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Mode I and Mode II critical fracture energy characterization of an epoxy adhesive: Experimental and computational analyses

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Abstract: Amongst the techniques for intralaminar fracture resistance of fiber composites the Double Cantilever Beam (DCB) and End Notched Flexure (ENF) are one of the most commonly applied. However, the standards methods available are complex and depends on real time crack length measurement, which it is difficult to perform and can easily lead to erroneous results. To overcome this problem the Compliance-based Beam Method (CBBM) has been the most commonly method used to obtain the adhesive fracture energies, since it requires only the data extracted from the Pvsδ curve (load-displacement). This work consists to obtain the fracture energy resistance in Mode I and Mode II of an epoxy adhesive respectively through Double Cantilever Beam (DCB) and End Notched Flexure (ENF) tests using the Compliance-based Beam Method (CBBM). The finite element software ABAQUS® and its embedded cohesive zone models (CZM) were used to perform the computational simulations for an estimation of the bond strength. Cohesive failure was achieved by grit blasting the adherends followed by cleaning with acetone. A constant adhesive thickness was guaranteed by placing nylon lines between the adherends. The CBBM method showed good agreement on comparing the experimental results with a computational model simulating the adhesive strength on single lap joints.

Keywords: CBBM, CZM, Bonded Joints, Composite Structures, Adhesives.

INTRODUCTION

To predict the onset crack propagation there are strain energies that must be calculated, they have direct relation with the fracture crack separation modes, most commonly known as the Mode I component due to interlaminar tension and Mode II component due to interlaminar sliding shear (Broek, 2012). To calculate the fracture resistance of a specified separation mode, the usual procedure is to obtain relations between the compliance, load and crack length of a pre-cracked specimen. The most common and acceptable tests used for characterization of fracture resistance are the Double Cantilever Beam (DCB) and End Notched Flexure (ENF) developed to obtain respectively fracture resistance in ModeI and Mode II. However, the available standard methods based on these tests are complex and dependents of crack length measurement during tests, which can lead to scattered data and erroneous results. In order to overcome these difficulties de Moura and de Morais (2008) proposed a method called Compliance-based Beam Method (CBBM), based on the Corrected Beam Theory with Effective Crack Length (Blackman et al., 2005) and classical data reduction schemes as the Compliance Calibration Method (CCM) (Kanninen and Popelar, 1985). The CCBM takes into account several effects as stress concentrations near the crack tip knows as the fracture process zone (FPZ) and rotation effects that are not included in beam theory. This method does not require the crack length measurement during the test, using an equivalent crack length instead allowing obtaining the fracture energy using only the Pvsδ curve (Chaves et al., 2014). This work consists to obtain the fracture energy in Mode I and Mode II of an epoxy adhesive respectively through Double Cantilever Beam (DCB) and End Notched Flexure (ENF) tests using the Compliance-based Beam Method (CBBM). ASTM D5528 and ASTM D7905 standards were used as reference for adhesive joints manufacturing, bonding together two unidirectional 0° carbon/epoxy composite adherents with a brittle epoxy adhesive. The finite element software ABAQUS® and its embedded cohesive zone model (CZM) formulation were used to perform computational simulations to predict the adhesive strength on single-lap joints (SLJ) submitted to a traction load.

EXPERIMENTAL WORK

Manufacturing of both specimens (DCB and ENF tests) were carried out by the same process. Adherents made by unidirectional 0° carbon/epoxy prepreg (TEXIGLAS) plates were bonded together with epoxy adhesive (EPHOXAL RAL120 / HAL115). To increase adhesion and avoid adhesive failures the surfaces were previously sand-blasted and cleaned with acetone. A 0.3 mm adhesive thickness was guaranteed by placing parallel nylon lines during adhesive curing process and an initial crack was achieved by a 8µm thickness Teflon insert. Adhesive curing was performed at room temperature under a 500 kg load in a hydraulic press. The specimens were obtained by cutting out the bonded plates over the nylon lines. Figure 1 shows DCB and ENF specimens geometry, in which piano hinges were bonded over the pre-cracked region to allow load application (Fig. 1a). DCB and ENF specimen's dimensions are presented in Tab. 1.

