DYNAMIC CHARACTERIZATION OF INTERLAMINAR TOUGHNESS IN CARBON FIBRE EPOXY COMPOSITE LAMINATES

M.A. Riezzo[1,3], M. Simmons[2], C. González [1,3], F. Sket[1]

[1]IMDEA Materials Institute, C/Eric Kandel, 2, 28906 Getafe, Madrid, Spain
Email: maria.azzurra@imdea.org, Web Page: http://www.imdea.org
[2]Hexcel Composites, Duxford, Cambridge CB22 4QB, United Kingdom
[3]Departmento de Ciencia de Materiales, Universidad Politécnica de Madrid, 28040 Madrid, Spain

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Abstract
In this work, the rate dependence of mode I interlaminar fracture laminates for three different materials systems, two unidirectional UD carbon-fibre epoxy composite laminates and one RTM plain woven fabric laminate have been investigated over a wide range of loading rates (0.5 mm/min – 500 mm/s) at room temperature. Quasi-static fracture tests are performed by the DCB (double cantilever beam) method with a screw-driven testing machine (INSTRON 5966), while the dynamic tests are performed by the WIF (wedge insert fracture) method using a Gleeble 3800 GTC hydraulic system for accurate measurement of impact fracture toughness. For performing the tests at high strain rate, a special setup was designed and manufactured. The experimental technique proposed by Kusaka et al. [1,2] is employed to provide accurate measurement of the fracture toughness under dynamic load. The compliance calibration method [3] is used for the data reduction, comparing the results with the area method obtained for quasi-static test for validation. For the three material systems the fracture toughness shows a rate-sensitivity.

1. Introduction
Loading rates effects on composite materials has been a subject of investigation for some time [1-9]. Particularly on mode I and II interlaminar toughness discrepancies in results are observed from the available reports in the rate effect on the initiation fracture toughness value in polymer composites. Some researchers reported that initiation fracture toughness increased with loading rate [4-6], while other studies contradict these findings [7-8]. Kusaka et al. [9] claimed a stepwise-drop of fracture toughness with increasing loading rate. On the other hand, a few researchers reported that dynamic initiation fracture toughness was insensitive to loading rate [10], and that the dynamic fracture toughness was insensitive to crack propagation speed [11]. It should be noted that most of these conclusions were based on test data that exhibited significant scatter and for different material systems. However, very few systematic studies have been carried out on the rate dependence of modes I and II interlaminar fracture behaviour from quasi-static to impact loading up to several tens of $m \cdot s^{-1}$, which will be necessary for the discussion of high-speed propagation of an unstable crack. This seems to be caused by the difficulty to estimate the fracture toughness under impact loading due to the influence of the inertia force both in the specimen and measurement system. Kusaka et al. [1,2,9] have, therefore, spent much effort in developing experimental methods for estimating the fracture toughness under impact loading demonstrating that fracture toughness decreased stepwise with increasing loading rate only in the region between 0.05 mm/min and 5 mm/min and was rate-insensitive above this speed range.
The purpose of this work is to characterize the rate dependence of mode I interlaminar fracture behaviour in two unidirectional UD and one plain woven carbon-fibre/epoxy composite laminates over a wide range of loading rates from quasistatic (displacement rate, $\dot{\delta}$= 0.5-450 mm/min) to high rate ($\dot{\delta}$= 0.5 m/s). The experimental technique proposed by Kusaka et al. [1,2,9] was employed to provide accurate measurement of the fracture toughness under high rate. A computational FEM model was also used to validate the methodology and to support the experimental part.

