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Procedures for Mixed Mode Fracture Testing of Bonded Beams in a Dual Actuator Load Frame

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ABSTRACT

Most of the common methods for conducting fracture tests on adhesively bonded specimens refer to pure mode measures and to traditional load frames, where only one actuator is present. The critical strain energy release rates that characterize mode I, mode II and mixed-mode I/II fracture of bonded adherends can be measured also using a dual actuator load frame in which there are two degrees of freedom. The geometry that is tested is the double cantilever beam (DCB) type. DCB specimens are commonly used in traditional load frames for pure mode I tests but the independent actuators permit testing at different levels of mode-mixity. The focus of this paper is to develop and present evaluations of experimental and analytical aspects for mixed-mode fracture tests performed with the dual actuator load frame. In fact, tests performed with the dual actuator instead of other techniques give new possibilities and simplify the experimental effort, but also introduces different possible issues. New testing procedures have to be implemented; goals of these procedures are to enhance the capabilities of the dual actuator frame maintaining some of the advantages of other techniques already in use with traditional testing and analysis. Moreover, nonlinear geometrical effects during the tests can play a role and are evaluated in this paper.

BACKGROUND

Methods based on fracture mechanics have proved to be useful for design practice and are commonly applied in the characterization of bonded joints. Fracture mechanics is generally used to analyze the correlation among crack growth, material properties, and input test parameters, which include the imposed displacements or loads [1, 2]. The stress intensity factor (*K*) is commonly applied in fracture study of monolithic materials, while the strain energy release rate (SERR or $\mathcal{G}$) is usually preferred for fracture analysis of bonded joints [3].

The applied SERR can have components associated with each of the three fracture modes. In particular, with mode I, the opening mode, the crack propagates with the opening of its faces normal to the crack plane due to tensile stresses. In mode II, the in-plane shear mode, the crack propagation results from in-plane shear stresses. Finally, in mode III, the out-of-plane shear mode, the crack propagation results from out-of-plane shear stress. The applied strain energy release rate $\mathcal{G}$ is a scalar quantity and it should be noticed that its applied value can be obtained as sum of the components applied in the pure modes.

$$\mathcal{G} = \mathcal{G}_I + \mathcal{G}_{II} + \mathcal{G}_{III} \qquad 1$$

Techniques for partitioning the strain energy release rate in the pure modes components of Equation 1 have been developed by Williams [4], Schapery and Davidson [5] and Hutchinson and Suo [6]. These techniques apply to geometries such as beams and plates subjected to different loading conditions resulting in mixed mode. The techniques describe how to compute the pure mode components of the applied strain energy release rates. Tay [7] and Hashemi [8] addressed mixed mode delamination in fiber composites, developing approaches and physical interpretations that are completely relevant to the fracture in bonded joints and orthotropic materials.

The critical values of SERR, $\mathcal{G}_c$, are typically experimentally measured. These values are also generally depending on the fracture mode that is present at the crack tip, where mode I, mode II, mode III, or combinations of these can cause the crack to propagate. The aspects of fracture in adhesive joints have been investigated by a number of researchers [9-11] who have addressed pure mode and mixed mode fracture using various experimental implementations.

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INTRODUCTION

The fracture studies performed with the dual actuator consider the superposition of fracture modes I (opening) and II (in-plane shear), with tests run in pure modes or in mixed-mode conditions. Specimens geometrically identical to the double cantilever beam (DCB) can provide fracture data for mixed-mode fracture conditions when tested by imposing asymmetric loads or displacements to the two beams. The specimen is clamped at the lower end and loads are applied to the debonded (upper) ends of the beams, as illustrated in Figure 1.

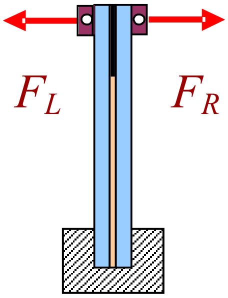

Figure 1: DCB type specimen used in dual actuator load frame

The dual actuator load frame is an instrument that simplifies the experimental effort that is required for collecting data associated with different values of mode-mixity, thus enhancing the possibilities of running tests with different material systems. The dual actuator testing machine illustrated in Figure 2 was built to our specifications before the beginning of the present research by McGaw Technologies Inc. (Fairview Park, OH), with support from the National Science Foundation.