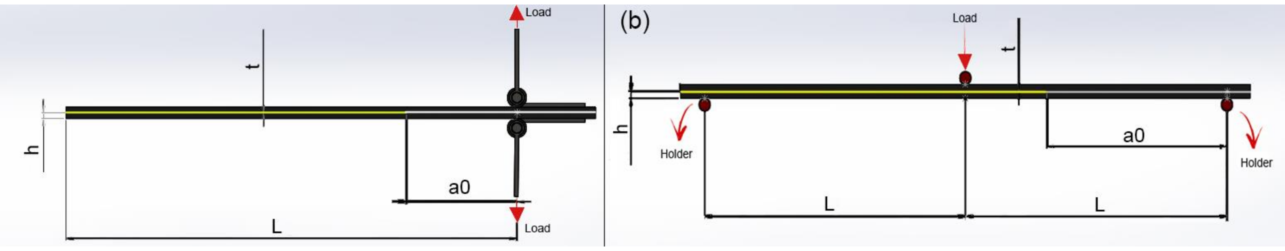

Figure 1 – Specimen geometry: (a) Double Cantilever Beam; (b) End Notched Flexure.

Table 1 – Double Cantilever Beam and End Notched Flexure specimen dimensions.

	Length L(mm)	Adherend Thickness h(mm)	Adherend Width B(mm)	Adhesive Thickness t(mm)	Initial Crack Length a0(mm)
DCB	210	1.85	17.80	0.30	60.00
ENF	120.5	2.85	17.78	0.30	91.00

DATA REDUCTION

According to De Moura and De Morais (2008) and De Moura et al. (2009), the respective critical strain energy release rates in Mode I and II can be obtained by the CBBM by a relationship between the equivalent crack length and the specimen compliance (C=δ/P) during crack propagation by means of the Irwin–Kies equation (Kanninen and Popelar, 1985):

$$G = \frac{P^2}{2B}\frac{dC}{da} \tag{1}$$

Where the specimen compliance can be calculated using the Timoshenko Beam Theory (Chaves et al., 2014):

DCB

$$C = \frac{a^3}{E_f Bh^3} + \frac{12a}{5BhG_{13}} \tag{2}$$

ENF

$$C = \frac{3a^3 + 2L^3}{8E_f Bh^3} + \frac{3L}{10G_{13}Bh} \tag{3}$$

Combining Equation (1) with Equations (2) and (3) gives the strain energy release rate respectively for Mode I and II:

Mode I:

$$G_{IC} = \frac{6P^2}{B^2 h}\left(\frac{2a_{eq}^2}{E_f h^2} + \frac{1}{5G_{13}}\right) \tag{4}$$

Mode II:

$$G_{IIC} = \frac{9P^2 a_{eq}^2}{16B^2 E_f h^3} \tag{5}$$

Where

P	Load
δ	Displacement
B	Specimen Width
L	Specimen Lenght
t	Adhesive Thickness
h	Adherend Thickness
a_0	Intitial Crack Length
a	Crack Lenght
a_{eq}	Equivalent Crack Lenght
E_f	Specimen Flexural Modulus
G_{13}	Specimen Shear Modulus

EXPERIMENTAL RESULTS

Experimental tests were carried out in a universal testing machine under a 1mm/min crosshead speed. Fig. 2a and Fig. 3a shows the load vs. displacement curve of DCB and ENF tests respectively for one case. According to Chaves et al. (2014) the critical energy release rate of the adhesive are represented by the plateau region of the energy release rate as a function of the crack length, well known as the resistance curve, which are represented by Fig. 2b and Fig. 3b. Table 2 shows the average fracture toughness of all specimens. All specimen exhibited cohesive failure of the adhesive layer.

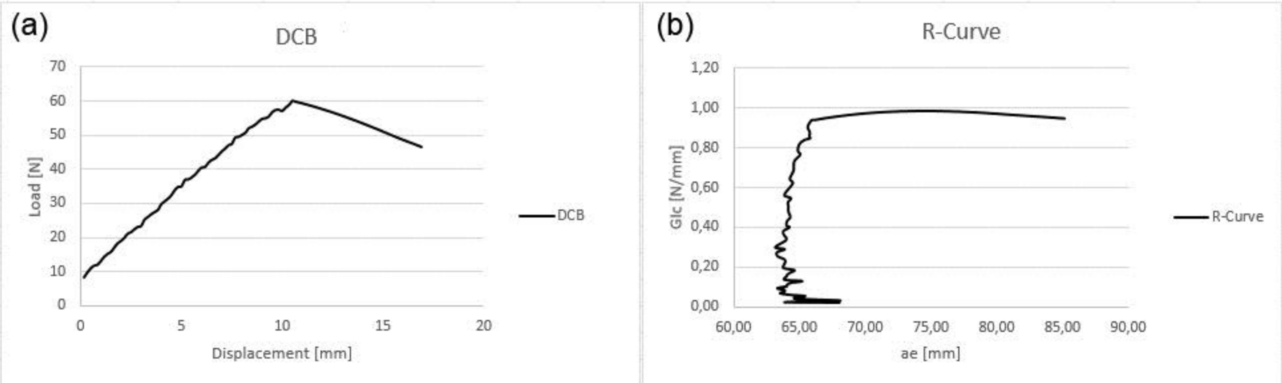

Figure 2 – (a) Double Cantilever Beam Load vs. Displacement curve of a selected specimen (b) Respective resistance curve.

