Towards a consensus on mode II adhesive fracture testing: experimental study.

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Abstract

The objective of this work is to define reliable test methodologies and data reduction methods to obtain comparable results among the most common mode II test methodologies: the End-Notched Flexure (ENF), the End-Load Split (ELS), the 4-point End-Notched Flexure (4ENF), and the Mixed Mode Bending (MMB) test at 100% of mode II.

For this reason, an experimental test campaign consisting of the abovementioned four mode II test methods was carried out. The J -integral was implemented in the ELS, the ENF and the MMB tests and a J -integral closed form was developed and implemented for the 4ENF test. Then the J -integral was compared to the data reduction methods based on Linear Elastic Fracture Mechanics (LEFM). The results obtained from the J -integral based methods were independent from the test methodology and obtained very good agreement among the tests.

In addition, from the experimental results the advantages and drawbacks of the different test procedures are analysed and discussed, concluding that the ELS test is the most suitable to measure mode II fracture toughness of adhesives.

Keywords: Mode II fracture toughness, Bonded joints, J -integral, FRP, Mechanical testing

1. Introduction

Nowadays, adhesive bonding is widely used in industrial applications as an alternative to traditional mechanical fasteners, especially in lightweight structures. Moreover, the use of adhesives is of great

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importance in composite materials repair.

Bonded joints are designed such that the adhesive is loaded in the direction of its maximum strength (i.e. shear), whereas tension or peel stresses are minimized. For this reason, determining mode II fracture toughness is extremely important.

There are various standardized test methodologies available to determine the mode II fracture toughness of fibre-reinforced polymer composites, namely the End-Notched Flexure (ENF) test [1], the End-Loaded Split (ELS) test [2] and, alternatively, the Mixed Mode Bending (MMB) test [3] used at 100 % mode II ratio. Although not standardized, the Four End-Notched Flexure (4ENF) test, due to its intrinsic stable configuration, also provides a suitable approach which has been used by many authors [4–9]. All these methods are widely used by the scientific community and the industry to obtain the fracture properties of the materials.

Assuming mode II fracture toughness as a material property, many authors have compared different tests and have obtained different results [5, 9–12]. These studies realized that one of the main problems in mode II testing is the poor comparability among the existing test methods. The causes of such discrepancies in results are diverse, ranging from the friction and large deflections involved, to the complex damage mechanisms occurring at the crack tip [5, 13–17].

In the case of adhesive bonded joints, they have been reported to entail a large Fracture Process Zone (FPZ) at the crack front due to the plasticity of the adhesive layer [18, 19]. Therefore, analysing situations involving large FPZ may fall outside the scope of the mode II delamination standards data reduction methods because they are based on Linear Elastic Fracture Mechanics (LEFM).

The interest in bonded joints failure has led to new data reduction methods being developed to determine fracture toughness in a non-linear framework. One that has enjoyed particular success is the J -integral developed by Rice [20], a path-independent contour integral that can be interpreted as a non-linear energy release rate. Simple closed form solutions of the J -integral have been used to obtain fracture toughness in tests such as ENF [21], ELS [22] and MMB [23], which could be good alternatives to the current data reduction methodologies.

The main problem in mode II adhesive testing is the poor reproducibility of the results among the different test types, from which many data reduction methodologies have emerged. The objective of this work is to obtain a reliable mode II fracture toughness test for structural adhesives.

To achieve this, a mode II experimental test campaign of bonded joints between Carbon Fibre Reinforced Polymers (CFRP) was carried out. Two different specimen configurations were used, which are manufactured with the same adhesive but with a different adherend.

Four mode II test methodologies were compared: ENF, ELS, 4ENF and MMB at 100% ratio of mode II. Different data reduction methods based on both LEFM and the J -integral were applied to each test methodology. A J -integral closed form solution for the 4ENF test is presented, as it is the only one from the tests studied for which a J -integral closed form does not exist in the literature. In view of the results, a discussion on the suitability of the tests and data reduction methods for the analysis of adhesives is presented.

2. Experimental test campaign

The tests were performed in the ISO17025 and NADCAP (National Aerospace and Defense Contractors Accreditation Program) for non-metallic materials certified AMADE research group testing laboratory, at the University of Girona. The specimens tested were 25 mm wide, 210 mm long, 4.8 mm thick with an adhesive layer of 0.22 mm. To induce a 60 mm long artificial crack in the bonding line, one doubled layer of PTFE (Polytetrafluoroethylene) film of about 0.02 mm to 0.03 mm was placed in between the two substrates.

Two different specimen types (M1 and M2) were manufactured with the same adhesive but each with a different adherend. The adhesive was a secondary bonded epoxy resin embedding a Mat / Polyester carrier.

Each two adherend used consist of carbon tape epoxy prepreg multidirectional balanced lay-ups ($[0^\circ/0^\circ/+45^\circ/-45^\circ/+45^\circ/-45^\circ]_s$), precured in an autoclave. They differ in the type of fibres and resin used.

79 Surface activation of the adherends for bonding was done by abrasion followed by solvent cleaning,
80 and after, bonded specimens were cured in autoclave.

81 The adherends and the adhesive are typical materials employed in the aeronautical industry mainly
82 used on primary and secondary aircraft structures. For reasons of confidentiality, the names of the
83 constituents and their basic properties are not listed.

84 From each material, M1 and M2, five different panels were made. In order to obtain comparable
85 specimens, from each panel, four specimens were obtained and each one was tested with a different
86 test type (ELS, ENF, 4ENF and MMB respectively). By doing so, each batch consist of five
87 specimens, each one coming from a different panel made with the same material as described before.

88 With the aim of avoiding unstable crack initiation from the insert, before the mode II tests a
89 pre-crack in mode I was made in all the specimens following the ISO25217 [24] standard. The
90 pre-crack propagation length differed from the standard's specifications, depending on the desired
91 mode II initial crack length, but minimum propagation of 5 mm was ensured.

92 After the pre-crack tests, the final crack length was measured with an optical microscope and marked
93 on the edge of the specimen. Afterwards, the edge was marked every millimetre with a vertical line
94 from the initial crack tip, a_0 , to the final propagation length, a_f (c.f. Figures 1, 2, 4 and 5).

