mechanism between bonded and unbonded parts of the joint. In the second case, the crack front process zone was revealed *in situ* in mode II, we believe for the first time. These new results permitted validation of simple or refined analytical/numerical models including those of the cohesive zone. In addition, the backface strain gauge monitoring technique exhibited unexpected mode I contributions, quantitatively evaluated. Finally, *R*-curves are presented, as estimated with various standard models and compared with that postulated, where the process zone is accounted for.

1. Introduction

Adhesively bonded structures are usually designed using either strength or fracture failure criteria (Banea and da Silva, 2009). While strength is relatively easy to evaluate with standard tests on bulk adhesive specimens, there is no consensus on the validity of transposing such data when considering bonded joints. Singular mechanical fields are produced near the edge of bonded specimens which substantially modify the local stress state and lead to crack onset (Erdogan, 1965; He and Hutchinson, 1989). Any structural imperfections in the bondline, such as voids, microcracks, *etc*., which are inherent in the adhesive joining technique, could produce similar behaviour. Apart from the crack onset problem, it is now commonly, but not unanimously, accepted that the failure of a bonded joint may be described as an unstable crack growth phenomenon amenable to study using linear elastic fracture mechanics formalism. Failure depends on intrinsic parameters of the given system *viz*. fracture energy, G_c, of the bondline, interface(s) and/or substrate(s) (Leguillon, 2002). The double cantilever beam (DCB) test was proposed by the adhesion community to evaluate G_{Ic}, in the case of mode I fracture (Mostovoy et al., 1967). In its classic version, the test piece is composed of two, geometrically and physically similar, beams/plates bonded with an adhesive. The specimen is loaded in opening mode to measure G_{Ic}, as recommended by the (ASTM D3433-99 and D3762-03) standards. Also, mode II (in-plane): G_{IIc}, and mode III (anti-plane): G_{IIIc}, loading have been studied even if considered of less interest since supposed less critical.

Cleavage loading is certainly the most dangerous separation mode for a bonded joint and, in practice, assemblies are designed to sustain shear loads which are associated to the in-plane mode II (Kuczmaszewski, 2006). The strength in such a configuration is evaluated from the popular lap shear joint (LSJ) test (ASTM D3165-07, D2919-01, D3166-99). Although this test was initially intended to evaluate shear *strength*, it is now suggested that this set-up could be treated as a mixed mode, fracture mechanics problem since both peel and shear peak stresses are produced on both sides of the overlap (Goland and Reissner, 1944; Kendall, 1975; Tsai and Morton, 1994). New experimental designs are required for proper evaluation of mode II failure. Using standard DCB specimen geometry, various fixing features and loading configurations have been proposed. Among them, the most frequently used are

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three-point bending end-notched flexure (ENF) (Barrett and Foschi, 1977), four-point bending end-notched flexure (4-ENF) (Martin and Davidson, 1999), end-loaded split (ELS) (Wang and Vu-Khanh, 1996) and tapered end-notched flexure (TENF) (Blackman et al., 2005). Due to the simplicity of the test protocol and sample preparation, the end-notched flexure test is often used. The ASTM task group has conducted a round robin test programme using the ENF specimen as a prelude for the development of an ASTM standard for measuring mode II interlaminar fracture toughness in composites (Mall and Kochar, 1986). This now appears as a draft for a future standard (Davidson and Sun, 2006; ASTM WK22949). In the three point bending configuration, the joint is simply supported by two rollers and loaded in the middle of the span by a third one. The specimen is partially cracked (or initially unbonded) with the crack tip being located between a side and the mid-span roller. If symmetric specimens are considered, pure mode II is expected at (de Moura et al., 2009). Nevertheless, a major inconvenience of the ENF test is that the crack progresses towards the maximal bending moment (under the mid-span) so that the test is unstable (Carlsson et al., 1986). Indeed, the three point bending ENF test is only conditionally stable, even in the case of a displacement controlled experiment. Carlsson et al. (1986) investigated stability conditions in the case of a rigid adhesive layer and found that 'stable' crack growth occurs when the initial crack length (a_0) is larger than a critical value, $a_{0c} \approx 0.35\ L$ ($2L$ = span). A similar formula was proposed by Chai and Mall (1988) when the load is not applied at the mid-span. In the work of Mall and Kochar (1986), the effect of friction between the interfaces was also analysed, using a finite element method. The authors conclude that the frictional effect is negligible when the crack length is greater than a quarter of the span.

