Theoretical and Applied Fracture Mechanics 74 (2014) 209–221

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

journal homepage: www.elsevier.com/locate/tafmec

Analytical and experimental investigations of crack propagation in adhesively bonded joints with the Mixed Mode Bending (MMB) test Part I: Macroscopic analysis & Digital Image Correlation measurements

N. Ben Salem [a,b,c,d], J. Jumel [a,b,c,*], M.K. Budzik [a,b,c,d,1], M.E.R. Shanahan [a,b,c], F. Lavelle [d]

[a] Univ. Bordeaux, I2M, UMR 5295, F-33400 Talence, France
[b] CNRS, I2M, UMR 5295, F-33400 Talence, France
[c] Arts et Metiers ParisTech, I2M, UMR 5295, F-33400 Talence, France
[d] French Space Agency (CNES) – DLA, 52 rue Jacques HILLAIRET, 75612 Paris Cédex, France

ARTICLE INFO

Article history:
Available online 11 June 2014

Keywords:
Bonded joint
Mixed Mode Bending test
Digital Image Correlation
Mixed mode fracture

ABSTRACT

Crack propagation resistance of Hysol®EA9321 toughen epoxy paste under mixed mode loading has been characterized using Mixed Mode Bending set-up. During the crack propagation stationary value of the fracture energy is measured. For finer investigation of the experiment, a phenomenological model consisting of two Timoshenko beams joined with a two parameters elastic foundation is derived to estimate the cohesive stresses distribution along the bondline. Digital Image Correlation measurements are performed together with classical macroscopic force versus deflection measurements which are compared with the displacement field predicted with the model. The evolution of the displacement field in the process zone evidences nonlinear behaviour of the adhesive prior the crack starts to propagate. However, the overall sensitivity of these experimental data is not sufficient to allow precise identification of the interface separation law.

1. Introduction

Fracture mechanic and cohesive zone models are now frequently used for the design of composites [51] and bonded structures [50]. These failure criteria are sometime found more reliable and easier to implement than stress based analysis [29,8]. Nevertheless, the development of complex systems and the need for fine prediction of damage initiation and evolution under severe conditions increase the complexity of the existing models and lead to the development of more demanding characterization techniques.

Delamination or debonding resistance is generally studied using specimens derived from the Double Cantilever Beam (DCB) proposed by Rippling and Mostovoy in the 60s [41]. This experiment was designed for measuring the Strain Energy Release Rate (SERR) of a bondline in between two flexible adherends. The fracture energy is derived from Griffith's theory [23] using analytical formulae of the specimen compliance which are obtained with simple beam bending analysis. Such approach is now described in the ASTM D5528 [5] standard, where numerous methods are proposed to refine the analysis of the experimental data and to evaluate the influence of experimental artefacts or of the specimen specific behaviour.

The DCB test is limited to the evaluation of crack propagation resistance under mode I loading which is considered to be the most critical one. However, to characterize the interface behaviour under more realistic loading conditions, numerous experimental test set-ups are now available to apply mode II, mode III or mixed mode conditions [20]. The most popular for mode II testing are the End Loaded Split (ELS) [47] and the End Notched Flexure (ENF) [54] configurations, while Edge Crack Torsion (ECT) [30] is recommended for mode III. To characterize the delamination in composite materials under mixed I/II conditions, Reeder and Crews introduce the Mixed Mode Bending (MMB) apparatus in 1988 [39], this test is now standardized in the ASTM D6671 [6]. Based on simple beam analysis, a simple mode partitioning analysis, resembling Bueckner principle [19], is proposed which cannot account for potential coupling between the two modes. Again, numerous analysis [13,33,48] and models [15,37,38,11] are regularly proposed to improve the traditional data reduction

* Corresponding author at: Univ. Bordeaux, I2M, UMR 5295, Bat A4, 351 cours de la libération, F-33400 Talence, France. Tel.: +33 540002296.

E-mail address: julien.jumel@u-bordeaux1.fr (J. Jumel).

[1] On leave from Technical University of Gdansk, Faculty of Mechanical Engineering, Dept. of Material Engineering and Welding, Narutowicza 11/12, 80-952 Gdansk, Poland.

http://dx.doi.org/10.1016/j.tafmec.2014.05.006
0167-8442/

techniques with the use of correction coefficients to take into account various types of artefacts [53] such as large displacement effect or roller contact position change.

The same experimental configurations are also used for the identification of more complex cohesive zone models [3,7,14,43,36]. In this case the parameters of the models are generally determined using numerical inverse identification methods trying to superimpose the results of numerical simulations on the measured macroscopic force versus displacement evolutions. Few methods have been specifically developed for "direct" measurement of the interface separation law which can be characterized with the $J(\delta)$ method proposed by Sorensen and Jacobsen [44,45,25] or using backface strain monitoring technique [9,16,46]. Finally, several authors have used Digital Image Correlation (DIC) and/or developed specialized image analysis tools to evaluate the evolution of cohesive force distribution at the vicinity of a crack from a series of images showing the crack propagation [52,55,31,22,1,32]. These methods are generally used in complex loading configurations to evidence highly heterogeneous strain/stress fields but no simple analysis protocol have been proposed for the experimental data reduction in standard configuration.

