International Journal of Adhesion & Adhesives 51 (2014) 148–158

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

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

On the experimental mixed-mode failure of adhesively bonded metallic joints

G. Stamoulis [a,*], N. Carrere [a], J.Y. Cognard [a], P. Davies [b], C. Badulescu [a]

[a] Laboratoire Brestois de Mécanique et des Systèmes (EA4325), ENSTA-Bretagne, 2 rue François Verny, 29806 Brest Cedex 9, France
[b] Materials & Structures Group, IFREMER, Centre de Brest, France B.P. 70, 29280 Plouzané Cedex, France

ARTICLE INFO

Article history:
Accepted 10 March 2014
Available online 18 March 2014

Keywords:
Fracture toughness
Linear Elastic Fracture Mechanics (LEFM)
Adhesive bonding
Finite Element Analysis (FEA)
Failure criterion

ABSTRACT

The use of adhesively bonded structures is widespread in various engineering fields, as they provide many advantages over other conventional types of mechanical joints. In this study, we use a crash optimized, single-component epoxy adhesive (SikaPower®-498 made of a rigid epoxy matrix containing soft, tough polymer inclusions that provide additional ductility to the adhesive layer) at a constant layer thickness of 0.5 mm to bond metallic substrates. We investigate its fracture properties under mode I and mixed-mode I/II loadings, in order to obtain the full fracture envelope. Mode I loading has been performed using the ISO 25217 standard: the substrates were designed according to the TDCB (Tapered Double Cantilever Beam) geometry, and the fracture toughness G_{IC} has been calculated by means of the ECM (Experimental Compliance Method). Mixed-mode I/II loading has been applied using the MMB (Mixed Mode Bending) experimental fixture described in the ASTM D6671 standard. The fracture toughness G_C has been calculated via Finite Element Analysis and mode partitioning has been determined according to the methodology described in the standard. The mixed mode fracture behavior measured using the previous two methodologies shows that the adhesive seems to follow the Benzeggagh–Kenane failure criterion (expressed in 2D).

1. Introduction

Adhesion technology is the most popular solution for many joining situations. It provides several advantages over other more conventional types of mechanical connections, such as more uniform stress distribution along the bonded area, the ability to bond dissimilar materials and an improved resistance to corrosion. It is also a key option for automotive and aeronautic industries to reduce the weight of modern means of transport. This continuous use of adhesives makes it imperative to predict the durability of adhesively bonded structures. To achieve this target, most of the researchers use concepts coming from the fracture mechanics. In fracture mechanics rupture is assumed to occur when a crack in a solid medium extends over a unit area. This crack extension is related to a net decrease in the stored potential energy of the loaded system: the critical strain energy release rate or fracture toughness (G_C, the term rate refers to the change in potential energy with the crack area). Based on the state at the end of the crack tip, three loading modes can be distinguished: mode I (the tensile opening mode), mode II (the in-plane shear mode) and mode III (the anti-plane shear mode).

Two substrate geometries have been widely employed in measuring the fracture toughness of the adhesive under pure mode I loading (G_{IC}): the DCB (Double Cantilever Beam) and the TDCB (Tapered Double Cantilever Beam). Their origins are found in the early work of Ripling and coworkers [1,2]. This work led to the publication of a standard (ASTM D3433 [3]). Later on, the tests have been reviewed [4,5] and a new standard has been published (ISO 25217 [6]). In both [3,6] standards, G_{IC} is calculated using the LEFM (Linear Elastic Fracture Mechanics) principles, and in particular the Irwin–Kies equation [7]

$$G_C = \frac{F^2}{2b}\frac{dC}{da} \tag{1}$$

where G_C is the fracture toughness for the case of a linear-elastic solid (it is obvious that $G_C = G_{IC}$ for the pure mode I loading case), F is the applied force, b is the specimen width and $dC/d\alpha$ denotes the rate of change of the system compliance C with respect to the crack length α. The calculation of G_C using Eq. (1) depends on the proper measurement of $dC/d\alpha$. Both [3,6] standards propose analytical and experimental methods to perform this measurement.

---

* Corresponding author. Tel.: +33 (0)298348749; fax: +33 (0)298348730.
E-mail address: georgios.stamoulis@ensta-bretagne.fr (G. Stamoulis).

http://dx.doi.org/10.1016/j.ijadhadh.2014.03.002
0143-7496/© 2014 Elsevier Ltd. All rights reserved.

Contrary to the pure mode I loading case, measuring the fracture toughness of adhesives under pure mode II loading (G_{IIC}) is a significantly more complex task, and is still not standardized. Tests have been developed mainly for fiber-reinforced polymer composites and have been implemented to study the mode II fracture of structural adhesives. The most popular of these are the ENF (End-Notched Flexure) and the ELS (End-Loaded Split) tests. Analytical expressions to determine G_{IIC} of an adhesive using the ENF test are given by Alfredsson [8] and Leffler et al. [9]. Blackman et al. [10] applied the ELS test to measure the G_{IIC} of an adhesive using carbon-fiber-reinforced composite adherends. In 1999, Martin and Davidson [11] presented a different version of the ENF test, the 4-point ENF test, for measuring the G_{IIC} fracture toughness of laminated composites. This test has also been applied to adhesive joints. Similarly to the pure mode II load case, the fracture characterization of adhesives under pure mode III loading is also very complicated to perform. It has been very little studied by researchers mostly due to the lack of industrial interest for this failure mode. In most cases the mode III fracture toughness (G_{IIIC}) has been considered as equal to the G_{IIC} fracture toughness. Examples of test methodologies for pure mode III fracture characterization of adhesives are given in [12] (the Notched Torsion Test) and by Chai [13].