95 The mode I pre-cracks and the mode II tests were carried out under displacement control in a
96 universal test machine. During the mode II tests, the load, the displacement, the crack length, and
97 the rotations at the loading application points and at the supports were recorded. The load and the
98 displacement were obtained from the test machine. During the test, the crack length was optically
99 monitored along one edge of the specimens using a video acquisition system consisting of a Canon
100 550D camera with a macro lens, mounted on a travelling fixture and the crack length considered
101 from the visual observation of the end the crack, but not the deformed vertical lines. The rotations
102 were measured with capacitive inclinometers NA3-30 from SEIKA Mikrosystemtechnik GmbH, with
103 a resolution of 0.005 degrees and a maximum linearity deviation over the whole measurement range
104 (± 30 degrees) of 0.06 degrees, according to the manufacturer's specifications.

105 Different methods were used for the data reduction: LEFM-based and J -integralbased methods.

106 The LEFM-based methods are derived from the Irwin-Kies formula,

$$\mathcal{G}_{IIc} = \frac{P^2}{2W} \frac{\partial C}{\partial a} \quad (1)$$

107 where P is the load, W is the specimen width, C is the compliance (the ratio between the
108 displacement and the load, δ/P) and a is the crack length.

109 To obtain the compliance, with respect to crack length rate ($\partial C/\partial a$), for each test geometry the
110 literature presents several LEFM-based data reduction methodologies which are based on Beam
111 Theory (BT), Compliance Calibration (CC) and the area method.

112 In BT-based methods, a closed form solution of the compliance (C) is derived based on specimen
113 geometry using Beam Theory. In CC-based methods, a compliance calibration is performed before
114 the test by loading and unloading the specimen at different initial crack lengths, and a relationship
115 between C and a is obtained. This function is then derived and applied in equation 1. Finally, in the
116 area method, the area enclosed in the load-displacement diagram (i.e. total energy dissipated) with
117 respect to the total amount of cracked area formation (i.e. ΔaW) is measured, and considered to be
118 the fracture toughness value.

119 Within the non-linear elastic fracture mechanics framework, and in the particular case of a
120 two-dimensional elastic problem, the J -integral is defined as

$$J = \int_{\Gamma} \left[\omega dx_2 - T_k \frac{\partial u_k}{\partial x_1} ds \right] \quad (k = 1, 2) \quad (2)$$

121 where w is the strain energy density, T_k is the tractions vector, u_k are the displacements vector and
122 ds is the length increment along a contour path Γ surrounding the crack. Several J -integral closed
123 form solutions have been derived for different test geometries [21–23]. In these, all the dissipation
124 mechanisms are considered inside the FPZ.

125 The parameters required for the data reduction are summarized in Table 1, and the different test

geometries, instrumentation and data reduction methods are described in the following subsections.

Parameter	Sensor	J -integral ¹	LEFM-based		
			BT	CC	Area
Thickness (H)	Caliper	-	✓	-	-
Width (W)	Caliper	✓	✓	✓	✓
Before testing	Initial crack length (a_0)	Optical microscope	-	✓	✓
Set up geometrical parameters ($L, c, \dots$)	Caliper	✓	✓	✓	-
Fitting parameters ($\Delta_{clamp}, m, \dots$)	Compliance Calibration test	-	-	✓	-
During the test	Load (P)	Load cell	✓	✓	✓
Displacement (δ)	Crosshead displacement	-	✓	✓	✓
Crack length (a)	Camera	-	✓	-	-
Rotations (θ)	Inclinometers	✓	-	-	-

¹ In the 4ENF test the specimen thickness is required to take into account friction effects only.

Table 1: Measurements before testing and during the test.

2.1. End-Loaded Split (ELS) test

The ELS tests were performed in a test rig designed in accordance with the ISO15114 standard [2].

The sliding fixture leads the horizontal displacement of the specimen, while the load is applied vertically through a block bonded at the bottom face of the cracked part of the specimen. The ELS test configuration is shown in Figure 1.

Figure 1: ELS geometry and instrumentation. Supports and loading applicators are represented in black. Two inclinometers are bonded at the load application points and at section S - S' . Dimensions: $L = 100$ mm, $a_0 = 55$, $a_f = 95$ mm and $L_S = 10$ mm.

The specimens were instrumented with two inclinometers, one bonded at the top face of the specimen at section S - S' and the other at the load application block (c.f. Figure 1).

134 The span length (L) was set to 100 mm with an initial crack length (a_0) of 55 mm. The tests were
 135 run at a 2 mm/min loading speed until the crack exceeded the final crack length mark ($a_f = 95$ mm)
 136 and then they were unloaded at 10 mm/min speed.

137 Before the test, a clamp calibration was performed in accordance with ISO 15114 [2]. These
 138 preliminary calibration tests were used to obtain the ELS clamp correction and the specimen flexural
 139 modulus (E); data required in Simple Beam Theory (SBT) and Corrected Beam Theory using
 140 Effective crack length (CBTE) data reduction methods. In the J -integral data reduction method,
 141 these previous calibrations can be avoided and the flexural modulus is obtained directly from the test
 142 by measuring the rotated angles at the loading application point and at section $S-S'$ (c.f. Figure 1).
 143 Different data reduction methods were used to obtain the fracture toughness (Table 2). The first
 144 three methods were the Simple Beam Theory (SBT), the Experimental Compliance Method (ECM)
 145 and the Corrected Beam Theory using Effective crack length (CBTE).

146 The fourth method used corresponds to the area method (AREA) proposed by Hashemi et al. [7]
 147 where the global energy dissipated (area enclosed in the load-displacement diagram per unit of
 148 delaminated area (ΔaW)) is evaluated.

149 Finally, the fracture toughness was measured by the J -integral, following the procedure proposed in a
 150 previous work [22] in which the J -integral was obtained from the applied loads, the rotations at the
 151 loading point and at section $S-S'$, and the strain profile at section $S-S'$. The strain profile was
 152 determined using the Beam Theory approach.

153 A detailed description of the data reduction methods can be found in each of the references included
 154 in Table 2.