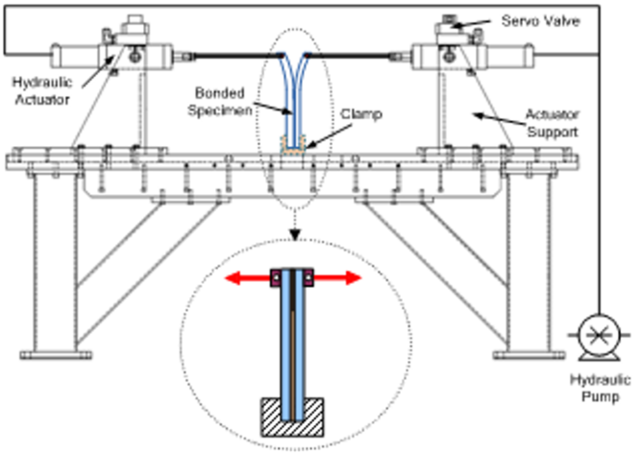

Figure 2: Dual actuator load frame

The dual actuator load frame utilizes two actuators that can impose loads or displacements independently to the ends of the two beams of the bonded specimen. Each actuator has a load cell and a displacement sensor (LVDT) that provides information for quantitative evaluation of specimen behavior. Unless the test is performed in pure mode I, the specimen must be clamped in a vise at the lower end. The loads are applied to the debonded ends of the beams by pins attached to clevises connected to the individual load cells and actuators. A controller drives the two actuators; displacements and forces of the two actuators, as well as time as the test progresses, are collected by a computer equipped with a data acquisition card (DAQ PCI 6229, National Instruments Inc., Austin TX). The crack length values of the specimen are read periodically by the operator running the test. The reading is performed using a magnification lens and facilitated by the white correction fluid and a paper ruler applied on a side of the specimen. The control design allows for imposing different combinations of displacement rates at the two actuators and this results in different levels of in-plane mode mixity with a standard DCB specimen.

The advantages of this testing frame can be summarized in the following points:

- mode mixity is not obtained by a variation of the geometry of the adherends or by the use of other fixtures, but by the imposition of asymmetric loads or displacements; thus, data can be collected from a single specimen type;
- the mode-mixity is infinitely variable between pure mode I and pure mode II;
- the mode mixity can be varied throughout the test without the need of repositioning the specimen.

Papers on experimental results coming from tests performed with the dual actuator load frame have already been presented by Singh et al. [12] and by Nicoli [13]. This paper does not focus on experimental results, but presents some of the specific aspects that are involved in the experimental and analysis procedures when fracture testing is performed with a dual actuator load frame. Parts of this paper include a description of a testing procedure that optimizes the use of the dual actuator and is currently applied and an analytical evaluation of the geometrical nonlinear effects that arise during the test

TESTING PROCEDURE WITH DUAL ACTUATOR LOAD FRAME

The tests performed with the dual actuator are conducted in displacement control to avoid unstable or catastrophic failures of the DCB specimens, but allowing multiple readings of crack length as the debonded part propagates in a controlled fashion. Tests involve imposing different displacement ramps on the two beams and measuring the forces on the left and right actuator. These forces, F_R and F_L in Figure 1, are then combined for evaluating the force F_I, that gives the mode I loading and F_{II} that gives the mode II with Equation 2.

$$\begin{aligned} F_I &= \frac{1}{2}(F_R + F_L) \\ F_{II} &= \frac{1}{2}(F_R - F_L) \end{aligned} \tag{2}$$

