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An experimental analysis of the fracture behavior of composite bonded joints in terms of cohesive laws

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ABSTRACT

Modeling adhesive joints by means of cohesive models relies on the definition of cohesive laws. Although cohesive laws are known to be dependent on the loading mode, there is a lack of experimental evidences to describe this dependence. At the same time, the adherend and adhesive thicknesses are known to affect the fracture toughness of the bond, but their effect on the cohesive law has not been clarified. In this work, an experimental characterization of an epoxy adhesive is presented. The effect that the mode mixity has on the bond toughness and its cohesive law is compared against the effect of the adhesive and adherend thicknesses. The impact of these two latest parameters is shown to be minor if compared to the influence of the mode mixity, which mainly defines the cohesive law shape. Finally, the implications of these experimental findings on the numerical simulation of adhesive joints are discussed.

1. Introduction

The mechanical properties of the bulk adhesive and the behavior of a thin adhesive layer confined in between two rigid adherends have been shown to be difficult to correlate [1], given the difficulty of thoroughly characterizing the plastic behavior of the adhesive under complex stress states. The constraint of the stress field in the adhesive layer determines its plastic deformation, which severely affects the bond toughness [2–4]. On one hand, the adhesive thickness has been repeatedly shown in the literature to influence the bond toughness [2,4–7]. On the other hand, although fewer works are available in the literature regarding the characterization of the effect of the adherend thickness, the adherend stiffness also influences the fracture toughness [3,6,8,9].

Adhesive joints usually involve large-scale fracture processes as a consequence of the large plastic and damage region developed ahead of the crack tip. A recent work by the authors [10] showed that limiting the characterization of adhesive joints to a Linear Elastic Fracture Mechanics (LEFM) framework can lead to unacceptable deviations in the fracture toughness measurement. Instead, the *J*-integral approach [11], defined as a non-linear energy release rate in a Non Linear Fracture Mechanics (NLFM) framework, can serve that purpose. Different closed-form solutions of the *J*-integral that do not require LEFM assumptions are available in the literature for different fracture mechanics tests [12–17], enabling the reliable characterization of adhesive joints under pure and mixed-mode loading.

In a finite element analysis framework, cohesive zone models [18] are an excellent approach for the analysis of adhesive joints fracture. They rely on a traction-separation law, which is assumed to be a material property dependent on the loading mode, that describes the behavior of the material due to plasticity and damage. Cohesive zone models can reproduce in detail the crack growth and the Fracture Process Zone (FPZ) behavior on a predefined interface. Under certain fracture processes involving small FPZs such as delamination in composite materials, accurate results are obtained by assuming any cohesive law shape provided that the amount of energy dissipated equals the fracture toughness of the material [19,20]. However, in general situations where the FPZ might have a significant size, its generation and propagation can play a key role in the load-displacement curve and in the failure of adhesive joints and, therefore, a detailed analysis of the FPZ behavior is required to accurately simulate the joint response. In such situations, the traction-separation law (or cohesive law) of the material must be known, so it should be experimentally measured.

Cohesive law measurement methods are far more recent than those for fracture toughness measurement and the influence the bond geometry has on the cohesive law is still an ongoing research topic. Sørensen and coauthors [8,21–24] developed the method for measuring cohesive laws originally proposed by Suo et al. [3] and extended it to mixed mode [22]. They applied the method to char-

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acterize the bridging laws in delamination specimens [8,23] and to characterize the effect of the loading rate in adhesive joints [21]. All these experiments were performed for a single adhesive and adherend thicknesses. More recently, Leone et al. [25] applied the same method to obtain the cohesive law of FM-300 K adhesive under pure modes I and II; also for a single adhesive and adherend thickness. Ji and coauthors characterized the effect of the bondline thickness on the Hysol 9460 adhesive cohesive law under pure mode in both metallic [26] and carbon/epoxy composite joints [27,28]. They observed a completely different effect of the bondline thickness on metallic and composite joints, which was attributed to the difference in the adherend stiffness. Ji and coauthors extended this study to mixed mode, albeit for metallic joints only [29]. However, the effect of the adherend thickness on the cohesive law of the adhesive has been never studied, and neither has the effect of the adhesive thickness on its cohesive law under mixed mode in composite joints.