155 2.2. End-Notched Flexure (ENF) test

156 While ENF tests were performed in a test rig designed according to delamination standard ASTM
 157 D7905 [1], the span length was enlarged to obtain a larger propagation region for the total FPZ
 158 development. The specimen, with a pre-crack, was sustained by two rollers and the load was applied
 159 centered on the top face of the specimen. Figure 2 shows a schematic representation of the ENF test

Method	Expression for fracture toughness	References
ECM ¹	$\mathcal{G}_{II} = \frac{3P^2 a^2 m F}{2W}$; $C = C_0 + m a^3$	[2]
SBT ^{1,3}	$\mathcal{G}_{II} = \frac{9P^2 a^2 F}{4W^2 H^3 E}$; $C = \frac{\delta}{P} = \frac{3a^3 + L^3}{2WH^3 E}$	[2]
CBTE ^{1,2,3}	$\mathcal{G}_{II} = \frac{9P^2 a_e^2 F}{4W^2 H^3 E}$; $a_e = \left(\frac{1}{3} (2W \frac{C}{N} H^3 E - (L + \Delta_{clamp})^3) \right)^{1/3}$	[2]
AREA ⁴	$\mathcal{G}_{II} = \frac{A 10^6}{\Delta a W}$	[7]
J -integral BT ⁵	$J_{II} = \frac{3}{5} \frac{P^2}{G_{12} W^2 H} + \frac{P}{W} (\tan \theta_P - \tan \theta_S) - \frac{EH}{3} \left(\frac{3}{2} \frac{P(L-L_S)}{EW H^2} \right)^2$	[22]

¹ Correction factor F for large displacements, included as described in [2].

² Correction factor N for load-block effects included as described in [2].

³ E deduced from slope (m) of the clamp calibration data, i.e. the slope of the linear regression to the $C^{1/3}$ versus L data, $E = 1/(2W(Hm)^3)$.

⁴ A is the integration of the area of the load-displacement curve.

⁵ The flexural modulus is deduced from the rotations at the loading application point (θ_P) and at section $S-S'$ (θ_S). $E = \frac{-3P(3a_0^2 + (L-L_S)^2)}{4WH^3(\theta_P - \theta_S)}$.

Table 2: ELS data reduction methods.

160 geometry and its instrumentation.

Figure 2: ENF specimen, test geometry and instrumentation. Black circles correspond to the bottom supports and the centered loading application roller, and white circles represent the inclinometers. Dimensions used were: $L = 60$ mm and $a_0 = 35$ mm, $a_f = 60$ mm and loading roller diameter = 10 mm.

161 The loading process was executed at 1 mm/min until the crack visually reached the final
 162 delamination crack length (a_f) or the system stiffened (when the FPZ reached the loading restrained
 163 section). Following this, the specimen was unloaded at 25 mm/min.

164 Different data reduction methods were used to measure fracture toughness. The methods based on
 165 LEFM were the Simple Beam Theory (BT) [13, 25], the Corrected Beam Theory (CBT) [13, 26, 27],
 166 and three compliance calibration based methods, called CCM, CC2 and CC3, according to the
 167 number of terms used in the third order polynomial used in the calibration, linear regression [27, 28],

second order [29] and third order [4, 30], respectively.

The compliance calibration was done by loading and unloading the specimen at different crack lengths, without propagation. The crack lengths used for calibrations were 15 mm, 20 mm, 25 mm, 30 mm and 40 mm.

As in the ELS test, the area method (AREA) proposed by Hashemi et al. [7] was considered in the analysis.

Finally, the fracture toughness was measured using the J -integral by following the procedure proposed by Stigh et al. [21]. For this purpose, three inclinometers were bonded to the specimen to measure the rotations at the contact points. The two external inclinometers (θ_1 and θ_3) are located between the line of the reaction force and the end of the beam while the centered inclinometer (θ_2) is located aligned with the upper loading roller.

Table 3 summarizes the ENF data reduction methods used.

Method	Expression for fracture toughness	References
BT ¹	$\mathcal{G}_{II} = \frac{9P^2a^2}{16W^2H^3E}$	[13, 25]
CBT ²	$\mathcal{G}_{II} = \frac{9P^2a^2C_0}{2W(2L^3+3a_0^3)}$	[13, 26, 27]
CCM	$\mathcal{G}_{II} = \frac{3P^2ma}{2W}; C = C_\alpha + ma^3$	[27, 28]
CC2	$\mathcal{G}_{II} = \frac{P^2}{2W} \frac{\partial C}{\partial a}; C = C_\alpha + C_\beta a + C_\gamma a^3$	[29]
CC3	$\mathcal{G}_{II} = \frac{P^2}{2W} \frac{\partial C}{\partial a}; C = C_\alpha + C_\beta a + C_\gamma a^2 + C_\lambda a^3$	[4, 30]
AREA ³	$\mathcal{G}_{II} = \frac{A10^6}{\Delta a W}$	[7]
J -integral	$J_{II} = \frac{P}{2W} (\tan(\theta_1) + \tan(\theta_3) - 2\tan(\theta_2))$	[21]

¹ E from elastic range load-displacement curve; $E = \frac{2L^3+3a_0^3}{8WH^3} \frac{\Delta P}{\Delta \delta}$.

² C_0 is the compliance of the initial, linear portion of the load versus displacement curve.

³ A is the integration of the area of the load-crosshead displacement diagram.

Table 3: ENF data reduction methods summary.

180 2.3. Four-point End Notched Flexure (4ENF) test

181 The Four-point End Notched Flexure tests were run in a test fixture designed by the authors, see
182 Figure 3.

Figure 3: 4ENF test fixture.

183 The bottom part of the fixture is the same as in the ENF and the top part allows for the free
184 rotation of the upper rollers, allowing them to be in permanent contact with the specimen.
185 A schematic of the 4ENF test geometry and the location of the inclinometers used to measure the
186 rotations at the loading application edges is shown in Figure 4.

Figure 4: 4ENF geometry and instrumentation. Black circles correspond to supports and loading rollers and white circles represent the inclinometers. Dimensions used were: $L = 60$ mm, $a_0 = 35$ mm, $a_f = 60$ mm and roller radius = 5 mm.