F_I and F_{II} are used for evaluating the mode I and mode II components of $\mathcal{G}_c$, which can be calculated as functions of the crack length, the elastic stiffness of the adherends, and the respective forces applied to the two beams of the specimen. These components can be easily computed with the simple beam theory and are equal to Equation 3. I and E are the second moment of area and the elastic modulus of the adherends, respectively, a is the crack length, and b the specimen bond width

$$\begin{aligned} \mathcal{G}_I &= \frac{F_I^2 a^2}{EIb} \\ \mathcal{G}_{II} &= \frac{3F_{II}^2 a^2}{4EIb} \end{aligned} \tag{3}$$

The angle of mode mixity, Ψ, is defined from the ratio between the two components of $\mathcal{G}$. Equation 4 shows this relation.

$$\Psi = ArcTan\sqrt{\frac{\mathcal{G}_{II}}{\mathcal{G}_I}} \tag{4}$$

For the analysis of DCB and other standard test configurations, several improved approaches can be used for analyzing the data. These approaches are more refined than the simple beam theory and include the corrected beam theory (CBT) and the experimental compliance method (ECM) described by Blackman and Kinloch [14, 15]. These techniques address some issues of the tests on DCB specimens adapting the simple beam theory for the geometry of DCB, where the two beams are connected through an adhesive layer. These issues are, for example, the root rotation at the crack tip, shear deformation at the beams, the effects of beam thickness, and inaccuracies in the crack length reading. The CBT evaluates the real elastic stiffness of the beams of the tested DCBs and corrects the crack length reading using a linear fit of the cube root of the compliance vs. crack length plot. The ECM similarly evaluates characteristics of the tested specimens with a differently arranged linear fit of the logarithm of the compliance vs. the logatitm of the crack length. ECM and CBT for DCB specimens are both traditionally based on mode I tests and require experimental data from pure mode I tests, although adaptations of the techniques to pure mode II have also been developed in [16, 17]. One goal of the fracture studies with the dual actuator is usually to test mixed mode conditions, but it is opportune to have each of the specimens partially tested at the same level of mode-mixity. In particular, it is useful to perform a part of pure mode I test in all of the specimens. So, the test procedure was arranged in three separate phases, the first and the latter are run in pure mode I in order to get data points for the CBT and ECM analysis procedures and in the second potion of the test the mixed-mode condition is obtained by imposing different displacement rates on the two beams. Performing the test portions at pure mode I at the beginning and the end of the test gives two advantages. First, the crack growth for short crack length is unstable for fracture modes close to mode II [18], but the first portion of the specimen can give stable data for mode I. Second, for large crack lengths, the presence of the clamping vise at the base of the specimen prevents full debonding of the specimen. Thus, only data from mode I, where clamping is not present, can be collected. The application of the procedure of Figure 3 can be considered beneficial since it tends to maximize the outcome of information that one can gain from the test of each specimen, consequently increasing the overall efficiency of the testing effort.

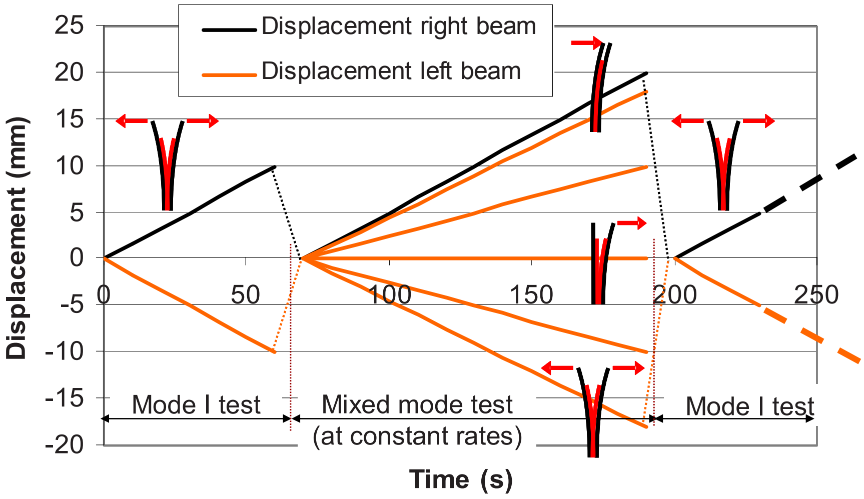

Figure 3: Typical test procedure

The use of CBT is particularly important when natural materials with considerable material properties variation from specimen to specimen are tested. In the calculation of the $\mathcal{G}_c$ components during the mixed mode part of the test, one has not to rely on the elastic modulus listed in tables, but can use the modulus of the specimen obtained in the first and third parts of the test.

