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Numerical analysis of the dual actuator load test applied to fracture characterization of bonded joints

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ABSTRACT

The dual actuator load test was numerically analyzed in order to assess its adequacy for fracture characterization of bonded joints under different mixed-mode loading conditions. This test enables asymmetric loading of double cantilever beam specimens, thus providing a large range of mixed-mode combinations. A new data reduction scheme based on specimen compliance, beam theory and crack equivalent concept was proposed to overcome several difficulties inherent to the test. The method assumes that the dual actuator test can be viewed as a combination of the double cantilever beam and end loaded split tests, which are used for pure modes I and II fracture characterization, respectively. A numerical analysis including a cohesive mixed-mode damage model was performed considering different mixed-mode loading conditions to evaluate the test performance. Some conclusions were drawn about the advantages and drawbacks of the test.

1. Introduction

Structural applications of adhesively bonded joints are increasing rapidly for a wide range of engineering structures and devices. As a consequence the development of design criteria based on fracture mechanics concepts has become increasingly important since the strength-based criteria are not adequate in the presence of singularities (Adams, 1989; de Moura et al., 2008; da Silva and Öchsner, 2008). In this context, fracture characterization of adhesive bonded joints acquire special relevancy. Pure mode I fracture characterization is usually performed by means of the double cantilever beam (DCB) specimen. This test is simple to execute and the fracture toughness, G_{Ic} can be mathematically defined according to beam theory (ASTM D 3433-99) or several improved approaches as compared in Blackman et al. (1991). In mode II, the end notched flexure (ENF) and the end loaded split (ELS) are frequently used (Blackman et al., 2005; Leffler et al., 2007; de Moura et al., 2008; da Silva et al., 2010) due to their simplicity and ability to provide pure mode II loading at the crack tip.

However, it should be noted that bonded joints in service are usually subjected to mixed-mode conditions due to geometric and loading complexities. In fact, due to their geometric characteristics (two adherends separated by a thin adhesive layer) the crack is frequently forced to grow in pre-defined planes even when the structure is under general non-aligned loading, which induce mixed-mode loading conditions. Consequently, the fracture characterization of bonded joints under mixed-mode loading is a fundamental task. There are some simple tests proposed in the literature concerning this subject, as is the case of the asymmetric double cantilever beam (ADCB), the single leg bending (SLB) and the cracked lap shear (CLS). Nevertheless, these tests are limited in which concerns the variation of the mode-mixity (Dillard et al., 2009), which means that different tests are necessary to cover the fracture envelope in the G_I–G_{II} space. Alternatively, the mixed mode bending (MMB) test, initially proposed by Reeder and Crews (1990) for interlaminar fracture characterization of composite materials, can be used. This test consists of a combination of the DCB and ENF tests and provides a simple alteration of the mode mixity by changing the lever length of the loading arm. In addition, the load applied to the specimens can be separated into mode I and mode II components by means of a mode partitioning method based on the beam theory (Crews and Reeder, 1998). Although the MMB test was also used in the context of composite and steel bonded joints by Ducept et al. (2000) and Liu et al. (2000), respectively, it requires a special test apparatus with significant dimensions, especially when testing stiff adherends. Furthermore, the MMB test does not cover the complete variation in mode mixity from mode I to mode II. Sørensen et al. (2006) proposed the DCB specimen loaded with uneven bending moments at the two free beams. By varying the ratio between the two applied

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moments, the full mode mixity range from pure mode I to pure mode II can be generated for the same specimen geometry. Högberg and Stigh (2006) proposed the mixed mode double cantilever beam specimen based on the geometry of a semi-infinite symmetric DCB specimen. The specimen is loaded by a pair of self-balancing forces whose orientation can vary to alter the mode mixity. The resulting loading combines the basic loading cases of DCB, ELS and CLS tests. An alternative solution is the dual actuator load (DAL) (Dillard et al., 2006; Singh et al., 2010), which can be viewed as a DCB test subjected to non-symmetric loading. Effectively, the test consists of two independent hydraulic actuators operating the arms of a standard DCB specimen clamped at the other extremity. This test allows easy variation of the mode mixity by applying different displacement rates to the specimen arms by means of the two independent hydraulic actuators.

The objective of this work is to perform a detailed numerical analysis on the DAL test. Cohesive zone modeling is used to simulate damage initiation and growth for several different combinations of mode-mixity. A new data reduction scheme based on specimen compliance, beam theory and crack equivalent concept is proposed in order to overcome some difficulties inherent to the test. In addition some aspects related to non-self-similar crack growth, fracture process zone development and dependency of the mode mixity as a function of crack length are discussed.

2. Dual actuator load test

The DAL test is based on a DCB specimen loaded asymmetrically by means of two independent hydraulic actuators (Fig. 1). The specimen is clamped at the bonded end and loaded at the debonded end by means of the independent hydraulic actuators that are attached to the specimen arms. Each hydraulic actuator pivots in order to allow some rotation to accommodate the small vertical displacements of each beam due to foreshortening. Each actuator is equipped with a load cell and a linear variable displacement transducer (LVDT), with the purpose of registering the two load–displacement curves during the test. Different combinations of applied displacement rates provide different levels of mode mixities, thus allowing an easy definition of the fracture envelope in the $G_{\rm I}$ versus $G_{\rm II}$ space.