187 The total lower span length ($2L$) was set to 100 mm. The upper rollers were centered at a span

distance of $L = 60$ mm. The initial crack length was set to 35 mm from the left bottom roller. The specimen was loaded at a speed of 1 mm/min speed and unloaded at 5 mm/min. Tests were stopped when the crack tip (visually inspected by the camera) reached the final distance of 60 mm (a_f). Three LEFM-based data reduction methods were considered: the Simple Beam Theory (SBT) [8], the Experimental Compliance Method (ECM) [5], and the Compliance Calibration Method (CCM) [5]. Additionally, a J -integral data reduction method, which takes into account the frictional effects was developed for this test:

$$J_{II} = \frac{P}{2W} (-\sin \theta_1 - \sin \theta_2 + \sin \theta_3 + \sin \theta_4 - \frac{3PL\mu \cos \theta_3}{2WH^2E}) \quad (3)$$

where P is the applied load, W is the specimen width, H is the half thickness of the specimen, L is the half span length, E is the adherend longitudinal modulus, μ is the friction coefficient between cracked surfaces, θ_1 and θ_2 are the rotations of the specimen at the arms between the edge of the bottom rollers and the end of the specimen and θ_3 and θ_4 are the rotations of the specimen at the upper roller application edges (c.f. Figure 4). Details of the J -integral derivation for the 4ENF test are described in Appendix A.

The last term in equation (3) takes into account the frictional effects. Davidson et al. [5] estimated the frictional resistance to the crack propagation in specimens similar to M1 and M2, obtaining a friction coefficient of $\mu = 0.345$ with a coefficient of variation of 8.5%. This friction coefficient value was used in the analysis to account for the friction effects.

Table 4 summarizes the 4ENF data reduction methods used in the fracture toughness calculation.

2.4. Mixed Mode Bending (MMB) test

While the Mixed Mode Bending (MMB) tests were done according to the ASTM D6671 test standard [3], the span length was modified to ensure total FPZ development during testing. The test geometry and instrumentation is schematically shown in Figure 5. The specimens are subjected to loading by two load blocks (bonded at the pre-cracked end of the specimen) and supported by the

Method	Expression for fracture toughness	References
BT ¹	$\mathcal{G}_{II} = \frac{9P^2L}{32WH^2E}$	[8]
ECM ²	$\mathcal{G}_{II} = \frac{P^2m}{2W}$; $m = \frac{C-C_0}{a_{VIS}}$	[5]
CCM ³	$\mathcal{G}_{II} = \frac{P^2C_1}{2W}$; $C_1 = \frac{C-C_0}{a_{cal}}$	[5]
AREA ⁴	$\mathcal{G}_{II} = \frac{A10^6}{\Delta aW}$	[7]
J -integral ^{1,5}	$J_{II} = \frac{P}{2W}(-\sin\theta_1 - \sin\theta_2 + \sin\theta_3 + \sin\theta_4 - \frac{3PL\mu\cos\theta_3}{2WH^2E})$	eq. (3)

$$^1 E = \frac{L^2(L+9a_0)}{32WH^3} \frac{\Delta P}{\Delta \delta}$$

² Direct measure of a_{VIS} during the test.

³ C_1 obtained from compliance calibration (C Vs a_{cal}).

⁴ A is the area of the load-crosshead displacement curve.

⁵ $\mu = 0.345$ [5].

Table 4: Summary of 4ENF data reduction methods.

lower base of the test tool. The load is introduced vertically via the upper lever which pushes the specimen down at its half span length point and, at the same time, pulls the upper arm of the cracked region up by its end. The length of the lever arm (c) is used to adjust the mode mixture. To apply a pure mode II, it was set to $c = L/3$, [3]. The loading process was done at 0.5 mm/min until the crack visually reached the final delamination crack length (a_f) or the system stiffened. The specimen was then unloaded at 2.5 mm/min.

Figure 5: MMB geometry and instrumentation. In black, the supports and the loading applicators, white circles represent the inclinometers. Dimensions used were: $L = 60$ mm, $a_0 = 35$ mm, $a_f = 60$ mm and roller radius = 5 mm.

Two data reduction methods were used in calculations. Firstly, the method proposed in standard [3], which is based on crack length measurement (a),

$$\mathcal{G}_{II} = \frac{9P^2(c+L)^2a^2}{16W^2H^3L^2E_{1f}} \quad (4)$$

where E_{1f} is the modulus of elasticity in the fibre direction measured in flexure,

$$E_{1f} = \frac{8a_0^3(3c+L)^2 + [6a_0^3 + 4L^3](3c+L)^2}{16L^2WH^3\left(\frac{1}{m} - C_{sys}\right)} \quad (5)$$

and C_{sys} is the compliance of the MMB test system, m is the slope of the load-displacement curve

and a_0 , c , L , W and H are geometric parameters of the test (see Figure 5).

On the other hand, the J -integral was evaluated according to the expression [23],

$$J_{II} = \frac{P}{W} \left[\left(\frac{1}{2} - \frac{c}{2L} \right) \tan \theta_1 + \left(\frac{c}{2L} + \frac{1}{2} \right) \tan \theta_2 + \frac{c}{L} \tan \theta_3 - \left(\frac{c}{L} + 1 \right) \tan \theta_4 \right] \quad (6)$$

where P is the applied load, W is the specimen width, L is the half span length, c is the lever arm

and θ_1 , θ_2 , θ_3 and θ_4 are the rotations of the specimen at the supports and at the loading application

points (see Figure 5).

3. Results and discussion

The load-displacement curves of all the specimens tested are shown in Figure 6. The curves are

grouped by test configuration (ENF, ELS, MMB and 4ENF) and material (M1 and M2). No curves

were obtained for M2 specimens of 4ENF and MMB test configurations, since a premature failure

occurred in the adherend, invalidating the results.

Large differences in the load-displacement curves between the tests are observed, due to their

intrinsic configuration. For example, the ELS test involves low loading values but large deflections,

whereas in the 4ENF high loads are reached with small deflections.

In addition, the 4ENF load-displacement curves differ from the others due to their intrinsic stable

configuration. The load is kept constant during the steady state propagation [8].

236 On the other hand, as the crack was allowed to propagate all the way to the load point in the ELS,
237 the ENF and the MMB tests, when the FPZ reached the clamp point (in the ELS test) or restrained
238 sections (in the ENF and the MMB tests), a non-linear behaviour in load-displacement was observed.
239 Finally, differences between initial stiffness in the load-displacement curves for the same batch were
240 observed. The first cause is related to the precision on positioning the specimen or bonding the load
241 block to obtain the desired initial crack length, a_0 , which is a manual procedure. Secondly it is worth
242 noticing that every batch is formed by specimens coming from different panels.