2. Experimental procedure

2.1. Material and specimen preparation

Three different material systems, two unidirectional UD carbon-fibre epoxy composite laminates and one RTM plain woven fabric laminate, were studied in this work. One of the UD is a 8552/IM7, a second generation prepreg ,the second UD is a M91/IM7, a third generation prepreg. The RTM system is a 46290 WB1010 weave/ RTM 250 with improved toughness properties.
The unidirectional panels of 12 plies, with a lay-up of $[0]_{6s,}$ were cured in the autoclave according to the prepreg manufacturer's recommended curing cycle (180 °C for 135 min, with a heating/cooling rate of 2 °C/min). The cured thickness of the panel was 3 mm. The RTM panels of 12 plies, with a lay-up of $[0]_{6s,}$ were fabricated through RTM processing. The injection process took place at 160 °C with a pressure of around 2 bar. The cured thickness of the panel was 4 mm. A 25 µm thick polytetrafluoroethylene (PTFE) film was inserted between the plies at the mid-plane of the panel to introduce an artificial starter slit. A pre-crack of about 2-3 mm was first introduced with a razor blade for the WIF test, meanwhile for the DCB the sample was pre-cracked by loading and opening a few millimeters in order to reduce the effect of the resin rich region at the film's tip. The basic elastic constants of the present composite laminates are summarized in Table 1.

Table 1. Elastic constants of the composite laminates (1-fiber direction, 2-3 perpendicular to fiber direction).

Material	E_1 (GPa)	E_2 (GPa)	ν_{12}	ν_{23}	G_{12} (GPa)	G_{23} (GPa)
8552/IM7[15]	161	11.38	0.32	0.44	5.17	3.98
M91/IM7[16]	170	8.8	0.228	0.48	5.5	4.5
WB1010/RTM250[a]	72	72	0.03	0.03	5.5	5.5

[a]from experiment

2.2. Methodology for quasi static DCB and impact WIF test

The DCB method [12-13] which is commonly used to estimate the mode I interlaminar fracture toughness of composite laminates, was employed for quasi-static fracture tests ($\dot{\delta}$= 0.5-500 mm/min). Figure 1 shows the geometry of a DCB specimen, where P(= F,) is the load applied to the specimen and δ is the displacement of the loading point. b = (25 mm), 2h (3 mm) and a (initial crack length, a_0 = 25 mm) are the width, thickness and crack length of the specimen, respectively. For the dynamic loading conditions, the WIF (wedge-insert-fracture) method was applied to avoid any possible asymmetry during loading (only one side of the machine moves while the other one remains static) which will result in a mix loading mode, combining mode I and II of loading. The WIF method, which is a compression version of the DCB method, was used for the dynamic loading test at ($\dot{\delta}$= 0.5 m s^{-1}).

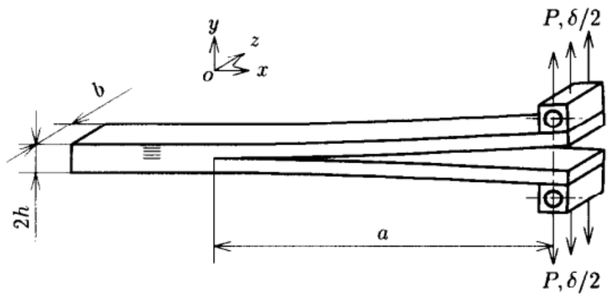

Figure 1. A double cantilever beam specimen from [9].

Figure 2 shows the geometry of a WIF specimen, where F_x (= P/2) and Fy are the x- and y-components of the load, P.

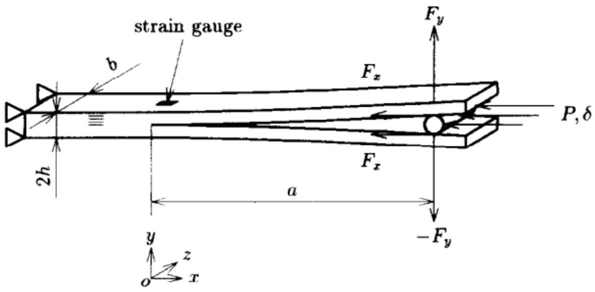

Figure 2. A wedge insert fracture specimen from [9].

Quasi-static DCB tests were carried out under constant crosshead speeds with a screw-driven testing machine (Instron 5966) and the standard specimens, Figure 1. WIF tests were carried out with a Gleeble 3800-GTC system from which the load, P, and the displacement, δ, under impact loading are measured using specimens shown in Figure 2. Figure 3 and Figure 4 show a picture of the Instron 5966 and the Gleeble 3800-GTC set up for both quasistatic and dynamic loading experiments.