In this work, we derive a complete analysis of a MMB test performed on specimen made with two aluminium slabs bonded with Hysol®EA9321 toughen epoxy adhesive. Both, standard force versus displacement and Digital Image Correlation measurements are derived. A two Timoshenko beam bonded with a two parameter elastic interface model is proposed for the evaluation of specimen and bondline deformation and modes I and mode II energy release rate. A systematic data reduction protocol is proposed to separate the contribution of both fracture modes. The comparison between theoretical and experimental results points out the limit of the standard analysis technique for the MMB test since satisfying agreement is found between experimental results and the theoretical ones obtained with a purely linear elastic model while nonlinear adhesive behaviour is expected. Therefore, it is suggested that such a protocol is not appropriate for precise determination of interface separation law.

2. Experimental

2.1. Materials

The tested specimen is made with two identical aluminium–zinc alloy AW7075-T6 adherends bonded with a two parts toughen epoxy paste Hysol®EA9321 (Henkel Corporation Aerospace Group, Bay Point, CA 94565, USA). To prevent from any irreversible strain in the adherend during the experiment, t = 5 mm thickness is chosen. The specimen is held in the tensile testing machine with end blocks directly machined in the aluminium adherend. The specimen length is 200 mm and its width is w = 12.5 mm along the bonded part. Other specimen dimension are indicated in Fig. 1.

Prior bonding, the surfaces of the two adherends were grit-blasted manually with 200 μm grain-size alumina particles (Al_2O_3 white corundum F80: Abralis) using a sandblasting (Guyson Formula 1400, 0.4 MPa pressure) machine until the surface appeared uniform. Then, the plates were washed in an ultrasonic bath of ethanol for 10 min with a 35 kHz frequency and then rinsed with acetone and dried with hot air gun. Subsequently a Phosphoric Acid Anodisation was effected following ASTM D3933 recommendation. Finally, an adhesion primer was deposited on the surface consisting of a 1% solution of 3-mercaptopropyltrimethoxy silane in deionised water solution. This silane layer was heated at 92 °C for 1 h to allow solvent evaporation.

Hysol®EA9321 is a two-component thixotropic epoxy paste adhesive used by the aerospace industries for structural bonding. This adhesive is obtained by mixing an epoxy resin derived from bisphenol A, with DETA (diethylenetriamine) curing agent which contains an aluminium oxide. The weight ratio between resin and the crosslinking agent is (100:50), as recommended in the supplier's documentation. The two components were hand mixed using spatula until a uniform compound was observed. Nevertheless, this manual procedure entrapped a large amount of porosities as seen on image of the adhesive microstructure presented in Fig. 2(a).

The aluminium plates were placed in an alignment jig before the adhesive was applied. Antiadhering PTFE spacers were used to obtain a 350 μm ± 30 μm thick adhesive layer as controlled with an optical microscope. The adhesive paste is manually deposited on the surface of the two adherends which are then pressed together in the alignment jig under 1 MPa pressure during 12 h. To complete the crosslinking the specimen is finally placed in an oven during 90 min at 82 °C. Before testing, a "natural" crack was created by inserting a wedge between both adherends. Such forced crack propagation was arrested with a clamping collar, giving an initial crack length, a_0, of *ca.* 50 mm.

The aluminium Young's modulus, E = 71 GPa, and yield stress, σ_y = 503 MPa, are determined with a three point bending test. Adhesive properties are also determined on moulded dumbbell tensile test specimen and using Dynamics Mechanical Analysis (DMA). 121 °C glass transition temperature was found with 1 Hz periodic loading. From the tensile tests presented in Fig. 2(b), Ea = 3 GPa was found for adhesive Young's modulus and *ca.* 52.5 MPa for the adhesive strength.

2.2. Mixed Mode Bending test

For the present experiment, we used the modified MMB apparatus recommended by Reeder and Crews [40] which minimize the geometrical nonlinearity due to large rotation of the lever. The experimental set-up is presented in Fig. 3(a). As mentioned previously, the piano hinges that are generally used to hold both sides of the specimen are replaced by two end blocks that are directly machined in the adherends. Additionally, two LVDT displacement

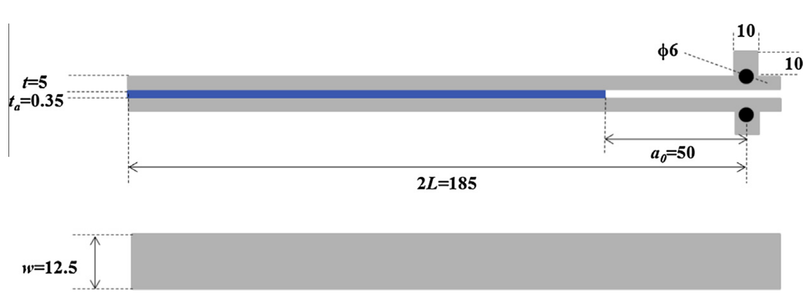

Fig. 1. Specimen geometry and dimensions.