International Journal of Solids and Structures 81 (2016) 110–116

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

On the validity of linear elastic fracture mechanics methods to measure the fracture toughness of adhesive joints

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ARTICLE INFO

Article history:
Received 16 March 2015
Revised 9 October 2015
Available online 2 December 2015

Keywords:
Fracture toughness
Experimental methods
Adhesive joints
J-integral

ABSTRACT

The analysis of large-scale fracture processes, such as those involved in the fracture of adhesive joints, falls outside the scope of Linear Elastic Fracture Mechanics (LEFM). However, experimental data produced in testing adhesive joints are usually reduced with LEFM methods. The consequent error has not yet been evaluated. In this work, an experimental characterization under pure-mode loading of an FM-300 epoxy film adhesive is presented for different adhesive and adherend thicknesses. The experimental data is analyzed using both LEFM-based and *J*-integral-based data reduction methods in order to study their suitability to analyze adhesive joints. LEFM-based data reduction methods are shown to entail a relevant deviation in the fracture toughness results that heavily depends on the size of the fracture process zone. It is concluded that LEFM methods are not suitable to characterize adhesive joints and that their use is restricted, at best, to the measurement of initiation values. The effect that the adhesive and the adherend thicknesses have on the fracture toughness and the R-curve of the material is studied. Adhesive and adherend thicknesses are shown to have a significant influence on the bond fracture toughness and the source of such influence is discussed.

1. Introduction

The use of mechanical fasteners in the assembly of composite structures creates areas of high stress concentration that, in conjunction with the low bearing capacity of composite materials, result in structurally inefficient joints. Conversely, adhesive joints are able to redistribute the loads so that stress concentrations can be lowered or suppressed. At the same time, the use of adhesive joints results in higher strength-to-weight ratios, better fatigue behavior and a reduction in the manufacturing processes that contributes to both weight and cost savings (Vinson, 1989). Despite their advantages over mechanical fasteners, the reliability of adhesive joints is still limited due to their sensitivity to manufacturing flaws and the difficulties that arise in their inspection, characterization and analysis.

The mechanical properties of a bulk adhesive have been proven hard to correlate with the behavior of a thin adhesive layer because of its confinement between two adherends (Adams and Coppendale, 1979). The plasticity of the adhesive layer is constrained as is its stress field, which has a direct impact on bond toughness (Daghyani et al., 1995; Kinloch and Shaw, 1981; Suo et al., 1992). Pardoen et al. (2005) classified the constraint effects of the adhesive layer in internal and external effects. Internal effects refer to the adhesive layer itself, whose thickness variation can cause the transition from small-scale fracture – and therefore a brittle behavior – to a fully developed plastic region. On the other hand, external effects comprise all the elements surrounding the adhesive layer, such as the adherend thickness or its layup, that can affect the size of the plastic zone or the amount of plastic deformation. The research devoted to the characterization of internal effects is extensive (Azari et al., 2011; Daghyani et al., 1995; Ikeda et al., 2000; Kinloch and Shaw, 1981; Pardoen et al., 2005) and shows the significant influence adhesive thickness has on the joint toughness. Fewer works are available in the literature regarding the characterization of the external effects on adhesive joints, but despite this the fracture toughness has also been shown to be influenced by the adherends stiffness (Pardoen et al., 2005; Wang et al., 2003). The effect of the adherend thickness has also been reported for specimens with fiber bridging (Sørensen and Jacobsen, 2003; Suo et al., 1992) that, despite being different in nature from adhesive joints, can be analyzed in a similar way to adhesive joints as both rely on the analysis of a Fracture Process Zone (FPZ) of relevant dimensions.

Linear Elastic Fracture Mechanics (LEFM) is the simplest existing approach for the analysis of crack growth in adhesive joints, as it relies on a single parameter – the fracture toughness – to describe the fracture process. Both its simplicity and its high accuracy in the analysis of delamination problems have motivated the use of LEFM in the analysis of adhesive joints (see e.g. the methods described in

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http://dx.doi.org/10.1016/j.ijsolstr.2015.11.016

Table 1
Specimen configurations tested. In the layup definition, *d* denotes the insert location.

Specimen codes	Specimen total thicknesses (mm)	Layup	Adhesive thickness (mm)
A1T1	3.12 ± 0.06	$[0]_8/d/[0]_8$	0.21 ± 0.02
A2T1	4.60 ± 0.08	$[0]_{12}/d/[0]_{12}$	0.21 ± 0.02
A2T2	4.80 ± 0.10	$[0]_{12}/d/[0]_{12}$	0.37 ± 0.01
A3T1	6.05 ± 0.23	$[0]_{16}/d/[0]_{16}$	0.21 ± 0.02

the ASTM D5528-13 and ISO 25217 standards for the mode I fracture toughness measurement of adhesive joints). However, small-scale fracture is assumed in LEFM, i.e. the FPZ that develops ahead of a crack tip must be small in comparison to any other relevant dimension of the component. Unfortunately, fracture in adhesive joints might involve large-scale fracture because of the large plasticity and damage regions formed near the crack tip and, therefore, their characterization falls outside the scope of LEFM. However, most of the works mentioned above rely on LEFM: they are based either on the stress intensity factor or on estimations of the crack length that require LEFM assumptions.

