FRACTURE TOUGHNESS OF ADHESIVE BONDED COMPOSITE JOINTS UNDER MIXED MODE LOADING.

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SUMMARY : This paper presents a study of the behaviour of different adhesive bonded composite joints. Based on linear elastic fracture mechanics, the concept of the total critical strain energy release rate is used to characterise the resistance to crack initiation of the adhesive bonded joint under mixed-mode loading. In order to investigate the effect of the nature of composite laminates on adhesive fracture toughness, the adhesive bonded joints of UD carbon/ epoxy on UD carbon/epoxy, 0/90 glass/epoxy on steel and +45/-45 glass/epoxy on steel were tested. Three tests were made to obtain the mixed mode ratio, in terms of G_{II}/G_{TC} , from 0 to 100% : DCB in mode I loading, ENF and ELS in mode II loading and IDCB in mixed mode I+II loading. Closed form models based on beam theory were for mode partitioning and for determination of the total critical strain energy release rate. A mixed-mode failure criterion was applied to predict the crack initiation of adhesive bonded joints.

KEYWORDS : adhesive bonded joints; testing methods ; fracture toughness; mixed-mode.

INTRODUCTION.

The success and efficiency of a mechanical structure in composite materials depends not only on its laminate design, but also on its joints. The latter is of great importance since the classical joint techniques used for metals, such as bolting and riveting, can be significantly detrimental to the weight advantages of composite structures and their mechanical properties.

The preferred joining technique for many composite materials is adhesive bonding, but many factors have to be taken into account to ensure good design. The adhesive used, the composite surface treatment, the joint geometry, the nature of fibre and matrix, the laminate stacking sequence, environmental factors..., all of these factors can influence the performance of adhesive bonded joints [1-6]. In addition, the stress distribution around joint edges is not easy to determine due to the stress concentrations and is all the more difficult because there are usually flaws in these zones.

Recently, more and more people have preferred to establish the fracture mechanics criterion for the bonded design [7-8] and the results seem very encouraging. However, most testing for determining the fracture toughness was performed under pure mode I and pure mode II loading and at the moment, experimental results are lacking in order to form a general conclusion.

This paper proposes to investigate the fracture toughness of adhesive bonded joints between different materials. The mixed mode loading test IDCB is developed and a criterion of crack initiation is discussed.

EXPERIMENTAL.

Static tests were carried out on three series of adhesive bonded joints :

- Series 1 : "carbon/epoxy - carbon/epoxy" specimens ; each carbon/epoxy panel of 1.5 mm thick was prepared from 12 plies of unidirectional T300/914 prepregs (Vicotex NCHR 914/34%/132/T300), whose arrangement of fibres is unidirectional ;
- Series 2 : " 0°/90° glass/epoxy – steel" specimens ; the glass/epoxy laminates of 2.1 mm thick were laid up from 5 plies of aligned balanced woven prepregs (Hexcel 7781/XE85/38%) ; they were bonded to a steel plate (XC48) of 1 mm thick ;
- Series 3 : " + 45°/-45° glass/epoxy - steel" specimens ; here, the glass/epoxy laminates are cut from the laminates of Series 2 at 45°.

The adhesive used in this study is an epoxy system, Permabond ESP 110. The thickness of the adhesive joint, fixed at 0.2 mm, is obtained by using steel foil tapes during the joining of the adherends. In order to initiate the crack, a PTFE film is placed in the adhesive during curing.

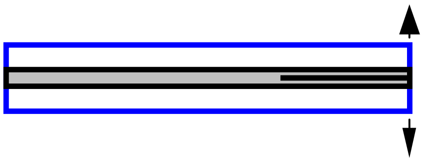
The elastic constants of the above materials are listed in Table 1.

Table 1 : Elastic constants of the materials used in this study.

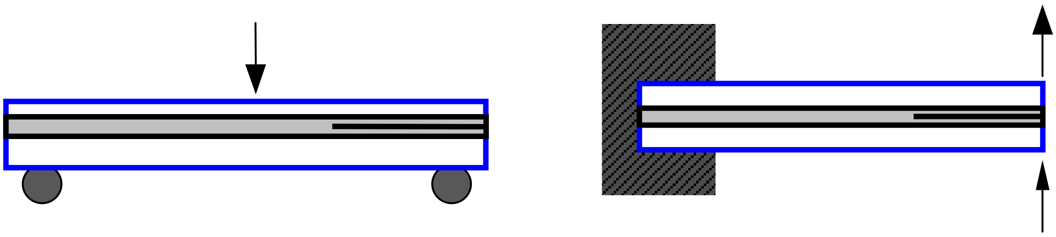
	E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	ν_{LT}
UD T300/914	131.9	9.51	5.27	0.326
0/90 Glass/Epoxy	23.2	23.2	3.95	0.146
± 45 Glass/Epoxy	17.2	/	/	/
Steel XC48	210	/	/	0.3
Epoxy ESP110	1.4	/	/	/