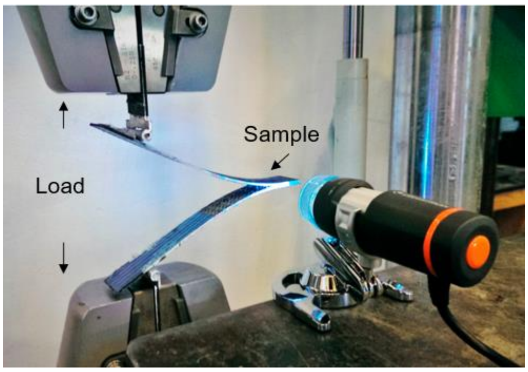

Figure 3. DCB testing set up using INSTRON 5966

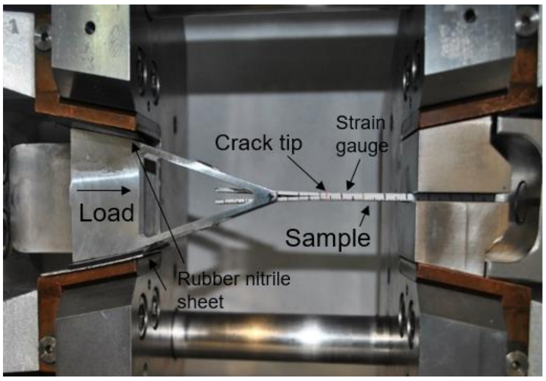

Figure 4. Wedge insert fracture testing setup using Gleeble 3800-GTC.

A strain gauge of 350 ± 0.3% Ohms is attached to the bending surface of the DCB specimen at the crack tip area. The strain monitored was used to estimate the opening force and, thus, to estimate the critical energy release rate, G_I. It was assumed that the compressive strain peak measured monitored the crack initiation process in the velocity tests. To avoid parasitic oscillations of the signals, a thin (1.5 mm) sheet of rubber nitrile was utilised for damping the rising of the incident stress wave and then suppressing the vibration of the specimen.

2.3. Estimation of energy release rate

Assuming a DCB specimen to be a pair of self-equilibrated cantilever beams, the mode I energy release rate, G_I, can be determined by Eq.1 [14]:

$$G_I=\frac{\{F_y(a+e)\}^2}{bE_xI} \qquad (1)$$

Where a, E_x and $I(=bh^3/12)$ stand for the initial crack length, Young's modulus and moment of inertia of area of the specimen, respectively. In addition, e is the correction value that accounts for local deformation effects around the crack tip, as studied by Hashemi at al. [14]. This correction value is necessary because there is some deflection and rotation at the crack tip. It has been shown experimentally by Hashemi at al. [17] that this effect can be modelled by adding a length (β*2h) to the real crack length where β is a constant given by the elastic properties of the material.
The compliance at the loading point $C(=\delta_y/F_y)$ is given by the following relation Eq.2 [13]:

$$\frac{a}{2h}=\alpha\sqrt[3]{b*C}+\beta \qquad (2)$$

where $\alpha(=\sqrt[3]{[\frac{E_x}{4}]})$ and $\beta(=-e/2h)$ are the constant depending on the elastic constants of the material, which can be determined experimentally from the DCB specimens by measuring the relation between the compliance, C, and the crack length a [13]. Substituting Eq. 2 to Eq. 1, the energy release rate, G_I, can be finally obtained by the following equation (Eq.3) for a DCB specimen:

$$G_{Ic}=\frac{3}{2(2h)}\left(\frac{F_y}{b}\right)2\,\frac{\sqrt[3]{(bC)^2}}{\alpha} \qquad (3)$$

Similarly, assuming a WIF specimen to be a pair of self-equilibrated cantilever beams of bending span, a+e, the mode I energy release rate, G_I, can be determined by Eq.4 [9]:

$$G_I=\frac{\{F_x r\cos\theta\}^2\,\{F_y(a+e)\}^2}{bE_xI} \qquad (4)$$

where r (=0.75 mm) is the radius of the wedge and θ is the contact angle between the specimen and the wedge with respect to the x-axis. The term related to the load, F_x, which involves a frictional force can be neglected, when the contact angle θ, is sufficiently small, as it is in this DCB case. Hence Eq. 4 yields the same form as Eq. 1. The strain monitored with the gauge attached to the surface of the DCB specimen can be estimated using the small deflection beam theory as (Eq.5)

