INTERLAMINAR FRACTURE OF COMPOSITE MATERIALS

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Under the auspices of the EGF Task Group on Polymers and Composites, 11 Laboratories have been involved in a Round Robin exercise with the objective of developing a standard for interlaminar fracture of composite materials. A synopsis of the tests undertaken is given with the principal results obtained so far and the problem areas that are currently under study.

INTRODUCTION

Interlaminar fracture in composite materials is the rupture between the individual layers of the structure. It is a very common type of failure mechanism in these materials and it derives from opening or shear stresses that are induced at free edges, at defects or at certain points in the structure (see Figure 1). These stresses are induced by the tendency of each layer to deform independent of the surrounding layers (in composites the moduli can vary from over 200 GPa to 8 GPa depending on the fibre direction). The energy necessary for crack propagation in the interlaminar layer frequently represents the value of fracture energy for minimum damage tolerance. For example, interlaminar G_{Ic} values can be as low as 100-200 J/m^2 whereas for a crack propagating parallel to the fibres fracture energy is of the order 10^5 J/m^2.

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The results from interlaminar tests give fracture parameters that can be understood, and are useful for both manufacturers and users of composite materials. The improvement of resistance to interlaminar fracture will increase the resistance to damage by for example, impact and fatigue loading. Up until now interlaminar testing has been used in a comparative manner essentially to rank materials. It is, however, highly desirable to integrate these parameters into an analysis of failure criteria in real composite structures. For this to be possible, standard test techniques are required to characterise the resistance to interlaminar fracture in modes I, II and III and mixed mode. Loading in modes I and II are of much greater importance in composites than in isotropic materials. This is because in composites, even though the loading is ostensibly mode I, due to the large mis-match of elastic properties between the layers, locally the stress distribution can give rise to mode II, and even mode III stresses.

Participating Laboratories. Eleven Laboratories participated in this Round Robin exercise to evaluate some of the parameters in interlaminar tests in mode I and mode II. These were: the University of Compiègne (F), ICI (GB), BASF (D), Ciba Geigy (CH), University of Hamburg (D), Frauhofer Institut für Werkstoffmechanik (D), Imperial College (GB), SINTEF (N), UNIREC (F), General Electric (USA) and the Swiss Federal Institute of Technology (CH).

MATERIALS AND TEST METHODS

The materials employed in the Round Robin tests were firstly, a composite based on unidirectional carbon fibres in an epoxy resin matrix and secondly, a composite with unidirectional carbon fibres in a poly(ether sulphone) (PES) matrix. The samples were manufactured into sheets and supplied to each Laboratory in a form ready for testing. This consisted of double cantilever beam-shaped specimens 5 and 4 mm thick respectively and 20 mm wide. A defect was moulded into one end of the specimen at the mid-plane as shown in Figure 2.

In this first series of measurements, testing was carried out in mode I and II. The **mode I** tests were conducted by bonding end tabs onto the specimen (see Figure 1a) and loading at a fixed crosshead speed of 2 mm/min. Part of the tests were conducted using continuous monotonic loading and part using load-unload cycles. The crack length was monitored during the test either optically, by painting typewriter correcting fluid on the edge of the specimen, or electrically, using a crack gauge. All the tests were conducted at 23°C.

The **mode II** tests were conducted using two types of loading, either end notch flexure (ENF) or end loaded split (ELS) as shown in Figure 1. The ENF geometry gives unstable crack propagation up to nearly the mid-span and hence only one value for G_{IIc} is obtained. The ELS geometry is, however, stable and thus G_{IIc} can be measured as a function of crack length.

<u>Data Analysis.</u> In **mode I** the data can be analysed in a number of ways. These have been discussed in detail in reference (2) and will thus be mentioned briefly here.

The **load method** derives from beam theory giving:

$$G_{Ic} = n\,P\,d\,/\,2\,B\,a \quad \text{(n =3 from beam theory)}$$

where P is the load, d is the specimen deflection, B is the specimen width and a is the crack length. This method does not take into account either the rotation at the crack tip or shear deformation.

The **area method** was first suggested by McGarry et al (3) and used more recently by, for example, Whitney et al (4). This is a direct method which relates the area under the load-displacement curve to the area of crack generated by:

$$G_{Ic} = \Delta A\,/\,B\,\Delta a$$

where A is the area under the curve and Δa the crack growth.

To employ this method several load-unload cycles must be conducted and it is, hence, difficult to use if unstable crack propagation occurs.

