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The fracture toughness of bast fibre reinforced polyester composites

Part 1 *Evaluation and analysis*

M. HUGHES
The BioComposites Centre, University of Wales, Bangor, Gwynedd, LL57 2UW, UK
E-mail: Mark.hughes@bangor.ac.uk

C. A. S. HILL
School of Agricultural and Forest Sciences, University of Wales, Bangor, Gwynedd, LL57 2UW, UK

J. R. B. HAGUE
CSIRO, Forestry and Forest Products, Private Bag 10, Clayton South, Victoria 3169, Australia

Hemp and jute fibre reinforced polyester composites were fabricated to various fibre volume fractions (V_f) up to 0.45. Laminates reinforced with a chopped strand mat (CSM) glass fibre were also manufactured. The tensile properties of these materials were evaluated. Fracture toughness was assessed, using linear elastic fracture mechanics (LEFM) principles, under quasi-static loading conditions. At equivalent V_f (0.2) it was found that the fracture toughness (K_{Ic}) of the CSM glass fibre reinforced material was approximately 3 times greater than that of the natural fibre reinforced laminates and an order of magnitude greater than the unreinforced polymer alone. Critical strain energy release rates (G_c) and plastic zone radii were computed. The G_c of the natural fibre reinforced laminates was approximately an order of magnitude lower than that of the CSM reinforced material at the same V_f. It was hypothesised that the size of the crack-tip plastic zone influences the energy absorbing capacity of the material. By comparing the relative volumes of the plastic zones, implications regarding the toughening mechanisms operative in natural fibre reinforced composites have been made. The applicability of LEFM to characterise toughness in these materials is discussed.

1. Introduction

1.1. Background

Bast fibres such as flax, hemp and jute with their excellent specific properties offer good potential as alternatives to glass and other manmade fibres used as reinforcement in thermosetting polymer matrix composites (PMCs). In conjunction with non-woven technology to form the fibres into useful reinforcement preforms, there exists the opportunity to produce inexpensive and lightweight composite materials from these renewable and potentially sustainable resources.

It is a pre-requisite of most engineering materials that they possess adequate toughness along with good stiffness and strength. One of the great attractions of many manmade composites, such as the ubiquitous glass fibre reinforced unsaturated polyester, is that they often exhibit good toughness or crack-stopping capability. It must, nevertheless, be remembered that, like natural composites such as wood in which the toughness across the grain is equivalent to that of ductile steel [1], this property is generally directionally dependent. If non-woven bast fibre reinforced PMCs are to be utilised in structural or semi-structural applications, then it must be ensured that they too possess adequate toughness.

Previous studies utilising qualitative techniques such as the Izod and Charpy impact tests have, however, suggested that the toughness (measured as the work of fracture) of natural fibre reinforced thermosetting PMCs is substantially inferior to that of their synthetic fibre reinforced counterparts.

Roe and Ansell [2] using the Charpy test (notched samples), for example, found that at a fibre volume fraction (V_f) of 0.2, the work of fracture of unidirectional jute fibre reinforced polyester laminates was around 4 kJ m^{-2}, rising to around 22 kJ m^{-2} at a V_f of 0.6. By way of contrast, for a unidirectional glass fibre-epoxy system of $\sim$0.7 V_f, fracture energies of around 200 kJ m^{-2} have been reported [3]. Sanadi *et al.* [4], reported a fracture energy of 21.5 kJ m^{-2} using the lzod test for a 0.24 V_f uniaxial Sunhemp polyester composite. Prasad *et al.* [5], on the other hand, reported a Charpy impact value of only 7.4 kJ m^{-2} for an untreated coirpolyester composite at 0.2 V_f, less than the 8.3 kJ m^{-2} reported for the un-reinforced resin alone. White and Ansell [6] using straw to reinforce a

polyester resin, found that at a V_f of 0.7, fracture energies of around 7 kJ m^{-2} were obtained. More recently, O'Dell [7] observed Charpy impact energies in resin transfer moulded jute-polyester laminates around an order of magnitude lower than those of glass fibre reinforced equivalents. Similarly Hughes *et al*. [8] and Sèbe *et al*. [9] noted fracture energies around ten times lower in non-woven hemp reinforced polyester laminates than in chopped strand mat (CSM) glass fibre reinforced material. Impact tests, provide indications of the relative toughness at high strain rates, however, work of fracture measurements under quasi-static conditions (three point flexure) have corroborated these findings [10].