NONLINEAR GEOMETRICAL EFFECTS

As previously described, the DCB specimens tested in the dual actuator load frame are clamped at the base and the debonded ends of the two beams are connected to the actuators. The two actuators can rotate around two pinpoints, thus allowing for beam foreshortening and avoiding stresses due to an over-constrained configuration. The geometrical changes that the specimen and load frame encounter during a test are shown in Figure 4.

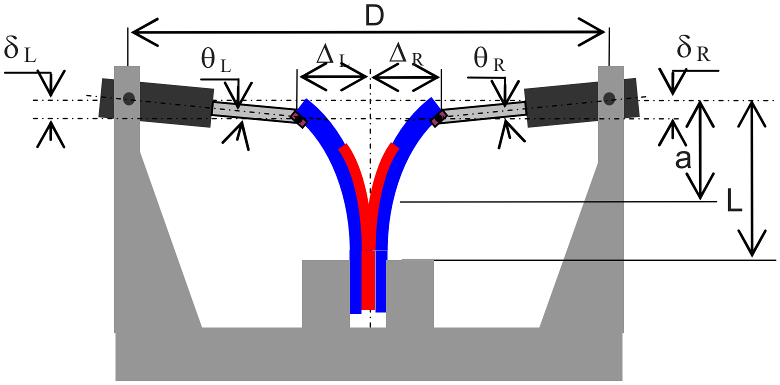

Figure 4: Schematic view of geometry changes during a test on the dual actuator

The DCB specimen consists in two beams bonded together, with a crack that grows during the test and modifies the geometry of the specimen during the test. The evaluations focused on the beam foreshortening (δ), cylinders rotation (θ), illustrated in Figure 4, and the actual moments imposed on the adherends at the crack tip. These three parameters were described as functions of the actuator positions and crack length. The evaluations were carried out for pure mode I and pure mode II and took into account the geometric nonlinear effects in the system. The analysis particularly focused on our dual actuator, where, with reference to Figure 4, D is equal to 1400 mm and L is 220 mm. Also, the maximum displacement of the two actuators, Δ_L and Δ_R, is +/- 50 mm. Figure 5 illustrates that the applied moment decreases not only because of beam foreshortening, but, due to actuator rotation, also because the applied force F has two components F_V and F_H which are generating opposite moments at the crack tip.

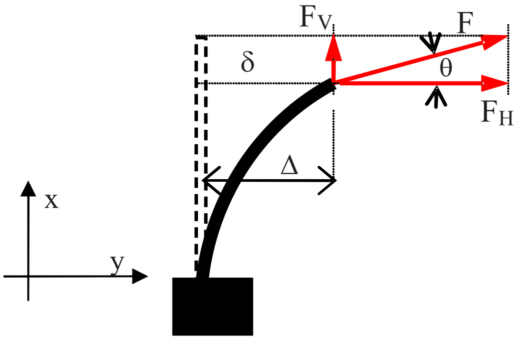

Figure 5: Representation of beam foreshortening and force rotation on a beam tested on a dual actuator load frame.