The tests are those used in the literature : DCB (Double Cantilever Beam) in pure mode I loading and ENF / ELS (End Notch Flexure / End Loaded Split) in mode II pure loading. The test in mixed mode I+II loading is an original specimen, named IDCB (Imposed Displacement Cantilever Beam) [1], which makes it possible to vary the participation of mode II according to the imposed displacement (Fig.1)

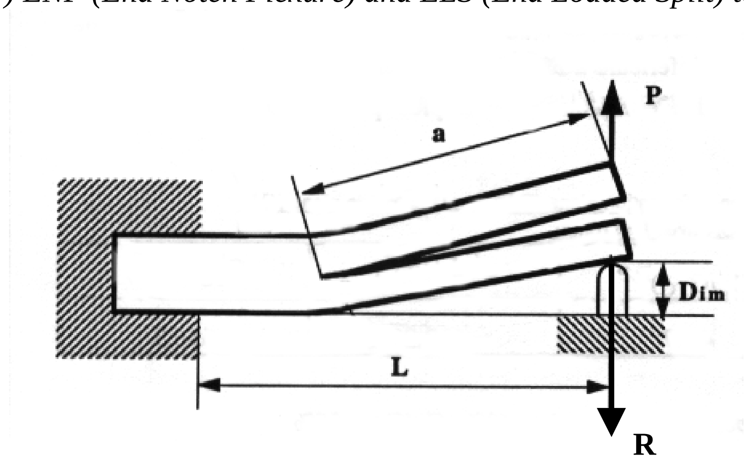
All tests were performed on an Adamel DY36 test machine using a mixed mode bending test apparatus. The cross-head speed varied between 1 and 4 mm/mn. Load/displacement curves were established from the data recorded during the tests in order to determine the critical load at crack initiation. For IDCB specimens, the load P and the reaction R are recorded in the same time during the tests. The critical point of crack initiation is assumed to be the point at which the load/displacement curve is no longer linear.



(a) DCB test (Double Cantilever Beam).



(b) ENF (End Notch Flexure) and ELS (End Loaded Split) tests.



(c) IDCB test (Imposed Displacement Cantilever Beam)

Figure 1 : Testing configurations.

DATA REDUCTION.

The analytical model based on beam theory was developed using the hypotheses of Williams [9] for mode partitioning (Fig.2). This approach assumes that :

- the opening mode only requires moments M_I in opposite senses ; in other words, DCB test loading always produces pure mode I fracture regardless of different material constants, E, and the thickness of two arms ;
- the pure mode II fracture can be obtained when the curvature in the two arms is the same.

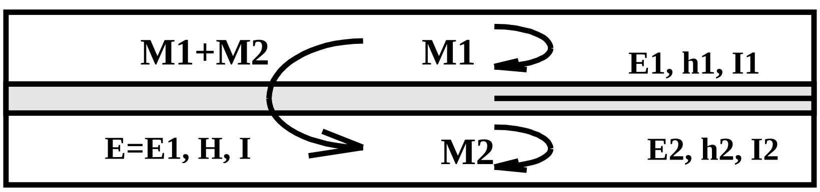


Fig. 2 : Moments applied to the arms of the specimen.

In our case, the stiffness of the adhesive is negligible compared to that of the steel and the composites used. So the expressions of the energy release rate components can be expressed by the following formulae :

$$G_I = \frac{1}{2BE_1I_1}\frac{(M_2 - \psi M_1)^2}{\psi(1+\psi)}$$

$$G_{II} = \frac{1}{2BE_1I_1}\left[\frac{1}{1+\psi} - \frac{1}{K}\right](M_1 + M_2)^2 \qquad (1)$$

$$G_T = G_I + G_{II}$$

with $\psi = \frac{E_1I_1}{E_2I_2}$ and $K = \frac{I}{I_1}$, where I is the equivalent second moment of the total area.