Although the toughness of an otherwise brittle thermoset polymer can be substantially improved by the incorporation of natural fibre, it would appear that a gulf still exists between the toughness of the natural fibre reinforced material and that of material reinforced with synthetic glass fibre. It is likely that this will be a significant impediment that may well hinder the commercial exploitation of these natural fibre reinforced materials. In order to overcome these deficiencies, it is clearly necessary to understand the underlying reasons for this behaviour. Whilst qualitative tests such as those note above provide comparative data on the relative toughness for similar specimen configurations and test procedures, they provide little further information on the underlying mechanisms controlling toughness. In view of the success of fracture mechanics in quantifying toughness in metals and non-metals alike, it was considered that this approach might prove useful in investigating toughness in natural fibre reinforced thermosetting polymer systems. Fracture mechanics can not only, under suitable conditions, provide a quantitative measure of a material toughness but can also be used to relate the macroscopic toughness of a material to its microstructure. In this way, possible means of stimulating toughening mechanisms might be highlighted [11].

As a first step in this investigation, it is clearly necessary to establish the applicability of fracture mechanics to quantify toughness in this class of materials. This paper describes the use of linear-elastic fracture mechanics (LEFM) techniques to measure the toughness of unsaturated polyester laminates reinforced with two bast fibre types; hemp (*Cannabis sativa*) and jute (*Corchorus capsularis*) as well as with a commercial glass fibre reinforcement. Jute was considered because of its commercial importance as a fibre crop, whilst hemp was selected because it currently enjoys much attention as a potential industrial fibre crop. Possible reasons for the lack of toughness that are observed in natural fibre reinforced thermosets are postulated. As will be discussed in this, and in Part II of this series, the use of LEFM to characterise toughness in this class of materials is, however, open to some criticism. Nevertheless, it should be borne in mind that this work was conducted primarily in order to gain further insight into the mechanisms controlling the toughness of these materials. In Part II, the applicability of LEFM will be discussed further and an alternative analysis, based on yielding fracture criteria will be presented and compared with the LEFM approach.

1.2. Fracture mechanics

Fracture mechanics provides a means of quantifying the toughness of a material by considering the conditions under which a pre-existing sharp crack begins to propagate unstably [12]. Both energy and force based failure criteria have been developed for materials exhibiting brittle or quasi-brittle behaviour [13, 14]. These are collectively known as linear elastic fracture mechanics (LEFM). Primarily developed for metals [15, 16], LEFM has nonetheless been applied, with varying degrees of success, to non-metallic materials including; wood, wood-based panels and synthetic PMCs [17–21], as well as to biological materials [22–24].

2. Materials and method

2.1. Laminate fabrication

2.1.1. Fibre

Bast fibres like jute and hemp are isolated from the stem in a process which first involves partially rotting the straw (retting) to loosen the fibres from the surrounding tissue. The fibres are then separated mechanically in an operation known as scutching. Sidlaws of Dundee supplied retted and scutched jute fibre (grown in Bangladesh). Hemcore Ltd provided UK grown, retted and scutched hemp fibre. Both fibre types were supplied chopped to around 50 mm in length. No further fibre treatment had been carried out. The fibres were processed into needle-punched, non-woven felts by J.B. Plant Fibres, Holyhead, Gwynedd, UK. The areal density of the felts used in the preparation of the composites was approximately 350 grams per square metre. Prior to use, the felts were refluxed in a mixture of toluene, acetone and industrial methylated spirit (in the proportions 4 : 1 : 1 by volume) for 1/2 hour to remove waxes and other extractable material.