The beams in the dual actuator are bent with the application of the forces given by the two actuators. The deformed shape can be calculated in each case with the equation

$$\frac{d^2y}{dx^2}=\frac{M(x)}{EI} \qquad \mathbf{5}$$

For an imposed force the moment is linearly variable along the beam length, thus the function *y(x)* is not a simple arc, as it would be for an applied moment, but can be obtained via integration of Equation 5. The evaluation of the beam foreshortening can be performed with the following analytical geometry equation

$$\delta=\frac{\int_0^{L^*}\sqrt{(1+(y'(x))^2)}\,dx-L^*}{\sqrt{(1+(y'(L^*))^2)}} \qquad \mathbf{6}$$

where *L** is the length of the portion of the DCB specimen that bends during the test. In particular *L** is equal to the crack length in mode I configuration and total beam length above the clamp in mode II. *y(x)* is the equation of the deformed shape of the beams. The equation *y(x)* depends on the imposed displacements at the beam ends and on the crack length. From a geometrical point of view, the beam foreshortening of Equation 6 is a function of the imposed displacement Δ, that influences *y(x)* and thus *y'(x),* and the length of the crack. Graphs of the beam foreshortening as function of the two parameters are shown in Figure 6.

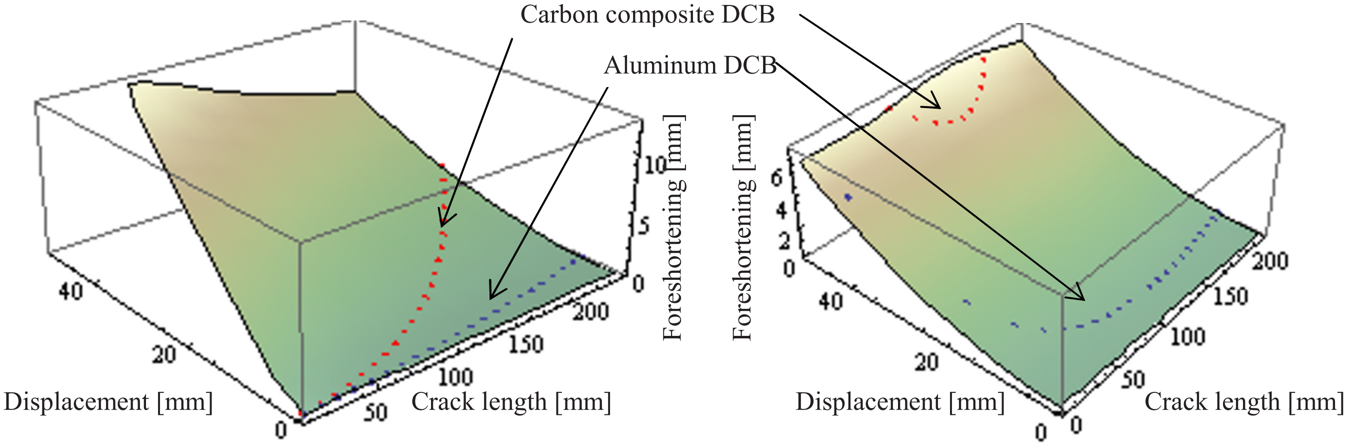

Figure 6: Beam foreshortening as function of imposed displacement and crack length for pure mode I (left) and pure mode II (right)

The graphs show with colored dots also the simulation of data points for two representative geometries: The points indicating lower foreshortening illustrate behavior of aluminum bonded samples (section 25x20 mm, elastic modulus 70 GPa, $\mathcal{G}_{Ic}$ = 5000 J/m^2 and $\mathcal{G}_{IIc}$ = 8000 J/m^2), while the points indicating larger foreshortening describe the behavior of carbon composite bonded samples (section 25x4 mm, elastic modulus 50 GPa, $\mathcal{G}_{Ic}$ = 1000 J/m^2 and $\mathcal{G}_{IIc}$ = 3000 J/m^2). In the two simulations of aluminum and carbon fiber bonded specimens, the crack length and the imposed displacement are not independent variables, but the first is function of the second and depends on geometry of the specimen and elastic and fracture properties of the adherends.

Another finding of the analysis was the variation of the moment at the crack tip in the two cases of mode I and mode II. This variation results from both beam foreshortening and actuator rotation. The moment variation is important; in fact the real moment present at the crack tip is the element that causes the crack growth. The comparison that was carried out and is shown in Figure 7 is the ratio between the real moment at the crack tip and the nominal one that is simply the product of the force F measured at the load cell and the crack length, without effect of beam foreshortening.