Whereas the fracture toughness has been repeatedly reported to depend on the bond configuration, it remains unclear how the cohesive law depends on it. The main goal of the present work is to provide experimental evidences of the dependence of the cohesive law on both load and bond configurations. To pursue that goal, an experimental characterization of the FM-300 epoxy film adhesive is presented. The R-curves and the cohesive laws of the adhesive joints are measured for four different loading modes: pure mode I, pure mode II and 50% and 75% of mixed mode I-II. The effects of the mode mixity on the R-curve and cohesive law of the bond are compared to the influence of both the adhesive and the adherend thicknesses. This influence is investigated by testing three different adherend thicknesses and two different adhesive thicknesses for each loading mode.

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

Two panels of unidirectional T800S/M21 carbon/epoxy prepreg for each batch of specimens were cured and then secondary bonded by means of an FM-300 film adhesive impregnated in a carrier. FM-300 is a rigid epoxy film adhesive commonly employed in aeronautic industry. The specimens were 25 mm wide and 250 mm long. The Teflon insert that triggers interface debonding was 60 mm long. The layup of the specimens and the different adhesive and adherend thicknesses tested are outlined in Table 1. Three different adherend thicknesses were manufactured by stacking a different number of layers, whereas the two different adhesive thicknesses were achieved by using one or two layers of adhesive.

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

Specimen	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

2.2. Tests and data reduction method

Double Cantilever Beam (DCB) [30], End Notched Flexure (ENF) [31] and Mixed Mode Bending (MMB) [32] tests were performed to characterize the adhesive under pure mode I, pure mode II and mixed mode loading, respectively. In Fig. 1, the configuration of each test is schematically shown.

Thirty-two tests in total were carried out. Two DCB, ENF, MMB 50% and MMB 70% tests were performed for each material configuration in Table 1. The experimental data were reduced using *J*-integral closed-form solutions available in the literature. Details of the equations used can be found in the description of each particular test.

The cohesive laws were computed according to [22] as

$$\sigma = \frac{\partial J}{\partial \Delta} \tag{1}$$

where σ is the cohesive traction, J is the J-integral measured according to the equations for each particular test and Δ is the total crack separation, which is measured at the initial crack tip and defined as the Euclidean norm of the crack separations perpendicular (mode I) and parallel (mode II) to the crack plane. In the present work crack separations were measured by means of the Digital Image Correlation (DIC) equipment described in Section 2.3. The method given by Eq. (1) is derived assuming that the measurements are taken while the FPZ is being formed [21], so the precracking step outlined in the test standards was skipped. The differentiation in Eq. (1) is done numerically. To avoid excessive noise, five consecutive points are taken for each derivative.

2.2.1. DCB test

The procedure described in the ISO25217 test standard [30] was followed to perform the DCB tests. The initial crack length was set to 35 mm for all tests by bonding the load introduction blocks at the corresponding distance. J was computed by means of the expression proposed by Paris and Paris [12] as

$$J = \frac{2P}{b}\theta \tag{2}$$

where b is the specimen width, P is the applied load and θ is the rotation angle at the load introduction point. The angles at both the upper and lower load introduction points of the DCB specimen were monitored in order to remove the initial rigid body rotations (points A and C in the DCB specimen in Fig. 1).

2.2.2. ENF test

The three point bending ENF tests were done based on the procedure described in the test method AITM 1.0006 [33]. This test standard is intended for delamination specimens with shorter FPZ than those generated in adhesive joints. For this reason, adhesive joints specimens may not have enough space to fully develop a FPZ before the damaged region reaches the midspan length of the specimen. Thus, as longer crack propagation than that obtained in

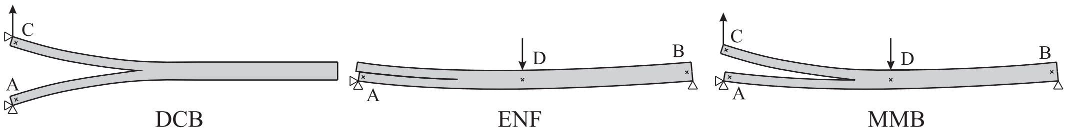

Fig. 1. Representation of the load introduction in the three test types performed in this work.