To attain a range of fibre volume fractions, the felts were first pre-pressed in a hot press at 105°C to thicknesses of 4.5 or 7 mm. The press was held closed for 5 minutes. It was found that when the pressure was released a permanent 'set' had been imparted to the fibre felts. Little 'spring back' was noted after removal of the clamping pressure. Higher volume fractions were achieved by pre-pressing multiple layers of felt. After pressing, the felts were allowed to recondition at 65% R.H. and 20°C for at least 24 hours. Very little further 'spring back' was evident. Because of a degree of in plane anisotropy, with laminates requiring several plies, multiple felts were stacked with the same orientation and subsequent testing undertaken bearing this in mind [10].

In addition to the natural fibre reinforcement, E-glass fibre was utilised for comparative studies. This was utilised in the form of chopped strand mat (CSM) supplied by Scott Bader. The areal weight was approximately 450 grams per square metre.

2.1.2. Matrix resin

A general purpose unsaturated polyester resin (manufactured by DSM resins) of 40% styrene content was

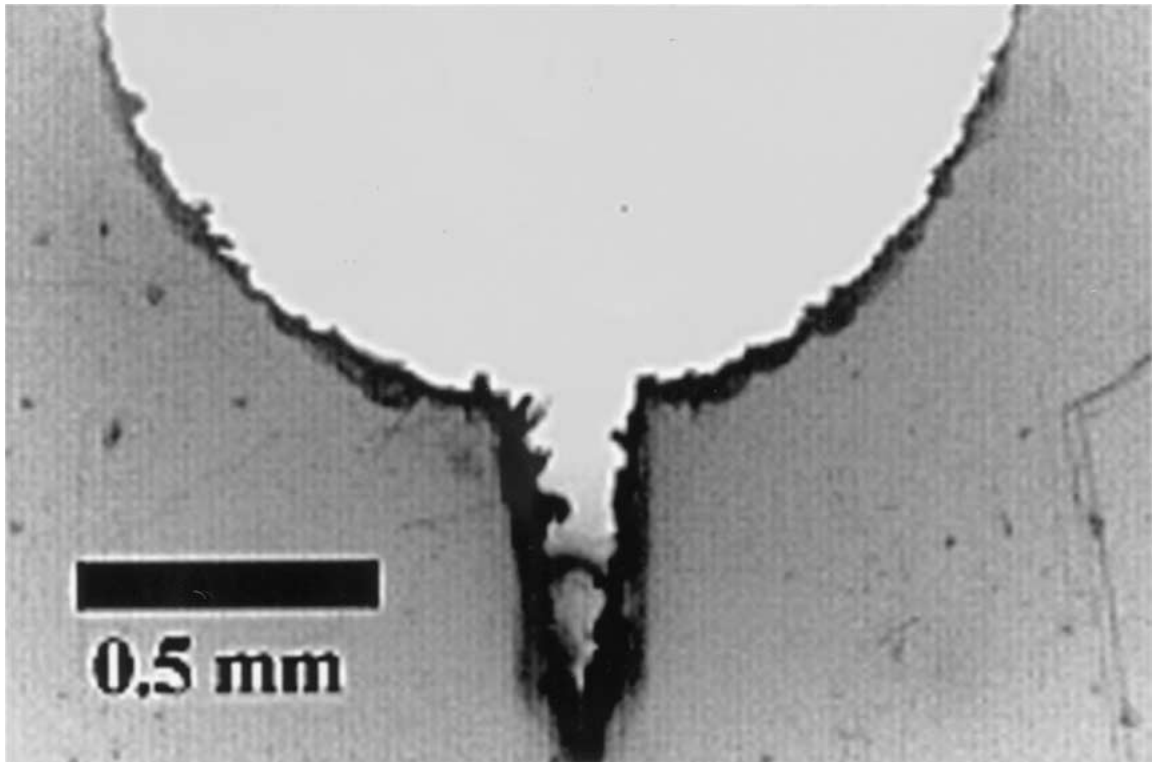

Figure 1 Transmitted light micrograph of a sharp 'starter crack' sawn at the root of a notch stress concentrator in an un-reinforced polymer laminate.

used for the matrix. This required accelerator (N,N-diethylaniline, 10% in aliphatic ester) and initiator (dibenzoylperoxide) for curing at room temperature (∼20°C). Accelerator and initiator, added at 3% (by weight) each, were found to give a gel time of approximately 1 hour, which was adequate for completion of the fabrication process. Prior to use, the catalysed resin was degassed under vacuum for 5 minutes.