$$\sigma=\frac{F_ya}{I}\frac{h}{2}\rightarrow\varepsilon_h=\frac{F_ya}{E_xI}\frac{h}{2} \qquad (5)$$

so, the strain measured with the gauge, ε_h, at the crack tip is given by Eq.5:

$$-\varepsilon_h/F_y=\frac{ha}{2E_xI}=D \qquad (6)$$

Where D is defined above for convenience.
Considering the contact angle, θ, to be small, the ratio of $2r/F_y$ is equivalent to the compliance, C, for a DCB specimen. Accordingly, $2r/F_y$, will be similarly designated by C for a WIF specimen.
Substituting Eq. 5 and Eq. 6 to Eq.3, the energy release rate, G_{Ic}, can be finally obtained by the following equation (Eq.7) for a WIF specimen:

$$G_{Ic} = \frac{3}{2(2h)} \left(\frac{\varepsilon_h}{bD^*}\right)^2 \frac{\sqrt[3]{(bC^*)^2}}{\alpha} \qquad (7)$$

The fracture toughness, G_{Ic}, can be obtained by measuring the critical values of the strain, ε_h and the crack length, a, at the onset of crack growth, when the compliance, C^*, and the coefficient, D^*, are determined in advance by a simulation with a DCB model. The reference crack length, a^*, was 25 mm. In this work, the fracture toughness, G_{Ic}, was determined from the maximum values of the load, F_y, and the strain, ε_h, for DCB and WIF specimens, respectively.

4.Results and discussion

The relationship between compliance and crack length for all the cross head speed in the quasi-static regime was experimentally determined (Figure 5) and it showed a unique relationship for all cross head speeds.

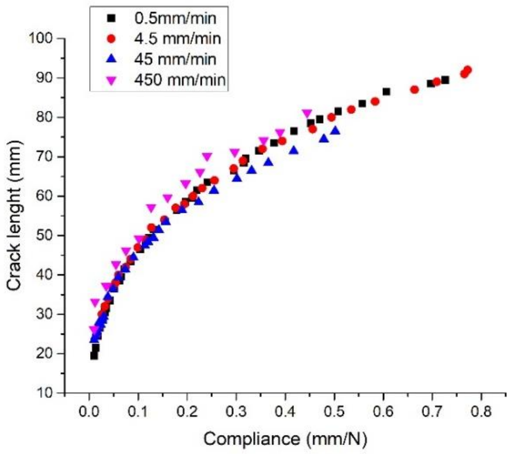

Figure 5 Relation between compliance and crack length

The obtained relationship was fitted according to equation (2) yielding the values shown in Table 2.

Table 2. Fitting values for the three materials.

Material	α ($N^{1/3}mm^{-2/3}$)	β
UD1	12.41	-0.98
UD2	14.31	-0.835
RTM	10.35	-0.304

A stable crack growth, that means a continuous crack growth with increasing displacement, is observed for the two UD system for all the quasistatic speeds, while an unstable crack growth occurring by high-speed propagation and arrest was observed for the RTM system at the slower strain rate range ($\dot{\delta}$=0.5-45 mm/min).

Figure 6, Figure 7 and Figure 8 show the relationship between the fracture toughness, G_{Ic} , and the loading rate, $\dot{\delta}$ for the three material systems.

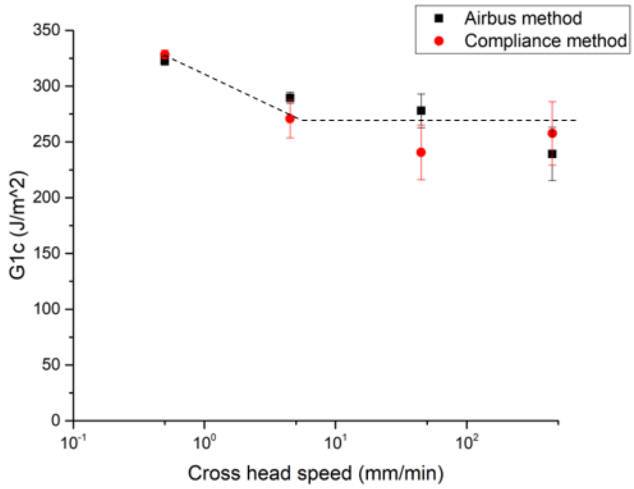

Figure 6. Results for 8552 system.