The **compliance methods** use the Irwin-Kies expression:

$$G_{Ic} = P^2/2B * dC/da$$

and thus require a relationship to be found between the compliance (C) and the crack length. This is either done by using the derivative of a polynomial regression from the experimentally determined relationship between C and a, or alternatively, Berry's method can be used (5) which derives from:

$$C = d/P = a^n/h$$

A plot of log C as a function of log a gives a line of slope n, then:

$$G_{Ic} = P^2/2B * dC/da = n\, P\, d / 2\, B\, a$$

This basic technique has been adapted by Benzeggagh (6) who conducted the compliance calibration on a series of samples of different initial pre-crack lengths. The compliance methods enable the construction of an R curve that is, G_{Ic} as a function of effective crack length.

In **mode II** tests on end notch flexure specimens, analysis from beam theory gives (7):

$$G_{IIc} = 9\, a^2\, P_c\, d/ 2B(2L^3 + 3a^3)$$

This approach gives, in general, conservative values as transverse shear and frictional effects are neglected.

In mode II end loaded split either beam theory can be used from (8):

$$G_{IIc} = 9\, a^2\, P_c\, d/ 2B(L^3 + 3a^3)$$

or, alternatively, an experimental compliance calibration can be conducted as described for mode I testing.

RESULTS

<u>Comparison of analysis methods in mode I.</u> It can be seen from the data shown in Figures 2 and 3 that for both the epoxy and the PES samples, the values of G_{Ic} analysed using beam theory were higher than those

for the other methods of analysis. This arises because the real value of n is ≤ 3. Analysis by the compliance hods or by areas gives equivalent values. One potential problem with the compliance method, as conducted traditionally, is that the calibration is effectively conducted on a damaged specimen. This can cause problems for tough materials where crack splitting may occur with secondary cracks propagating above and below the primary crack. A solution to this is to prepare samples with different lengths of moulded pre-cracks and conduct the experimental compliance on these specimens as has been reported (6).

R curve effects in mode I. Both materials show some R curve effect (as can be seen in Figure 2 and 3) but this is much more pronounced in the case of the tougher material - PES. These R curves derive principally from bridging of the crack by fibres and are, thus, amplified by for example, poor resin-fibre adhesion, thin specimens or low modulus materials that cause large specimen displacements. The value of G_{Ic} at initiation is perhaps the most useful value as it represents the minimium damage tolerance value. However, this initiation value is extremely difficult to define as it is influenced by the nature of the pre-crack and especially by the resin-rich area ahead of the pre-crack. This latter is governed, for example, by the fibre content, the viscosity of the resin in the liquid state at the cure temperature and the processing conditions. The propagation values have been shown to be dependent on the specimen dimensions for a certain composite with a thermoplastic matrix (2) and it is possible that they may not represent the real resistance to crack propagation. These propagation values can also be increased if the individual plies in the composite do not stay flat during processing but have a tendency to intermingle. This increases the likelihood of fibre bridging and accentuates the R-curve. This can be seen by comparison of Figures 3a and 3b in that 3a represents a sample where the plies were flat and 3b a sample with "wavy" plies. Analysis by means of a digitising table to account for the increase in surface due to the non-linear crack front showed that this simple explanation did not account for the higher values of G_{Ic}.

In most applications of composites multi-axial lay-ups will be used with fibres positionned at angles of 0^o, $+45^o$, -45^o, and 90^o. In this manner there will be less tendency for the plies to intermingle and, hence, the propagation values measured from samples with intermingled plies could be misleading.
The next series of tests of the group should examine the effect of the nature of the pre-crack using different thicknesses of defect and the generation of pre-cracks also by mode II loading.

Mode II testing Most Laboratories adopted the ENF geometry with only a few testing the ELS. The results for both materials are shown in Table I. It is clear from these results that for the epoxy composite the mode II value is considerably higher than in mode I and this is typical of the reports in the literature for such systems (8,9). In the case of PES, the mode II value is of the same order of magnitude as the "initiation" value for G_{Ic}, but considerably lower than the propagation value. This implies that this G_{IIc} value is critical. For other composites with thermoplastic matrices, such as poly(ether ether ketone), values of G_{Ic} and G_{IIc} were equivalent (9).