The calculation of the fracture toughness of the adhesive layer under all three loading modes often depends on the experimental measurement of the crack length. This is very difficult to accomplish due to the nucleation of micro-cracks in the fracture zone formed ahead of the crack tip. Some alternative methods to overcome this problem have been developed involving the experimental measurement of other quantities [14,15]. In the 1980s, cohesive zone models have also been introduced as an alternative to predict the strength of adhesively bonded structures [16]. Using cohesive elements, the adhesive layer can be modeled as a material volume with its constitutive parameters represented by a cohesive law. Cohesive elements have often been used together with the J-contour integral method to calculate the fracture toughness of adhesively bonded joints. The J-contour integral was first introduced by Rice [17] and is the fundamental principle of Elastic–Plastic Fracture Mechanics. It is given by

$$J=\int_{\Gamma}\left(W dy-\boldsymbol{T}\frac{\partial \boldsymbol{u}}{\partial x}\right) ds \tag{2}$$

where Γ is an arbitrary counterclockwise path around the crack tip starting at the lower crack face circumscribing the crack tip and ending at the upper face, $W=\int \boldsymbol{\sigma}\, d\boldsymbol{\varepsilon}$ is the strain energy density with $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ being the stress and strain tensors, respectively, $\boldsymbol{T}=\boldsymbol{\sigma} n$ is the traction vector with $\boldsymbol{n}$ being the unit vector normal to the contour Γ, and ds is the length increment along the contour Γ. Expression (2) implies that the coordinate system is oriented with the x-axis pointing to the direction of the crack propagation. In the case of a linear elastic material $J=G_C$, where G_C is the fracture toughness calculated from the Irwin–Kies equation (1).

The objective of the present study is to propose a mixed-mode energetic failure criterion for adhesively bonded metallic substrates derived from experimental measurements. The determination of such criteria for structural adhesives is of particular industrial interest. Indeed, if the mixed-mode energetic failure criterion of the adhesive is known, the strength of the metallic joint can be predicted by equating the energy release rate to the toughness at the appropriate phase angle. Chai [13] has proposed a general form of a power law [18] mixed-mode energetic failure criterion for adhesively bonded structures, which when neglecting the mode III failure takes the form

$$\left(\frac{G_I}{G_{IC}}\right)^m+\left(\frac{G_{II}}{G_{IIC}}\right)^n=1 \tag{3}$$

where G_I and G_{II} denote mode I and mode II strain energy release rates, respectively, after mode partitioning and m, n are material parameters to be determined. The power law criterion has been used by many researchers as a mixed-mode energetic failure criterion assuming either $m \neq n$ [19] or $m=n$ [20–23], along with different joint geometries. A meso-mechanical model to show how mixed-mode loading influences the fracture characterization of thin adhesive layers is proposed by Salomonsson [24].

In the present work, we have chosen to bond metallic substrates with the crash-optimized single-component epoxy adhesive SikaPower®-498 (made of a rigid epoxy matrix containing soft, tough polymer inclusions that provide additional ductility to the adhesive layer). Crash-optimized adhesives are of particular interest due to their high fracture resistance values. The SikaPower®-498 adhesive has also been investigated by Marzi et al. [25] who used metallic adherends to evaluate the influence of its layer thickness on the fracture toughness under pure mode I and pure mode II loadings. For the case of mode I loading, we chose the TDCB substrate geometry. This has been designed according to the general directions given in the ISO 25217 [6] standard. The advantage of this geometry is that it enables the fracture toughness G_{IC} to be measured without explicitly requiring the crack length measurements. The TDCB experiments have been evaluated using the Irwin–Kies equation (1) together with the Experimental Compliance Method (ECM) [6]. The mixed-mode I/II fracture behavior has been studied by means of the Mixed Mode Bending (MMB) test. This test has been standardized for composite materials (ASTM D6671 [26]). We used the experimental setup proposed in the standard, which was initially developed by Crews and Reeder [27] in 1988. It was designed to study crack growth behavior of composites under mixed-mode I/II loading. However, it can be easily adapted to adhesively bonded joints (Fig. 5). Its particular advantage is that a range of mixed-mode I/II load cases can be studied without having to change the specimen geometry. This can be achieved simply by changing the lever arm c (Fig. 5a). Thus, the MMB test fixture is particularly suitable to obtain the full fracture resistance envelope. It has already been used in the past to study the resistance of adhesively bonded composites [28]. To calculate the adhesive fracture toughness, we developed a Finite Element Model of the experiment using the Abaqus™ Ver.6.10-EF1 software. Mode partitioning has been performed according to the methodology described in the ASTM D6671 [26] standard. The results from the TDCB and MMB tests can be used to obtain the full mixed-mode I/II fracture envelope of the adhesive under investigation.

2. Experiments and discussions

The experiments have been carried out using an Instron tension machine (model 5566). All TDCB and MMB specimens were loaded at a constant crosshead speed of 0.5 mm/min. The TDCB substrates (Fig. 1a) have been fabricated out of Aluminum 2017A. Their width value has been set at 10 mm. It was chosen as a compromise between the need to create plane strain conditions in the center of the joint width during the test, and to ensure that the adherends behave like beams rather than plates. Marzi et al. [25] used TDCB steel substrates of 5 mm of width to test the SikaPower®-498 adhesive under pure mode I loading. However, the geometry of the substrates they used was based on different standards [3,29]. The dimensions of the MMB specimens are shown in Fig. 2. The MMB substrates were fabricated out of a high limit of elasticity steel (Raex 450). Their dimensioning has been performed so that, after bonding, the specimen size is as close as possible to the directions given in the ASTM D6671 [26] standard for the composite test specimens geometries. In order