2.1.3. Laminate fabrication

Laminates were prepared as flat plaques, approximately 300 mm square and of nominal thicknesses 4.5 mm (for tensile specimens) and 7 mm (for fracture toughness specimens). For the bast fibre reinforced specimens, pre-cut felts (either single 'ply' or pre-pressed 'multi-ply') were first impregnated with catalysed resin using a vacuum infusion process. Once thoroughly 'wetted', the felts were cured between glass plates at room temperature for 20 hours. After initial curing, the laminates were removed from the mould plates and post cured at 90°C for 6 hours.

The CSM reinforced laminates were prepared by careful hand lay-up directly onto the glass plates. This technique was chosen in preference to the infusion process, as there was a tendency for the resin impregnated glass fibres to become displaced during vacuum infusion, leading to laminates with poor reinforcement distribution. Once the desired thickness had been achieved, a second plate was placed on top, with spacers between the plates to give the required thickness. Curing proceeded in the same manner as for the natural fibre laminates. Un-reinforced resin laminates were prepared by casting between glass plates.

2.2. Specimen preparation

Parallel-sided tensile specimens were prepared from the natural fiber reinforced composite plaques by cutting with a circular cross-cut saw. The cut surfaces were abraded to remove artefacts. All CSM and un-reinforced polymer laminates were cut using a water-lubricated diamond saw. All specimens for the fracture toughness tests were also prepared using the diamond saw.

Single edge notched (SEN) specimens loaded in three-point flexure [15] were utilised for the fracture toughness tests. Starter notches were cut centrally in an edgewise plane using the diamond saw. To obtain a sufficiently sharp starter crack at the root of the notch, razor sawing, as described by Anderson [25] was utilised. Fig. 1 shows a sharp notch 'sawn' in a polyester resin specimen. This method proved satisfactory for all laminate types.

Prior to testing, all specimens were conditioned for a minimum of one week at 65% R.H. and a temperature of 20°C.

2.3. Evaluation of fibre volume fraction

Fibre volume fraction (V_f) may be calculated utilising Equation 1, provided the density of the fibre is known accurately.

$$V_f = M_f / V_c \rho_f \tag{1}$$

where M_f is fibre mass, V_c is the volume of the composite and ρ_f is fibre density.

Equation 1 was used to determine V_f for the CSM glass fibre reinforced laminates. However, due to the porosity of natural fibres, the following expression, which accounts for any void space in the laminates,

was adopted to measure the V_f of the natural fibre reinforced composites [2]:

$$V_f = (V_c - (M_c - M_f)/\rho_r)/V_c \quad (2)$$

where M_c is the mass of the composite and ρ_r is the density of the cured polymer.

2.4. Mechanical testing

Tensile tests were conducted on an Instron 1195 universal testing machine. Fracture toughness tests were carried out on an Instron model 4301, universal testing machine.

2.4.1. Tensile tests

Tensile testing was conducted in accordance with BS 2782 [26], at a cross-head speed of 2 mm min.$^{-1}$ using parallel sided (type II) specimens. Rather than using pin jointed ends, the specimens were clamped using self-tightening grips. To prevent damage to the specimen, where clamped, removable 'U' shaped aluminium tags were fitted over the ends, prior to clamping. This method proved entirely satisfactory, with nearly all specimens fracturing within the gauge length, remote from the end tags. Strain was measured with an extensometer. At each volume fraction and for each laminate type, a minimum of 8 specimens were tested.

2.4.2. Fracture toughness

The procedure adopted for the determination of fracture toughness was based upon the method described in BS 7448 [15].