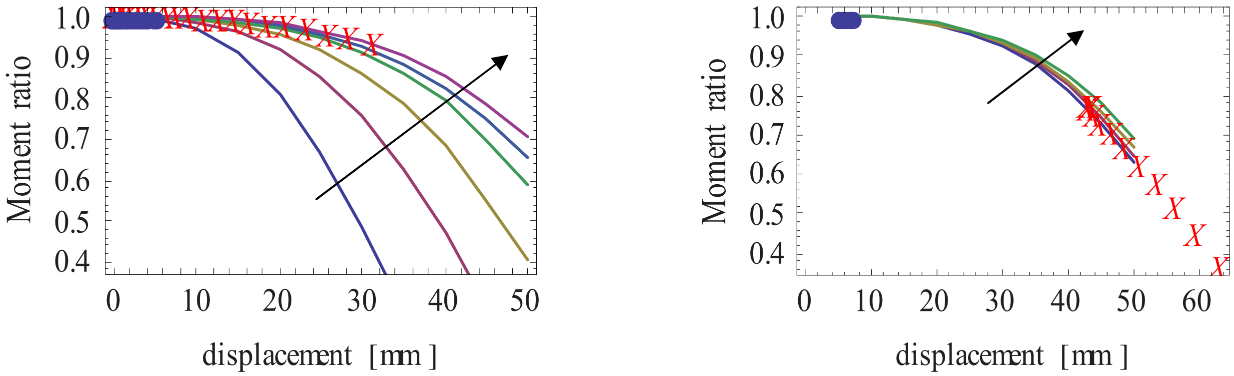

Figure 7: Variation of moment at the crack tip from the nominal value (left pure mode I, right pure mode II) The different curves represent different crack lengths; the arrow indicates increasing crack length.

Also in the case of Figure 7, the graphs illustrate curves coming from geometrical analysis and data points the data from the simulations; in particular dots indicate points from aluminum DCBs and Xs indicate points from carbon composite DCBs. The outcome of the analysis is that for the stiffer aluminum specimens the moment variation is less than 1% in both mode I and mode II, while for the more compliant carbon composite specimens the moment is reduced of 7% in mode I tests and around 40% in mode II tests, for the maximum possible displacement of 50 mm. For metallic specimens the issue is likely to be insignificant, while some care has to be taken in analyzing specimens where the imposed displacement gets large. Having this aspect been evaluated with this analysis, when analyzing the fracture data one could consider a correction factor, returning the real applied moment and thus the real forces F_I and F_{II} as function of imposed displacement and crack length. The forces F_I and F_{II} are in fact important when evaluating the components of $\mathcal{G}_c$,as illustrated in Equations 3.

CONCLUSIONS

The dual actuator test frame simplifies the experimental effort required for mixed-mode characterization of adhesively bonded and laminated beam specimens, since a single geometry type of specimen can be used for spanning from pure mode I to pure mode II loading conditions. The dual actuator introduces the possibility of easily applying different levels of mode mixity on a single specimen, thus allowing to applying some of the positive outcomes of traditional data analysis techniques such as the corrected beam theory (CBT) and the experimental compliance method (ECM) also in mixed mode tests. Especially the results of CBT can be useful also in mixed mode testing and a procedure for increasing the efficiency of each test has been proposed.

The construction characteristics of the testing frame introduce some nonlinear effects such as adherend foreshortening and the force rotation during the test. These variations were analytically evaluated. In particular two representative cases were shown. It has to be pointed out that a problems such as the beam foreshortening is common to most of the techniques that measures fracture properties with DCB type specimens. For the dual actuator load frame it was shown that the nonlinear geometrical effects can be accounted for a 1% variability of the results when testing relatively stiff materials, such as bonded metals, while can have higher influence in relatively compliant specimens, such as DCBs obtained from thin layers of carbon fiber composites. Graphs obtained in this paper can be used in testing practice with the dual actuator as correction factors for the mentioned nonlinear effects.

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