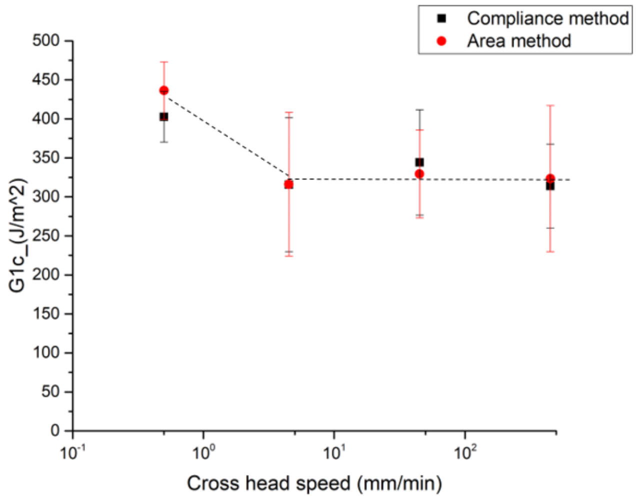

Figure 7. Results for M91 system.

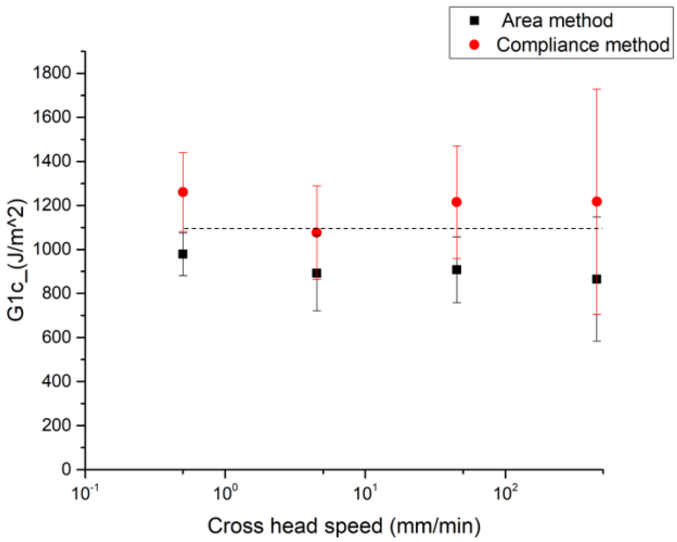

Figure 8. Results for RTM250 system.

The data shown in Figures 6, 7 and 8 show a good agreement between the two data reduction methods. It is evident that the fracture toughness decreased stepwise in the range of speed between 0.5 mm/min and 4.5 mm/min for the two UD system reaching a stable average value of 256 J/m^2 for the 8552 system and 324 J/m^2 for the M91 system. However, there was no rate dependent behaviour for loading rates higher than the standard rates. In the case of the RTM 250 system, the material was insensitive to strain rate in the whole range of cross-head speed analyzed. The RTM 250 system showed an average fracture toughness value of 1192 J/m^2, much higher than the two UD systems analyzed. On one hand, wovens usually exhibit higher toughness due to the more complex cracking pattern including meandering and and fiber bridging. On the other hand, the use of an improved toughness matrix also contributes to such enhancements. The analysis of fracture toughness for the speed range between 450 mm/min and 30,000 mm/min (=500 mm/s) is still in progress.

5. Conclusion

The rate dependence of mode I interlaminar fracture toughness for three different material systems, two unidirectional UD carbon-fibre epoxy composite laminates and one RTM plain woven fabric laminate have been investigated over a wide range of loading rates from quasi static to impact at room temperature. The fracture toughness G_{IC} decreased stepwise in the range of speed between 0.5 mm/min and 4.5 mm/min for the two UD systems. A cross-head speed threshold was detected in both UD cases showing a minimum speed to exhibit non rate dependence behaviour. In the case of the plain woven lamiante, the G_{IC} was significantly higher than the UD systems and almost rate insensensitive in the range of velocities analyzed.

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