Many analytical and numerical analyses have been proposed for finer evaluation of fracture energy. Current practices exploit only macroscopic quantities, such as applied force and imposed displacement, to derive crack position and fracture energy. Data reduction methods are based on simple beam theory (SBT) models, which have been progressively improved by the use of correction coefficients calculated from finer analysis and/or numerical methods. Today, these fracture mechanics tests are also used as a reference for the identification of complex interface models. Alfredsson (2004), Corleto and Hogan (1995) and Ouyang and Li (2009) compared the response of fracture specimens in the case of an interface having elastic, elastic–plastic or nonlinear behaviour. However, the macroscopic, experimental data remain too poor for reliable identification of the complex interface model (Alfano, 2006). More local crack tip opening measurements with J based approach analysis have been proposed for cohesive zone model (CZM) identification (Sørensen and Jacobsen, 2003).

The instrumented beam technique is a complementary method to investigate the cohesive force distribution along the process zone. This protocol has been introduced for mode I and mode III fracture tests (Budzik et al., 2011a,b; Jumel et al., 2011). It consists of attaching a series of resistive strain gauges along the substrates to infer the local cohesive force with these distributed 'load cells'. This also improves the monitoring of crack propagation during the test.

In this paper, the existing methods for analysing ENF three point bending are applied to a mode II fracture test on aluminium specimens bonded with a structural epoxy adhesive. Application of the backface strain monitoring technique (Zhang et al., 1995) to the ENF specimen is also presented. First, simple beam and corrected beam theories are used to evaluate crack propagation kinetics and energy release rate. These results are compared with those obtained from measurements of shear displacement at the edge of the sample, as found with a digital image correlation technique. Finally, the Timoshenko beam on elastic Pasternak type foundation model (two-parameter elastic interface), whose derivation is presented in detail elsewhere (Jumel et al., 2012), is used for finer analysis of the process zone in the vicinity of the crack front, and to improve the evaluation of fracture energy. Theoretical results are in good agreement with experimental data.

This methodology demonstrates its value for refined experimental investigation of cohesive forces in the ENF specimen during fracture tests. The new technique proposed should allow better identification of theoretical interface models such as CZM, based on enriched experimental data.

2. Experimental

2.1. Materials

The end notched flexure test pieces consist of two aluminium alloys plates bonded with a structural epoxy adhesive. Aluminium alloy (Al–Zn) AW7075 – T6 plates were 5 mm thick (t), 25 mm wide (w) and 210 mm long. The Young's modulus of the plates, as evaluated from three point bending was 70 ± 3 GPa. Before bonding, plates were grit blasted using 320 μm (average diameter) SiC particles and subsequently cleaned in an ultrasonic bath (35 kHz) in ethanol for 15 min. Plates were bonded with an epoxy-based adhesive, Hysol® EA 9395™ supplied by Henkel (Henkel Corporation Aerospace Group, Bay Point, CA 94565 USA). The curing agent for this adhesive is based on tetraethylenepentamine (TEPA). As recommended in the supplier's documentation, a 100:17 mixing weight ratio (resin-to-crosslinker) was used for preparation of the adhesive. Both components were hand-mixed with a spatula until a homogeneous aspect was obtained. Substrates were bonded along 160 mm. Two pieces of 1 mm diameter steel wire were inserted between the plates of the specimen, one at each end, in order to obtain constant bondline thickness. A similar configuration was used by Leffler et al. (2007). The distance between the wires was 180 mm, which also corresponds to support span. Curing was performed for one day at 23 °C under 10 bars pressure, and subsequently for 90 min at 66 °C without additional pressure, subsequent cooling being in the oven. A 1 mm thick (t_a) homogeneous bondline was obtained, as controlled with an optical microscope. The adhesive Young's modulus (E_a) was evaluated using a dynamic-mechanical analyser (Metravib + 150, 01 dB-Metravib, Limonest, France) to test dumbbell adhesive specimens of 12 mm gauge length (experimental conditions: 1 Hz, 5 μm dynamic displacement). At ambient temperature, E_a was found to be 4 ± 0.2 GPa.

Three ENF test samples were prepared and tested to evaluate the reproducibility of the results in terms of force–displacement curves. One specimen was fully instrumented with strain gauges.

2.2. End notched flexure (ENF) test

A schematic representation of the ENF test is shown in Fig. 1.

In the standard test configuration, evaluation of fracture data is based on global force–displacement measurements. The ENF sample was loaded with a force, P, normal to the bondline, applied at

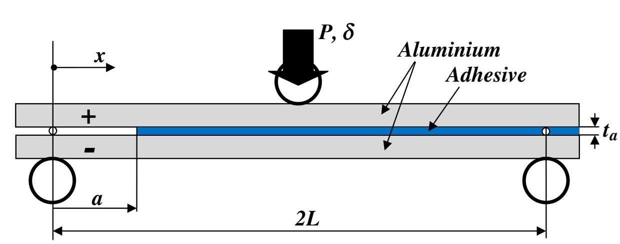

Fig. 1. Schematic representation of the joint geometry and test principle.