PROBLEM AREAS TO BE STUDIED IN FUTURE TESTS

The detection of initiation. The initiation values represent conservative, minimum damage tolerance values. However, in common with other types of testing, they are very difficult to characterise accurately, particularly for tough materials which may exhibit non-linearity in the load-displacement diagram. In a standard it is necessary to define which values of load should be used to calculate the critical fracture energy, whether it is the load at the point of visually defined initiation, or the load at the onset of non-linearity or the peak load. In addition, in the interlaminar test the initiation values may be influenced by the defect geometry and the resin-rich area ahead of crack tip and these effects should be studied in greater detail.

Fibre bridging and the R-curve effect. Fibre bridging behind the crack front can radically alter mode I fracture energies and gives rise to an R-curve effect. This is especially important in tough materials. It is necessary to determine whether the initiation and/or propagation values are real material properties or whether they are dependent on the specimen geometry and dimensions.

Mode II. In mode II the similar problems of detection of crack initiation can arise. Furthermore, it it is important to characterise in greater detail the relative values of G_{Ic} and G_{IIc} in other types of composites with thermoplastic matrices. The results obtained for this PES composite system imply that the mode II fracture energy may be critical.

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TABLE I <u>Mode II Fracture Energies for Epoxy and Poly(ether sulphone) Composites</u>

Material	Result no.	Type of test	G_{IIc} (J/m^2)
Epoxy	1	End notch flexure	690
	2	End notch flexure	800
	3	End notch flexure	580
	4	End notch flexure	680
	5	End notch flexure	740
	6	End notch flexure	700
	7	End notch flexure	640
	8	End loaded split	700
PES	1	End notch flexure	1290
	2	End notch flexure	760
	3	End notch flexure	1150
	4	End notch flexure	1120
	5	End notch flexure	1880
	6	End notch flexure	1350
	7	End loaded split	850

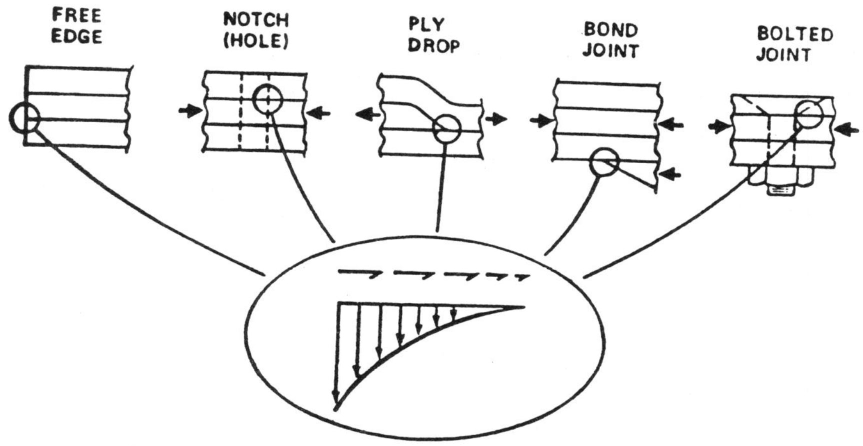

Figure 1. Examples of structures which may induce interlaminar stresses (after ref.1)

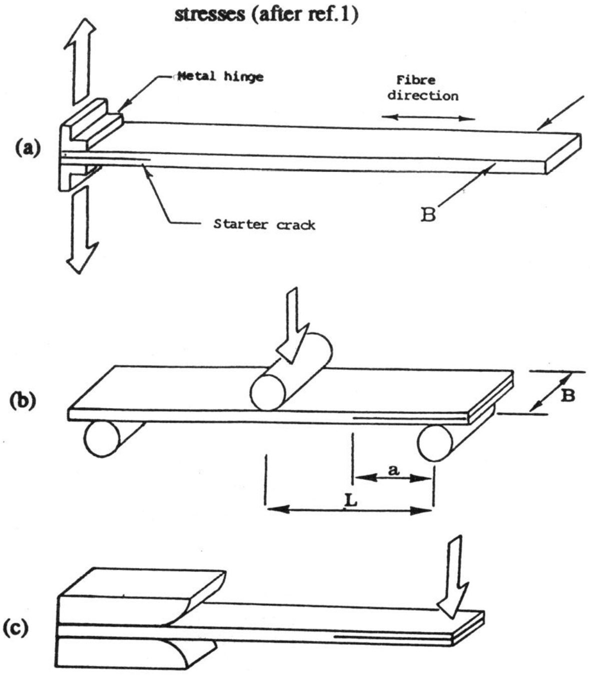

Figure 2. Specimen geometries used in the interlaminar tests
(a) Double Cantilever Beam, mode I.
(b) End Notch Flexure, mode II.
(c) End Loaded Split, mode II.