DCB Tests (Fig. 1-a)

Under DCB test conditions, we have $M_1 = -M_2 = -Pa$, and the Eqs.1 become :

$$G_I = \frac{1+\psi}{2BE_1I_1}\frac{(Pa)^2}{\psi} \ , \ G_{II} = 0$$

If in particular, $E_1 = E_2 = E$, $h_1 = h_2 = h$ and $I_1 = I_2$, we obtain the well known result :

$$G_I = \frac{12P^2a^2}{EB^2h^3}$$

ENF and ELS tests (Fig. 1-b)

Under pure mode II loading, we have $M_2 = \psi M_1$, and the equations (1) become :

$$G_I = 0 \ , \ G_{II} = \frac{1}{2BE_1I_1}\left[\frac{1}{1+\psi} - \frac{1}{K}\right](M_1)^2(1+\psi)^2$$

For ENF tests, in the case of $E_1 = E_2 = E$, $h_1 = h_2 = h$ and $M_1 = M_2 = Pa/4$, we obtain likewise the well known result in pure mode II loading :

$$G_{II} = \frac{9P^2a^2}{16EB^2h^3}$$

IDCB Tests (Fig. 1-c).

IDCB tests [10] give varying ratio mixed mode testing, their mixed mode ratios depend on the displacement imposed before loading. The load P and reaction at imposed displacement position R were measured during tests, thus allowing us to easily determine the G_I, G_{II}, and G_T values by using Eqs.1 with M_1 = - Pa and $M_2 = Ra$.

In the particular case of $E_1 = E_2 = E$, $h_1 = h_2 = h$, we obtain the following expressions :

$$G_I = \frac{12P_s^2 a^2}{EB^2 h^3} \text{ and } G_{II} = \frac{9P_a^2 a^2}{16EB^2 h^3}$$

where $P_a = (P-R)/2$ and $P_s = (P+R)/2$.

RESULTS AND DISCUSSIONS.

Fig.3 gives the variation of critical strain energy release rate $G_{TC} = G_I + G_{II}$ of three composite adhesive joints as a function of the mixed mode ratio in term of G_{II}/G_{TC}. It is interesting to note that :

- the results obtained present a large dispersion ;
- G_{TC} values of each adhesive bonded joint increase with the mixed mode ratio G_{II}/G_{TC}, a well known fact ;
- under pure mode II loading, ENF and ELS tests give nearly identical results for specimens of series 1 ; however for glass/epoxy - steel bonded joints, the determination of the critical point becomes more difficult because of evident non-linear behaviour before crack initiation was observed ;
- it seems that the rupture of the adhesive bonded joint depends not only on the participation of mode II but also on the strength of the adherends. Indeed, when the strength of the composite is low, the damage in the adjacent plies of the laminate occurs due to the stress concentration and provokes adhesive or mixed fracture (the case of series 2 and 3), whereas for series 1, cohesive fracture is observed because of higher strength of the carbon/epoxy. Moreover, the values of G_{IC} in pure mode I for series 1 are higher than those of series 2 and 3, whereas in pure mode II, the values of G_{IIC} are similar (in spite of the large dispersion) for the three series. In fact, under pure mode I loading, the damage of the adjacent plies of the carbon/epoxy laminate is very low because of its high longitudinal tensile strength. In the case of the glass/epoxy laminates, their tensile strength is lower so that damage occurs very early in the adjacent plies. It is followed by a stress redistribution in the adhesive and then fracture by cracking ; this is explained by very low values of G_{IC}. On the other hand, the interlaminar shear strength for the three laminates are almost identical; thus the values of G_{IIC} are very close. With regard to mixed mode I+II loading, the values of G_{TC} of series 1 and 2 increase significantly when the mixed mode ratio G_{II}/G_{TC} attains 50%, unlike those of series 3. The influence of the fibre orientation of adjacent plies also has an effect ;
- an another remark is that for series 1 and 2, the fracture toughness G_{TC} can be higher than G_{IIC} if the participation of mode II becomes important. This phenomenon, still unexplained, is also revealed in the works of Ducept, Gamby and Davies [8].

The results obtained were examined to obtain a mixed mode criterion expressed by :

$$G_{TC} = G_{IC} + (G_{IIC} - G_{IC})(G_{II}/G_{TC})^m \qquad (2)$$

This criterion, proposed initially for predicting the initiation of composite delamination [11], requires an interpolation of experimental data to determine the empirical constant m (see Figs. 4 - 6). It seems that for three groups of specimens, the difference in G_{IC}, G_{IIC} values is not negligible, as well as the value of constant m. In this respect, the effect of the nature of adherends on the bonded joint toughness has been observed and more experimental data is needed for a better understanding of this phenomenon.