Figure 6: Load-displacement curves of tested specimens.

Figure 7 shows the R -curves (energy release rate vs. crack length), obtained from each data reduction method, for a representative M1 specimen from each test. For convenience, the results are normalized with respect to the averaged value of J_{IIc} obtained from M1 specimens tested with the

ELS, which had a fracture toughness of $J_{ELS}(M1) = 4.64 \text{ KJ/m}^2$. Although the J -integral does not make use of the crack length in calculations, for comparison purposes it is represented against the equivalent crack length, measured from compliance calibration methods; from CC in ENF and 4ENF tests, and from CBTE in ELS test (Tables 2 to 4). In the MMB tests, the equivalent crack length was not measured, and Figure 7d shows only visual propagation values of $\mathcal{G}_{II}$. In this case, the values of J -integral are represented against the visual crack length, instead of an estimated value. Each measured or calculated crack length has its associated load, deflection and rotations values. These are used to measure and represent the J -integral in front of an equivalent crack length. In each curve, the fracture toughness is measured when the R -curve reaches a plateau, which is indicated in each curve in Figure 7 by filled dots or a thick line.

Figure 7: R -curve for each data reduction method of a representative M1 specimen from each batch. The energy release rate values are normalized with respect to the averaged value of J_{IIc} from the M1 ELS batch (blue line in (a)).

For each test and data reduction method, the fracture toughness is obtained from the plateau value. Tables 5 to 8 list the average values of the fracture toughness and the standard deviation of each specimen batch. Each table provides information from one of the tests, i.e. Table 5 corresponds to the ELS, Table 6 to the ENF, Table 7 to the 4ENF and Table 8 to the MMB. The columns indicate the data reduction method described in Section 2 and the rows the materials: M1 and M2. As previously stated, Tables 7 and 8 only show results from M1 because no results were obtained for material M2. All the values are normalized with respect to J_{IIc} from the M1 obtained from the ELS test (Table 5). It is worth noticing that cohesive failure within the adhesive occurred in all specimens, except for the unstable propagation cases.

Batch		J_{IIc}	$\mathcal{G}_{IIc}$ (CBTE)	$\mathcal{G}_{IIc}$ (ECM)	$\mathcal{G}_{IIc}$ (SBT)	$\mathcal{G}_{IIc}$ (AREA)
M1	Average	1.00	0.94	0.68	1.22	0.92
	SD ¹	0.17	0.11	0.11	0.20	0.15
M2 ²	Average	1.06	1.10	1.12	1.15	-
	SD ¹	0.07	0.09	0.35	0.29	-

¹ Standard Deviation.

² Final unstable crack growth invalidate $\mathcal{G}_{IIc}$ (AREA) data reduction method.

Table 5: ELS tests summary of results. All values are normalized with respect to the averaged value of J_{IIc} from the M1 ELS batch.

Table 5 summarizes the ELS test results for materials M1 and M2. There are no values from the AREA method for the M2 batch because unstable propagation occurred after reaching steady state propagation, thus invalidating the measure of the final crack length. Some of the data reduction methods present large differences with respect to the reference value and between them (i.e. $\mathcal{G}_{IIc}$ (ECM) and $\mathcal{G}_{IIc}$ (SBT), having differences of more than a 20% in the mean value). Furthermore, the average fracture toughness of each batch results in large SD for all test methods, probably due to the fact that each batch contains specimens from different panels. However, the discrepancies between the data reduction methods are too large to be considered as material heterogeneity. Therefore, to a large extent they must be attributed to the data reduction method used. From the comparison

between M1 and M2, the authors expected no changes in the fracture toughness, because the adhesive layer was the same. In this sense, the J -integral and the CBTE are the data reduction methods that provide fewer differences between both materials, with J -integral giving the smallest difference. The relative error between both methodologies is less than 6%. A discrepancy of $\mathcal{G}_{IIc}$ (ECM) and $\mathcal{G}_{IIc}$ (SBT) results compared to those obtained with the CBTE method was expected, as this has been stated in a round-robin study on carbon-fibre epoxy material [31].

Batch		J_{IIc}	$\mathcal{G}_{IIc}$ (CCM)	$\mathcal{G}_{IIc}$ (CC2)	$\mathcal{G}_{IIc}$ (CC3)	$\mathcal{G}_{IIc}$ (BT)	$\mathcal{G}_{IIc}$ (CBT)	$\mathcal{G}_{IIc}$ (AREA)
M1	Average	0.99	1.00	1.01	1.03	1.23	0.87	1.02
	SD ¹	0.17	0.15	0.13	0.28	0.21	0.18	0.11
M2	Average	0.98	1.01	1.07	1.26	1.41	1.04	0.98
	SD ¹	0.22	0.18	0.30	0.54	0.31	0.16	0.28

¹ Standard deviation.

Table 6: ENF tests summary of results. All values normalized with respect to averaged value of J_{IIc} from the M1 ELS batch.

Similarly to what it is observed in the ELS results, there are significant differences in some of the methods (of more than 20 %). Only the J -integral and CCM provide values of $\mathcal{G}_{IIc}$ closer to those obtained from the ELS test. Besides this, both methods are independent of the adherend used, having small differences, of less than 2%, in the fracture toughness measurement between M1 and M2. The increment in the number of terms in the third order polynomial used in the calibrations (CC2 and CC3 in Table 3), which may be interpreted as an improvement in the correlation between C and a , has in some cases, a negative effect on the fracture toughness measurement, increasing the difference between the J_{IIc} from the M1 ELS and the $\mathcal{G}_{IIc}$ (CC3) from M2 ENF up to 26%. As the calibrations have been run in a crack length range between 10 mm to 40 mm and the crack propagation region is from 35 mm to 60 mm, the discrepancy may be attributed an inadequate definition of the calibration range.

It is also observed that the standard deviation of the J -integral obtained with the ENF is higher

than the homonym obtained from the ELS. This increment may have been produced by the fact that in ENF tests the self-similar growth region is smaller than in the ELS (c.f. Figures 7b and 7a, respectively), consequently increasing the difficulty in defining a propagation range in the R -curve, thus incrementing the dispersion in the results.