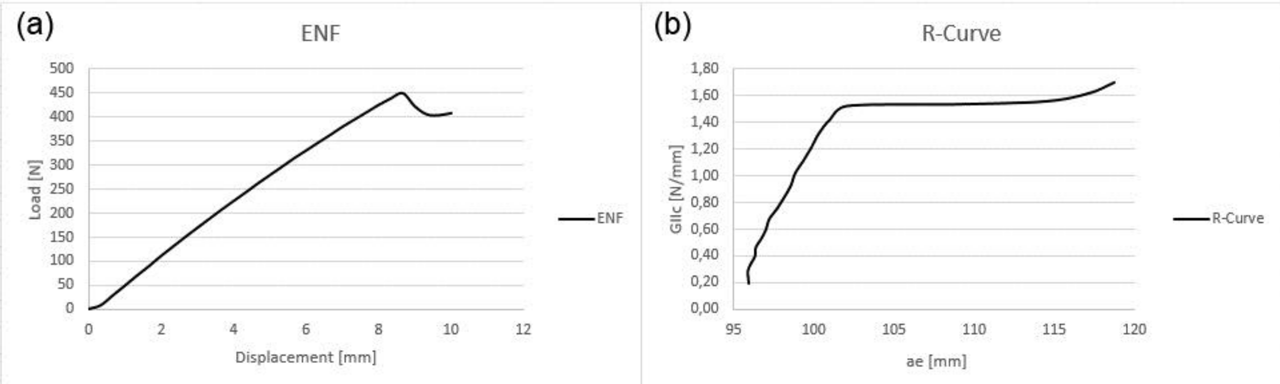

Figure 3 – (a) End Notched Flexure Load vs. Displacement curve of a selected specimen (b) Respective resistance curve.

Table 2 – Adhesive critical fracture energies.

	Critical Fracture Energy [N/mm]
G_{Ic}	0.97±0.01
G_{IIc}	1.54±0.02

NUMERICAL MODEL

In order to validate the adhesive critical fracture energy obtained by the Compliance-based calibration method, a computational model using a cohesive zone model (CZM) was developed to predict the adhesive strength of a Single Lap Joint (SLJ) under traction load. Experimental single lap joint tests using unidirectional Glass Fiber-Epoxy (EP-GF) adherents bonded with an epoxy adhesive (EPHOXAL RAL120 / HAL115), the same used on the fracture toughness tests, were carried out to compare the joint strength with the computational model. The adherents and tabs were modeled as an 8-node quadrilateral continuum shell (SC8R - ABAQUS (2014)) with six degrees of freedom per node. The adhesive layer was modeled as an 8-node three-dimensional cohesive element (COH3D8 - ABAQUS (2014)) with a 0.3 mm adhesive thickness. All the geometry of the tabs and adherents followed ASTM specifications D5868 (2014), the same used in the experimental samples. For the boundary conditions, the movements were restricted on the left tab and partially at the other one, thus allowing only a uniaxial translation at x direction according to Fig. 4 below:

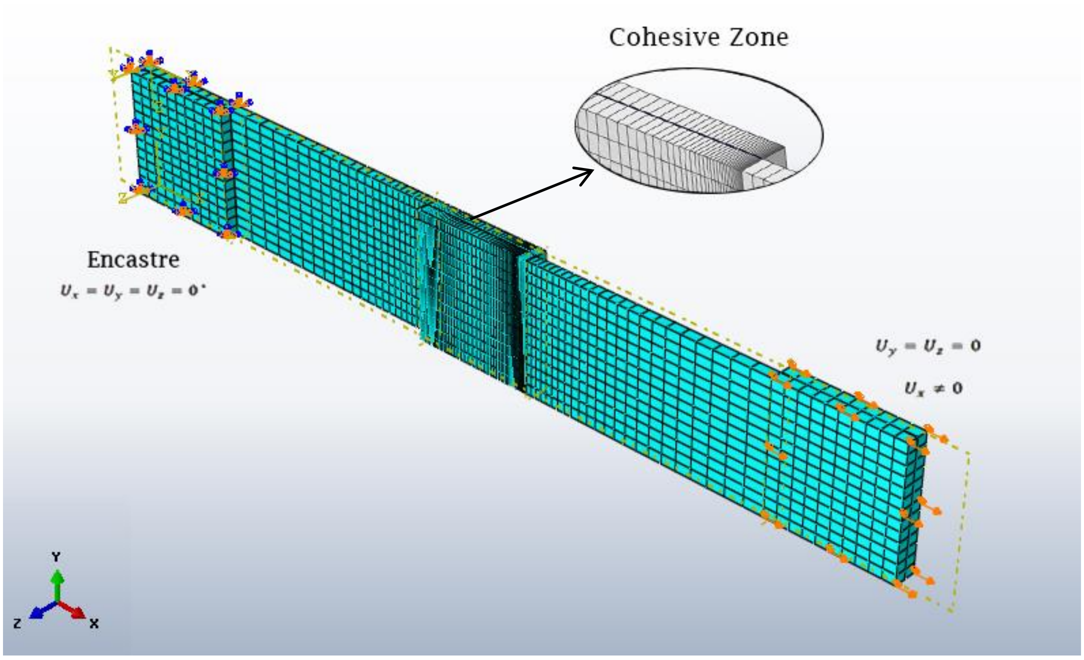

Figure 4 – Single Lap Joint computational model and boundary conditions.

Table 4 and 5 specifies respectively the adherends (modelled as elastic orthotropic) and adhesive (EPHOXAL RAL 120/HAL 115) properties used in the models.

Table 4 – Unidirectional Glass/Epoxy mechanical properties

Young's modulus in longitudinal direction– E_{11}	44.0	GPa
Young's modulus in transverse direction – E_{22}	12.7	GPa
Shear modulus in ply plane – G_{12}	3.65	MPa
Poisson´s ratio – υ_{12}*	0.16	–
Poisson´s Ratio – υ_{23}	0.26	–

*$\nu_{12} = \nu_{13}$ (orthotropic)

Table 5 – Adhesive properties

Young's modulus – E	2288	MPa
Shear modulus – G	846	MPa
Tensile failure strength – σ_u	55	MPa
Shear failure strength – τ_u	42	MPa
Tensile failure strain - ε_u	4.6	%
Poisson´s ratio – υ	0.35	–
G_{Ic} –	0.97	N/mm
G_{IIc} –	1.54	N/mm

Based on the experimental tests, a displacement of 4 mm was applied on the x direction of the numerical model, and to simulate the damage evolution a traction-separation law considering exponential softening behaviour was applied at the cohesive layer. Figure 5 shows the comparison between experimental and numerical data. Experimental results showed slightly superior stiffness compared to the numerical model, however, they have been able to withstand almost the same load as can be observed in Tab. 6. The stiffness increase in the experimental results can be explained by the small distortion due to clamping settling of the universal testing machine and nonlinear effects not considered on the single lap joint model.

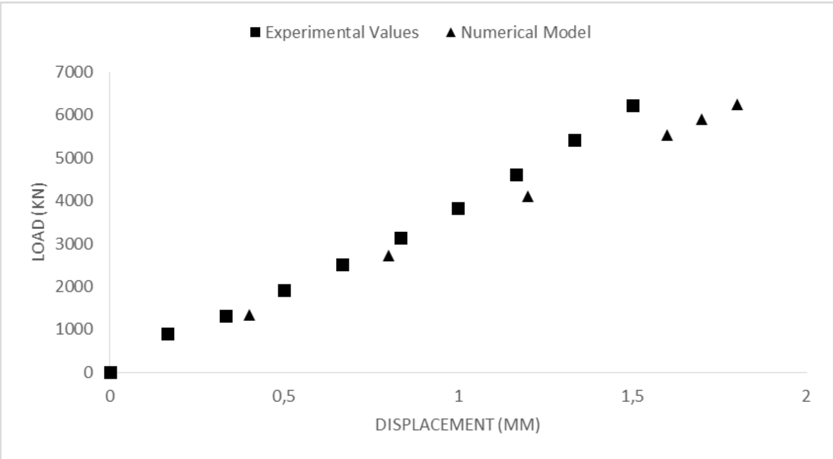

Figure 5 – Load vs. Displacement comparison between experimental and numerical tests.

Table 6 – Ultimate force comparison between experimental and numerical tests.

Models	**Ultimate Force (kN)**	**Crosshead Displacement (mm)**
Experimental	6238	1.5
CZM	6250	1.8
Δ%	0.2	20

CONCLUSIONS

In this work, an equivalent crack length approach was used to calculate the critical energy release rate of an epoxy adhesive. The adhesive energy release rate was then used on a cohesive zone model to predict the adhesive strength of a single lap joint, comparing the numerical results with experimental data of SLJ tests using the same adhesive. The Compliance-calibration beam method has proved to be a good tool for calculating the adhesive critical energy release rate since the cohesive model showed a good agreement for damage prediction of the maximum force supported by an SLJ.

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