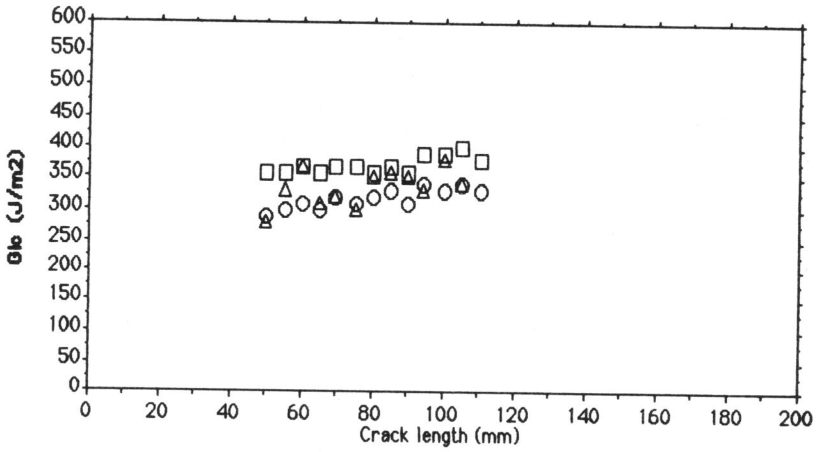

Figure 3a. The variation in the interlaminar fracture energy in mode I with crack length for an epoxy composite typical results: sample with flat plies. o compliance method
□ load method Δ area method

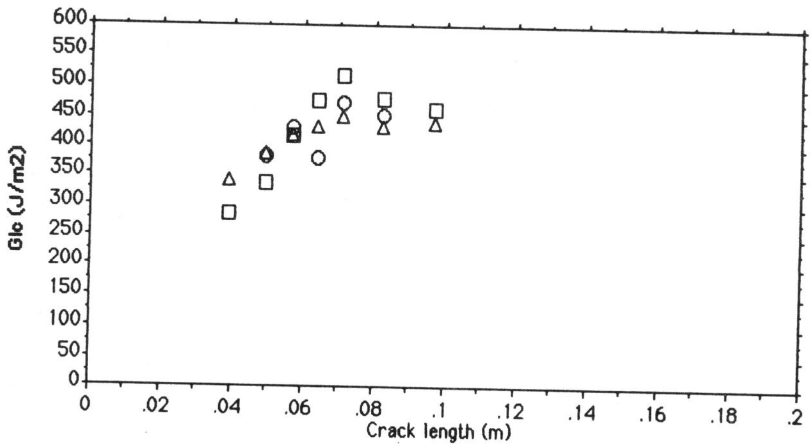

Figure 3b. The variation in the interlaminar fracture energy in mode I with crack length for an epoxy composite typical results: sample with wavy plies. o area method
□ compliance method via polynomial
Δ compliance method via Berry's method

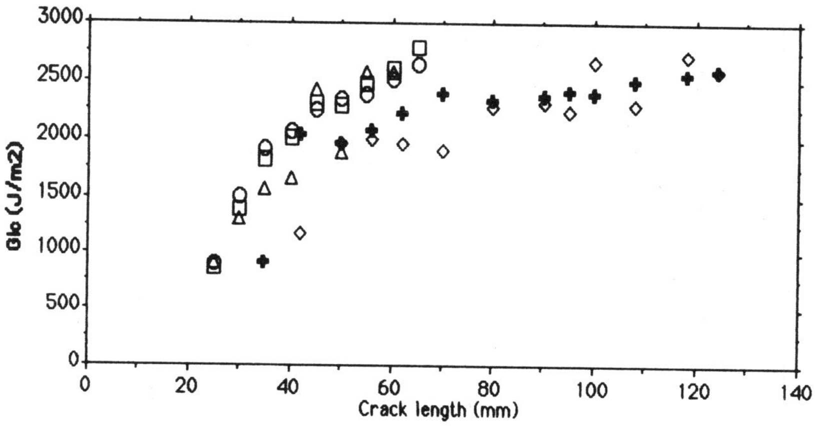

Figure 4. The variation in the interlaminar fracture energy in mode I with crack length for an poly(ether sulphone) composite.
o load method data 1 □ compliance method data 1
Δ area method data 1 ◊ area method data 2
+ compliance method data 2