Table 7 shows a summary of results obtained in the 4ENF tests. In those carried out with M2 adherend, failure occurred at the initial stage of propagation and the results could not be obtained. None of the data reduction methods takes into account the friction effects, albeit except for the J -integral, in which the friction coefficient is defined as $\mu = 0.345$ [5].

M1 batch	J_{IIc}	$\mathcal{G}_{IIc}$ (CCM)	$\mathcal{G}_{IIc}$ (ECM)	$\mathcal{G}_{IIc}$ (BT)	$\mathcal{G}_{IIc}$ (AREA)
Average	0.96	1.08	0.93	1.54	1.28
SD ¹	0.18	0.15	0.10	0.24	0.44

¹ Standard deviation.

Table 7: 4ENF summary of results. All values normalized with respect to the averaged value of J_{IIc} from the M1 ELS batch.

Again, the J -integral offers similar results to those obtained from the ENF and ELS tests. Results from the CCM are also in fairly good agreement with those obtained from the other tests. On the other hand, large differences are encountered in the methods that directly depend on the crack length measurement, i.e. BT and AREA. Despite also depending on the crack length measurements, like the CCM, the ECM provides acceptable results of $\mathcal{G}_{IIc}$ (less than 10% difference). The discrepancies between the J -integral and the other methods can be explained by the friction effects and the difficulties in mode II crack length measurement.

As in the 4ENF test, in the MMB tests M2 specimens were broken before crack propagation, thus invalidating the results. For the M1 specimens, the results obtained following the MMB test standard [3] ($\mathcal{G}_{IIc}$) are higher than those obtained in the ENF, ELS or 4ENF tests, similar to what occurred in the previous test methodologies that depend on crack length measurements. Again the J -integral offers close values to the previous tests.

M1 batch	J_{IIc}	$\mathcal{G}_{IIc}$
Average	0.93	1.33
SD ¹	0.11	0.24

¹ Standard deviation.

Table 8: MMB tests summary of results. All values normalized with respect to the averaged value of J_{IIc} from the M1 ELS batch.

312 To graphically observe the deviation between the methods, Figure 8 shows the average results, with
313 their corresponding standard deviation, for the J -integral and compliance calibration based methods
314 (except the CC2 and CC3 from ENF). In essence, all the data reduction methods that depend
315 directly on crack length measurement are not included in the plot.
316 A very good agreement between J -integral-based results is observed for all test typologies (differences
317 between them below 10%) and materials (differences below 6%).
318 On the other hand, the CC-based data reduction methods are also providing similar results of
319 fracture toughness regardless of the test used (CBTE in ELS, CCM in ENF and CCM in 4ENF), and
320 despite not providing the same accuracy as the J -integral-based methods. However, larger
321 differences, compared with the J -integral case are observed between the M1 and M2 batches when
322 using CC-based methods (differences up to 16% in the ELS test).

Figure 8: Summary of results. Batch average and standard deviation of each batch normalized with respect to the J_{IIc} average value from all specimens tested.

4. Conclusions

With the aim of obtaining a reliable mode II fracture toughness test procedure for structural adhesives, four delamination-based mode II test methods (ELS, ENF, 4ENF and MMB) have been compared through an experimental test campaign with bonded joints between CFRP. Additionally, two specimen typologies (M1 and M2) were tested, with the same adhesive but each with a different adherend. For each test, different data reduction methods were used to obtain the fracture toughness, LEFM and J -integral. For this purpose, a data reduction method based on the J -integral was developed for the 4ENF test.

From the analysis of the results, in determining the fracture toughness there were some discrepancies between the tests and the data reduction methods.

The methods based on the visual crack length monitoring show differences in the determination of the fracture toughness because they mainly depend on the measurement of the crack length, and a well defined crack tip does not exist when testing adhesives under mode II loadings. Therefore they

are not reliable for measuring fracture toughness. On the contrary, methods that are not based on a direct measurement of the crack length, such as CC-based (CBTE in ELS, and CCM in ENF and 4ENF) and the J -integral, result in small differences between the different test typologies and materials. Even though the CBTE and CCM methods are based on LEFM, they rely on calculating an equivalent crack length that somehow takes into account the FPZ length. This is why their results show better agreement with the J -integral approach, based entirely on a non-linear fracture mechanics framework.

In all the tests carried out, the J -integral was independent of the test typology and material, but the CC-based methods were also in acceptable agreement with those obtained with the J -integral.

During the data analysis, some limitations in the test methods were detected that are summarized next.

The ENF test is very simple, only requiring a common three point bending test fixture. However, the propagation region must be large enough to allow the fracture process zone to fully develop. Even though the span length was increased from 100 mm to 120 mm in the specimens tested, the propagation occurred just before the load application point thus resulting in a small range with which to calculate the propagation fracture toughness. This caused larger standard deviations than in the rest of the tests.

Taking into account the same total span length in all the tests (120 mm), the M2 specimens were broken when tested with the MMB and 4ENF, showing that these tests are more prone to causing premature failure to the specimen before any propagation occurs. Apart from that, they also involve complex test fixtures. In addition, the 4ENF showed to be highly affected by the friction at the adhesive layer.

Despite involving large deflections and needing to use a more complex test fixture, the ELS test is the best candidate for testing adhesives due to its intrinsic configuration that provides stable and large propagation regions.

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Appendix A.

The J -integral closed form for the 4ENF test has been derived following an analogous procedure to that of the MMB test [23].

The tractions vector in equation (2) is defined as $T_i = \sigma_{ij}n_j$, where σ_{ij} is the stress tensor and n_j is a unit vector normal to the integration path. The path enclosing the crack tip (Γ) and bounding a region R selected in 4ENF is shown in Figure A.1a. Γ runs along the external contour of the specimen and results in the summation of Γ_a , Γ_b , Γ_c , Γ_d , Γ_e , Γ_f and Γ_g . As the selected region R enclosing the FPZ, the integration path along the specimen external contour, J_Γ , is equal to J_{TIP} .

Figure A.1: External applied loads and integration paths Γ in 4ENF specimen for J -integral derivation.

According to Figure A.1a, Γ_a , Γ_c and Γ_f paths are stress-free, therefore $J_{\Gamma_a} = J_{\Gamma_c} = J_{\Gamma_f} = 0$. If the vertical tractions in Figure A.1a are considered as concentrated forces applied in an infinitesimal region dx_1 at points P1 to P5, then $\int \sigma_{22}^i dx_1 = P_i/W$. Due to the 4ENF configuration (c.f. 4), in points P1 to P5 $P_i = P/2$.