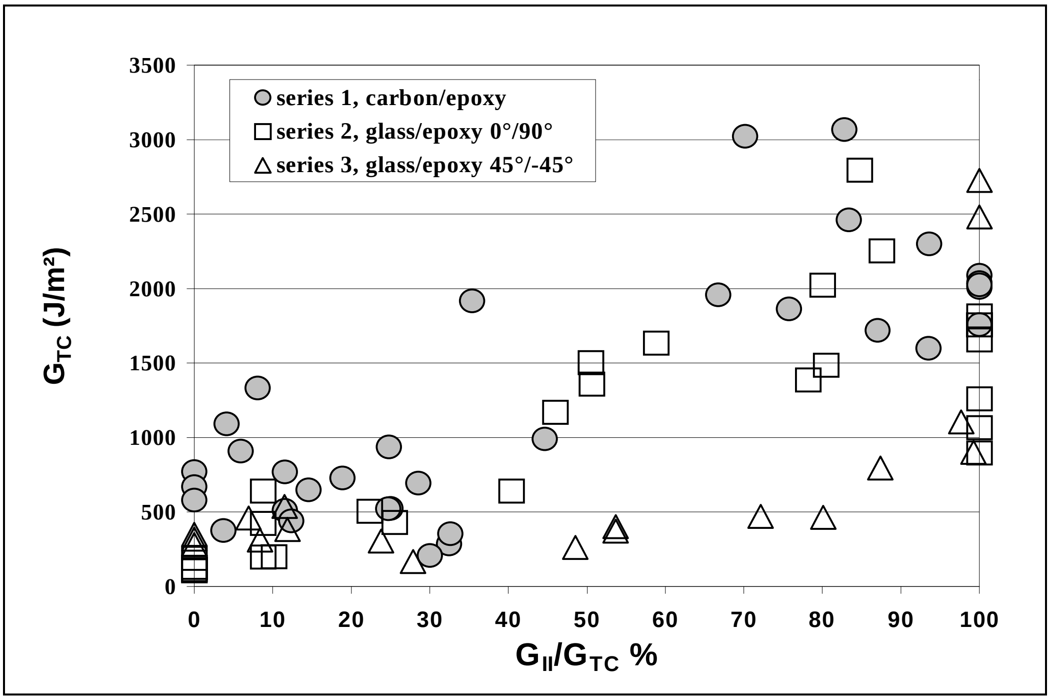


Figure 3 : Variation of critical strain energy release rate G_{TC} as a function of G_{TI}/G_{TC}.

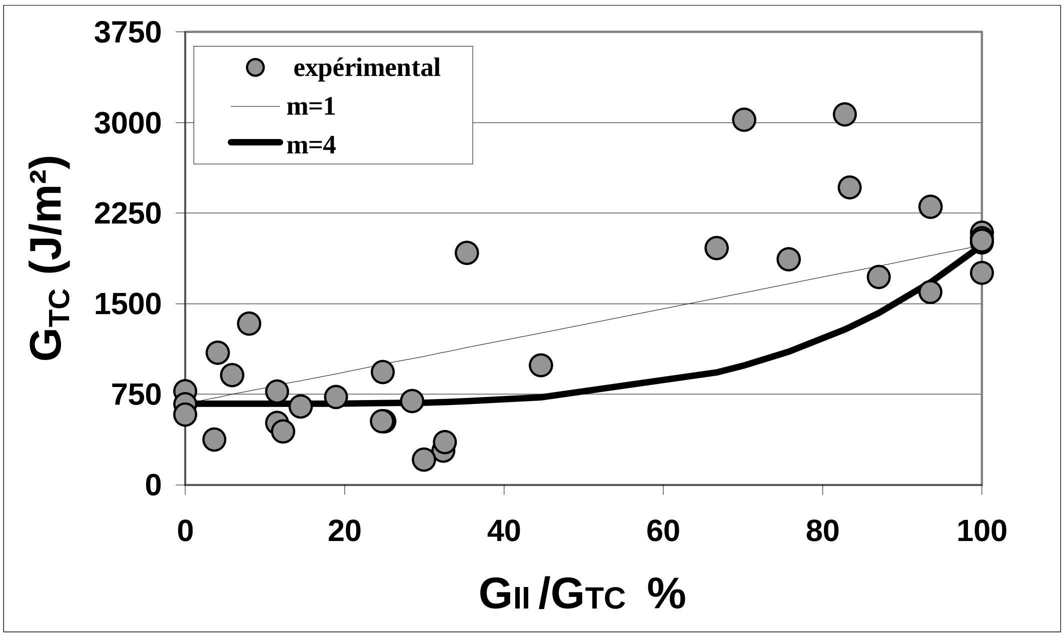


Figure 4 : Application of the criterion $G_{TC} = G_{IC} + (G_{IIC} - G_{IC})(G_{II}/G_{TC})^m$
for carbon/epoxy-carbon/epoxy adhesive bonded joints.