Alternative methods for the fracture toughness measurement that do not rely on LEFM are available in the literature. The *J*-integral approach, first introduced by Rice (1968), is one of the most widespread methods for the analysis of large-scale fracture. The *J*-integral is defined as a non-linear energy release rate and, unlike LEFM, is not limited to small-scale fracture processes. In the recent few years, *J*-integral closed-form solutions independent of LEFM assumptions have been derived for different interlaminar fracture tests (Gunderson et al., 2007; Paris and Paris, 1988; Sarrado et al., 2015; Sørensen et al., 2006; Stigh et al., 2010; 2009). While LEFM-based and *J*-integral-based experimental data reduction methods are expected to provide the same results in cases of small-scale fracture processes, their results are expected to differ for larger FPZs (Suo et al., 1992). However, a comparative study that evidences and quantifies such differences is still missing.

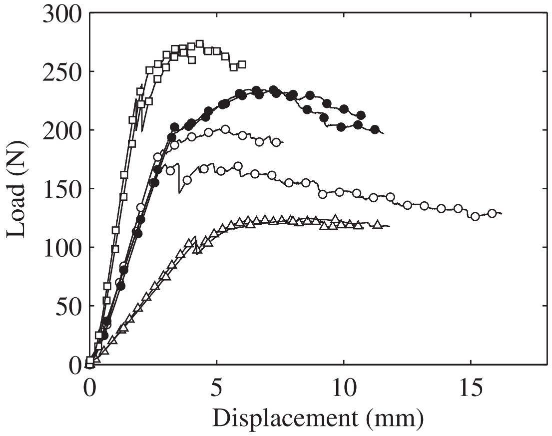
In the current work, an experimental characterization of the FM-300 epoxy film adhesive under pure modes I and II is presented. The effect of the adhesive and the adherend thicknesses on the bond fracture toughness and the R-curve is studied. Test data is reduced by means of both LEFM-based and *J*-integral-based data reduction methods. The discrepancies between both methods are analyzed and their suitability for the characterization of adhesive joints is discussed.

The experimental tests performed and the data reduction methods applied in this work are described in Section 2. The experimental results are presented in Section 3 and, in Section 4, they are discussed and compared to the observations in the literature.

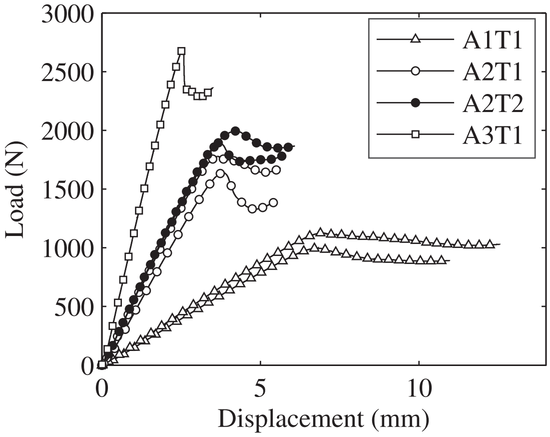
2. Methodology

2.1. Material and specimen configuration

The specimens were manufactured using a unidirectional T800S/M21 carbon/epoxy prepreg. Two panels for each batch of specimens were cured and then secondary bonded using FM-300 epoxy film adhesive impregnated in a carrier. A Teflon film was used to form the 60-mm-long insert that triggers the interface debonding.



(a) DCB



(b) ENF

Fig. 2. Load-displacement curves (only 1 out of every 1000 points is depicted for clarity).

The specimens were 25 mm wide and 250 mm long. Three different adherend thicknesses and two adhesive thicknesses were tested, as outlined in Table 1. The two adhesive thicknesses were achieved by using one or two layers of adhesive. The in-plane elastic properties of the adherends are $E_{11} = 134.7$ GPa, $E_{22} = 7.7$ GPa and $G_{12} = 4.2$ GPa (Marín et al., 2012).

2.2. Tests and data reduction methods

Double Cantilever Beam (DCB) (ISO 25217:2009, 2009) and End Notched Flexure (ENF) (ASTM D7905/D7905M-14, 2014) tests were performed to characterize the adhesive joint under pure modes I and II, respectively. The load configuration of each test is depicted in Fig. 1. A total of 16 tests were carried out. Two DCB and ENF specimens of each material configuration in Table 1 were tested.

The DCB tests were performed according to the procedure described in the ISO 25217 test standard. The initial crack length was set to 35 mm for all tests by bonding the load introduction blocks at the corresponding distance. The LEFM-based method described in the ISO 25217 standard was used. The *J*-integral method was based

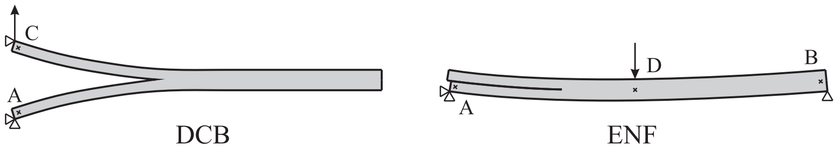


Fig. 1. Representation of the load introduction in the two test types performed in this work.