In path Γ_b , $dx_2 = 0$, and the first term in equation (2) disappear and the normal vector to path Γ_b is $n = [1 \ 0]$. As σ_{12} is zero at points P3 and P4, and σ_{22}^{P3} and σ_{22}^{P4} take the value of the half external

379 applied load, $P/2$, the traction vectors at points P3 and P4 results in $T_k^{P3} = T_k^{P4} = -[0 \ \frac{P}{2W}]$.

380 Following an analogous procedure for path Γ_g , the corresponding traction vectors for points P1 and
381 P2 are obtained; $T_k^{P1} = T_k^{P2} = [0 \ \frac{P}{2W}]$.

382 In path Γ_d , the stresses are given by the contact between crack surfaces. Only the friction between
383 the cracked surfaces has been taken into account in the calculations. As contact pressure is much
384 higher below the load application roller, the contact load has been assumed to be a punctual load
385 below the roller contact point (Figure A.1).

386 The normal vector to path Γ_d is $n = [-1 \ 0]$ and the corresponding traction vector at point P5+
387 results in $T_k^{P5+} = \frac{P}{2W}[\mu \ 1]$. The analogous procedure applied to path Γ_e results in the traction vector
388 at point P5- $T_k^{P5-} = \frac{-P}{2W}[\mu \ 1]$

389 The derivative of the displacements at points P_i is defined as $\frac{\partial u_k}{\partial x_1} = [\frac{\partial u_1^{P_i}}{\partial x_1} \ \frac{\partial u_2^{P_i}}{\partial x_1}] = [\varepsilon_{11}^{P_i} \tan \theta_{P_i}]$, where
390 θ_{P_i} is the rotation angle at point P_i , positive in counterclockwise direction, and $\varepsilon_{11}^{P_i}$ are the
391 longitudinal strains.

392 The derivation of J is analogous for all points (P1 to P5) only changing the T_k as described before,
393 and ds depending on the path direction. In doing so, the following expression of the J -integral in
394 4ENF specimen is obtained:

$$J_{II} = \frac{P}{2W}(-\tan \theta_1 - \tan \theta_2 + \tan \theta_3 + \tan \theta_4 - \mu \varepsilon_{11}^{P5+} E + \mu \varepsilon_{11}^{P5-} E) \quad (A.1)$$

395 where μ is the friction coefficient between crack surfaces, E is the adherend longitudinal young
396 modulus and ε_{11} are the corresponding longitudinal strains at the contact points in cracked surfaces.

397 By applying Beam Theory, ε_{11} at points P5+ and P5- are obtained as a function of the span length
398 (L), the specimen dimensions (W and H) and the longitudinal young modulus of the adherend (E)
399 reading

$$\varepsilon_{11}^{P5+} = -\varepsilon_{11}^{P5-} = \frac{3PL}{4WH^2E} \quad (A.2)$$

As the rotations at the load application points must be known to calculate the J -integral (equation A.1), these can be used to take into account large rotations. If only the vertical component of the forces ($P \cos(\theta_n)$) is used in the J -integral calculation, and replacing equation A.2 into equation A.1 it results in:

$$J_{II} = \frac{P}{2W} (-\sin \theta_1 - \sin \theta_2 + \sin \theta_3 + \sin \theta_4 - \frac{3PL\mu \cos \theta_3}{2WH^2E}) \quad (A.3)$$

where P is the applied load, W is the specimen width, H is the half thickness of the specimen, L is the half span length, μ is the friction coefficient and θ_1 , θ_2 , θ_3 and θ_4 are the rotations of the specimen at the roller application edges (c.f. Figure 4).

References

- [1] ASTM D7905M-14 . Standard Test Method for Determination of the Mode II Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer. American Society for Testing and Materials 2014;.
- [2] ISO 15114:2014 . Fibre-reinforced plastic composites - Determination of the mode II fracture resistance for unidirectionally reinforced materials using the calibrated end-loaded split (C-ELS) test and an effective crack length approach. International Standard Organization, Geneva, Switzerland 2014;(1):1–26.
- [3] ASTM D6671/D6671M . Standard Test Method for Mixed Mode I-Mode II Interlaminar Fracture Toughness of Unidirectional Fiber Reinforced Polymer Matrix Composites. American Society for Testing and Materials 2013;.
- [4] Schuecker C, Davidson B. Evaluation of the accuracy of the four-point bend end-notched flexure test for mode II delamination toughness determination. Composites Science and Technology 2000;60:2137–46.

- 421 [5] Davidson B, Sun X, Vincierra A. Influences of Friction, Geometric Nonlinearities, and Fixture
422 Compliance on Experimentally Observed Toughnesses from Three and Four-point Bend
423 End-notched Flexure Tests. *Journal of Composite Materials* 2007;41(10):1177–96. URL:
424 <http://jcm.sagepub.com/cgi/doi/10.1177/0021998306067304>.
- 425 [6] Carité D, Davies P, Peleau M, Partridge IK. The influence of hydrostatic pressure on the
426 interlaminar fracture toughness of carbon/epoxy composites TITRE. *Composites Part B:*
427 *Engineering* 2006;37(4-5):292–300. doi:10.1016/j.compositesb.2005.12.002.
- 428 [7] Hashemi S, Kinloch A, Williams J. The analysis of interlaminar fracture in uniaxial
429 fiber-polymer composites. *Proceedings of the Royal Society A* 1990;427:173–99.
430 doi:10.1098/rspa.1990.0007.
- 431 [8] Martin R, Davidson B. Mode II fracture toughness evaluation using four point bend, end
432 notched flexure test. *Plastics, Rubber and Composites* 1999;28(8):401–6. doi:ISSN 1465-8011.
- 433 [9] Davidson B, Sun X. Effects of friction, geometry, and fixture compliance on the perceived
434 toughness from three- and four-point bend end-notched flexure tests. *Journal of Reinforced*
435 *Plastics and Composites* 2005;24(15):1611–28.
- 436 [10] Blackman BRK, Kinloch AJ, Rodriguez-Sanchez FS, Teo WS. The fracture behaviour of
437 adhesively-bonded composite joints: Effects of rate of test and mode of loading. *International*
438 *Journal of Solids and Structures* 2012;49(13):1434–52. URL:
439 <http://dx.doi.org/10.1016/j.ijsolstr.2012.02.022>. doi:10.1016/j.ijsolstr.2012.02.022.
- 440 [11] Davies P, Blackman BRK, Brunner A. Standard test methods for delamination resistance of
441 composite materials: current status. *Applied Composite Materials* 1998;5(Iso 4585):345–64.
442 doi:10.1023/a:1008869811626.
- 443 [12] Davies P, Kausch H, Williams J, Kinloch AJ, Charalambides M, Pavan A, et al. Round-robin
444 interlaminar fracture testing of carbon-fibre-reinforced epoxy and PEEK composites.