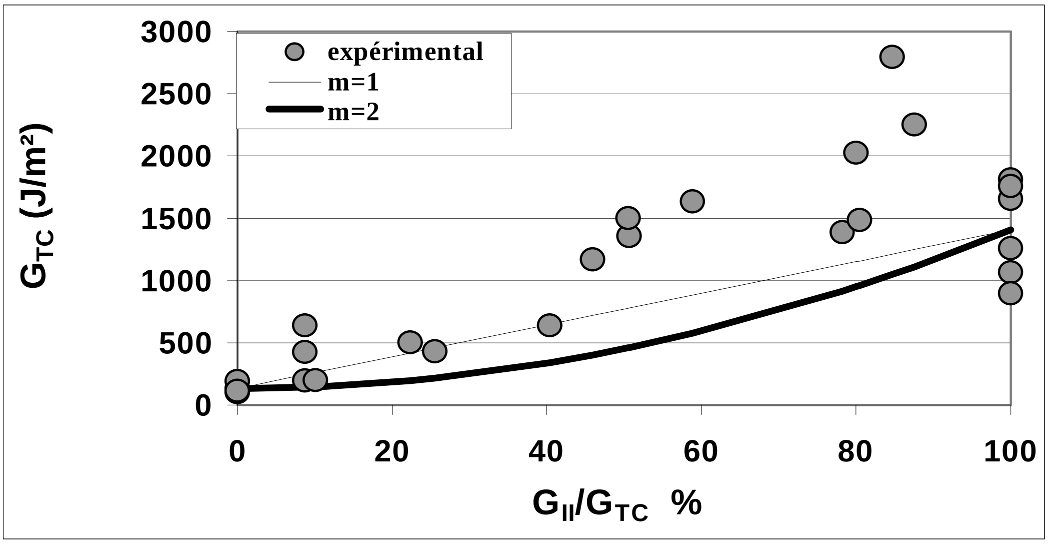


Figure 5 : Application of the criterion $G_{TC} = G_{IC} + (G_{IIC} - G_{IC})(G_{II}/G_{TC})^m$ *for (0/90) glass/epoxy-steel adhesive bonded joints.*

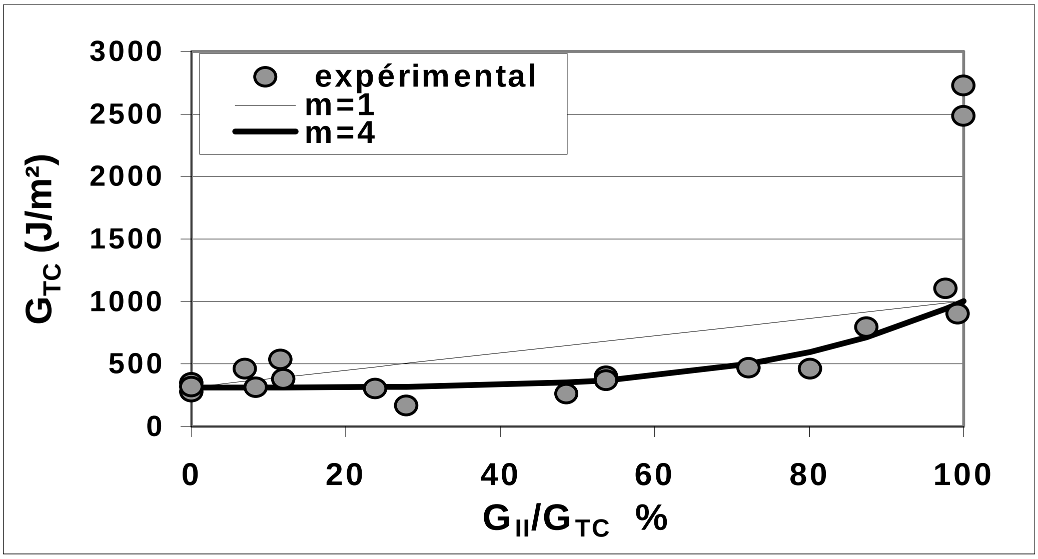


Figure 6 : Application of the criterion $G_{TC} = G_{IC} + (G_{IIC} - G_{IC})(G_{II}/G_{TC})^m$ *for (+45/-45) glass/epoxy-steel adhesive bonded joints.*

CONCLUSION.

The study showed an influence of the composite adherends on the fracture toughness of the adhesive bonded joint, as well as an influence of the fibre orientation in the adjacent plies of the laminates on the behaviour of the adhesive bonded joint.

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