3. Compliance based beam method

The classical data reduction schemes based on compliance calibration and beam theories require crack length monitoring during its growth. This can be considered an important limitation in cases where crack tip is not easily identified, which is the case of mode II predominant loading cases, since the crack tends to close during propagation. On the other hand, when the fracture process zone (FPZ) ahead of the crack tip is non-negligible (as is the case of adhesives with some ductility) the energy dissipation in the FPZ must be taken into account, which does not happen when the crack length is used as a fracture parameter.

In order to overcome these drawbacks, an alternative data reduction scheme based on specimen compliance, beam theory and crack equivalent concept is proposed. Using Timoshenko beam theory, the strain energy of the specimen (Fig. 2) due to bending and including shear effects is

$$U = \int_0^a \frac{M_{\rm R}^2}{2EI_{\rm R}}\,dx + \int_0^a \frac{M_{\rm L}^2}{2EI_{\rm L}}\,dx + \int_a^L \frac{M_{\rm T}^2}{2EI_{\rm T}}\,dx + \int_0^a \int_{-h/2}^{h/2} \frac{\tau_{\rm R}^2}{2G} B\,dy\,dx + \int_0^a \int_{-h/2}^{h/2} \frac{\tau_{\rm L}^2}{2G} B\,dy\,dx + \int_a^L \int_{-h}^{h} \frac{\tau_{\rm T}^2}{2G} B\,dy\,dx \quad (1)$$

where M is the bending moment, the subscripts R and L stand for right and left adherends and T refers to the total bonded beam (of thickness $2h$), E and G are the longitudinal and shear modulus, respectively, B is the specimen and bond width and I is the second moment of area of the indicated section. For the particular case of adherends with same thickness, considered in this analysis, $I_{\rm T} = 8I_{\rm R} = 8I_{\rm L}$. The shear stresses induced by bending are given by

$$\tau = \frac{3}{2}\frac{V}{Bh}\left(1 - \frac{y^2}{c^2}\right) \quad (2)$$

The parameters c and V represent, respectively, the beam half-thickness and the transverse load, on each arm for $0 \leqslant x \leqslant a$, and on total bonded beam for $a \leqslant x \leqslant L$.

From Castigliano's theorem ($\delta = \partial U/\partial P$, where P is the applied load and δ the resulting displacement at the same point) the displacements of the specimen arms can be written as

$$\delta_{\rm L} = \frac{(7a^3 + L^3)F_{\rm L}}{2Bh^3E} + \frac{(L^3 - a^3)F_{\rm R}}{2Bh^3E} + \frac{3L[(F_{\rm L} + F_{\rm R}) + a(F_{\rm L} - F_{\rm R})]}{5BhG}$$

$$\delta_{\rm R} = \frac{(7a^3 + L^3)F_{\rm R}}{2Bh^3E} + \frac{(L^3 - a^3)F_{\rm L}}{2Bh^3E} + \frac{3L[(F_{\rm L} + F_{\rm R}) + a(F_{\rm R} - F_{\rm L})]}{5BhG} \quad (3)$$

The DAL test can be viewed as a combination of the DCB and ELS tests (Fig. 3). Effectively, the DAL test consists of a mixture of opening and shear loading provided by the respective pure mode tests. Thus, the load applied to the specimen can be separated into mode

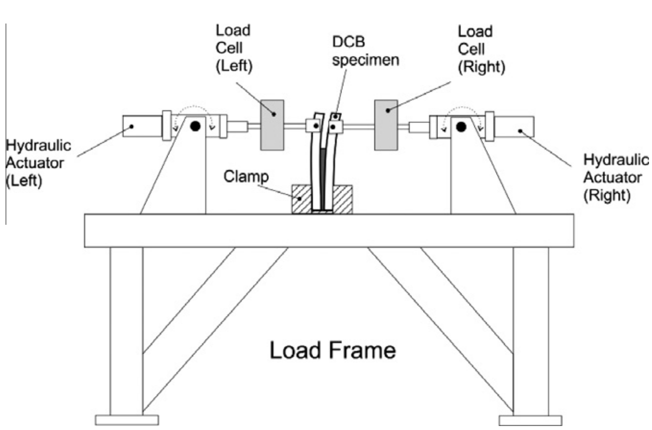

Fig. 1. DAL frame (Singh et al., 2010).

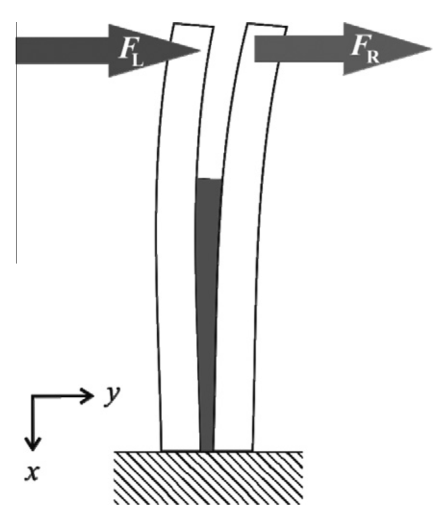

Fig. 2. Schematic representation of loading in the DAL test.