- 445 Composites Science and Technology 1992;43(2):129–36. URL:
446 <https://www.sciencedirect.com/science/article/pii/026635389290003L>.
447 doi:[https://doi.org/10.1016/0266-3538\(92\)90003-L](https://doi.org/10.1016/0266-3538(92)90003-L).
- 448 [13] Davies P, Sims G, Blackman BRK, Brunner A, Kageyama K, Hojo M, et al. Comparison of test
449 configurarions for the determination of GIIC: results from an international round robin.
450 Plastics, Rubber and Composites 1999;28(September):432–7.
- 451 [14] Davies P. Summary of results from the second VAMAS mode II round robin test exercise using
452 the 4ENF specimen. IFREMER Report TMSI/RED/MS 9982 1999;.
- 453 [15] Davies P. Review of standard procedures for delamination resistance testing. In: Delamination
454 Behaviour of Composites. 2008, p. 65–86.
- 455 [16] Carlsson L, Gillespie J. Mode-II Interlaminar Fracture of Composites. In: Friedrich K, editor.
456 Application of Fracture Mechanics to Composite Materials; chap. 4. 1989, p. 113–57.
- 457 [17] Vassilopoulos AP. Fatigue and Fracture of Adhesively-bonded Composite Joints Behaviour,
458 Simulation and Modelling. 2015. ISBN 9780857092700. doi:10.1016/C2013-0-16372-6.
- 459 [18] Blackman BRK, Kinloch A, Paraschi M. The determination of the mode II adhesive fracture
460 resistance, GIIC, of structural adhesive joints: an effective crack length approach. Engineering
461 Fracture Mechanics 2005;72(6):877–97. doi:10.1016/j.engfracmech.2004.08.007.
- 462 [19] Högberg J, Sørensen B, Stigh U. Constitutive behaviour of mixed mode loaded adhesive layer.
463 International Journal of Solids and Structures 2007;44(25-26):8335–54.
464 doi:10.1016/j.ijsolstr.2007.06.014.
- 465 [20] Rice J. A Path Independent Integral and the Approximate Analysis of Strain Concentration by
466 Notches and Cracks. Journal of Applied Mechanics 1968;35:379–86. doi:10.1115/1.3601206.
- 467 [21] Stigh U, Alfredsson KS, Biel A. Measurement of cohesive laws and related problems.

- 468 IMECE2009: Proceedings of the ASME International Mechanical Engineering Congress and
469 Exposition 2009;(11):293–8.
- 470 [22] Pérez-Galmés M, Renart J, Sarrado C, Rodríguez-Bellido A, Costa J. A data reduction method
471 based on the J-integral to obtain the interlaminar fracture toughness in a mode II end-loaded
472 split (ELS) test. *Composites Part A: Applied Science and Manufacturing* 2016;90:670–7.
473 doi:10.1016/j.compositesa.2016.08.020.
- 474 [23] Sarrado C, Turon A, Renart J, Costa J. An experimental data reduction method for the Mixed
475 Mode Bending test based on the J-integral approach. *Composites Science and Technology*
476 2015;117(117):85–91. doi:10.1016/j.compscitech.2015.05.021.
- 477 [24] ISO 25217:2014 . Adhesives - Determination of the mode I adhesive fracture energy of
478 structural adhesive joints using double cantilever beam and tapered double cantilever beam
479 specimens. International Organization for Standardization, Geneva, Switzerland 2009;.
- 480 [25] AITM 1.0006:1994 . Carbon Fibre Reinforced Plastics Determination of interlaminar fracture
481 toughness energy (Mode II GIIC-TEST). Airbus Industries Test Method 1994;(2):1–8.
- 482 [26] Russell A, Street K. Moisture and Temperature Effects on the Mode I and Mode II Interlaminar
483 Fracture of Graphite/Epoxy Composites. *Key Engineering Materials* 1989;37:199–208.
484 doi:10.1520/STP36314S.
- 485 [27] Carlsson LA, Gillespie JW, Trethewey BR. Mode II Interlaminar Fracture of Graphite/Epoxy
486 and Graphite/PEEK. *Journal of Reinforced Plastics and Composites* 1986;5(3):170–87.
487 doi:10.1177/073168448600500302.
- 488 [28] de Moura M, Campilho RDSG, Gonçalves JPM. Pure mode II fracture characterization of
489 composite bonded joints. *International Journal of Solids and Structures* 2009;46(6):1589–95.
490 URL: <http://dx.doi.org/10.1016/j.ijsolstr.2008.12.001>.
491 doi:10.1016/j.ijsolstr.2008.12.001.

- 492 [29] Bhashyam S, Davidson B. Evaluation of data reduction methods for the mixed mode bending
493 test. Aiaa J 1997;35(3):546–52. doi:10.2514/3.13538.
- 494 [30] Polaha J, Davidson B, Hudson R, Pieracci A. Effects of Mode Ratio, Ply Orientation and
495 Precracking on the Delamination Toughness of a Laminated Composite. Journal of Reinforced
496 Plastics and Composites 1996;15(2):141–73. URL:
497 <http://journals.sagepub.com/doi/pdf/10.1177/073168449601500202>.
- 498 [31] Blackman BRK, Brunner A, Williams J. Mode II fracture testing of composites: a new look at
499 an old problem. Engineering Fracture Mechanics 2006;73(16):2443–55.
500 doi:10.1016/j.engfracmech.2006.05.022.

Experimental mode II test campaign of adhesive joints.

Comparison among ENF, ELS, 4ENF and MMB test results.

Comparison between LEFM and NLFM (J-integral) data reduction methods.