Specimens were loaded in three-point flexure. The load-line displacement rate (cross-head speed) was 5 mm min.$^{-1}$. In addition to noting the overall dimensions of the specimen, the notch depth was measured to an accuracy of 0.01 mm prior to testing by means of a dial micrometer equipped with a sharp edge which 'sat' in the sawn notch. Control of the loading device and data capture were via PC. The data capture rate was set at 20 points sec^{-1}. Specimens were loaded until a maximum force reading was attained. Captured data was saved in 'ASCII' format to facilitate subsequent analysis in propriety software. For each laminate type and V_f, a minimum of 7 replicates were tested.

3. Results

3.1. Tensile properties

As volume fraction is the single most important parameter controlling the mechanical properties of composites [27], laminates were compared on a like for like basis. Since it was not possible to fabricate laminates with exactly matching volume fractions, for comparison purposes, plots of property data, (i.e., Young's modulus and yield stress) versus V_f were first constructed. Computer software curve fitting functions were applied to these data and regression equations obtained. Fig. 2 shows the variation of Young's modulus (E) with V_f, whilst Fig. 3 demonstrates the variation of yield stress (σ_{ys}) with fibre volume fraction. Property data at the required volume fraction (0.2) were then obtained by invoking the appropriate regression equation. Yield stress (Fig. 3) data

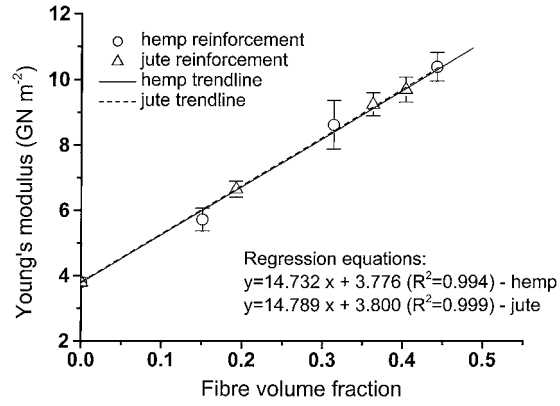

Figure 2 Variation of Young's modulus with fibre volume fraction.

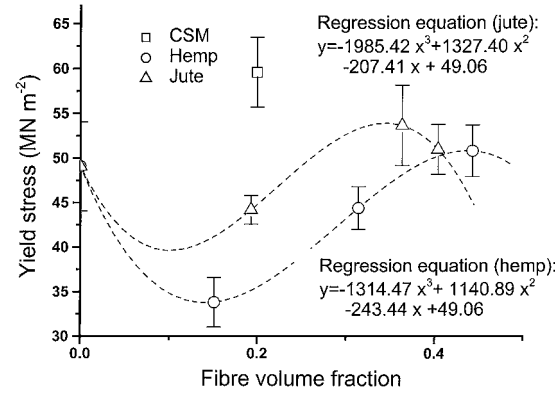

Figure 3 Variation of yield stress (0.2% proof stress) with fibre volume fraction.

at 0.2 V_f, must be treated with some caution, however, due to the limited number of data points available for curve fitting and a degree of uncertainty over the exact relationship between yield stress and volume fraction in the region of interest. Nevertheless, it is believed that any error is small and would not affect significantly the computed value for yield stress at 0.2 V_f. The results are summarised in Table 1. These values were subsequently used in the analysis of the fracture toughness data.

3.2. Fracture toughness

3.2.1. Data analysis

When analysing the force versus load-line displacement curve for a fracture toughness test, the point of interest on the record is the load at which unstable crack extension begins. For linear elastic materials, this load can be taken to be the maximum force reading on the load-displacement record. For materials that exhibit a limited amount of non-linear behaviour prior to the attainment of a maximum force or 'pop-in' (a jump in the force-displacement curve corresponding to sudden, unstable, crack advance) on the load-deformation

TABLE I Tensile properties of laminates at 0.2 volume fraction

Laminate type	Young's modulus (GN m^{-2})	Tensile strength (MN m^{-2})	Yield stress (MN m^{-2})
CSM glass fibre	7.95	73.40	59.60
Non-woven jute	6.79	47.35	45.04
Non-woven hemp	6.70	37.82	36.94
Polymer	3.80	49.10	49.10

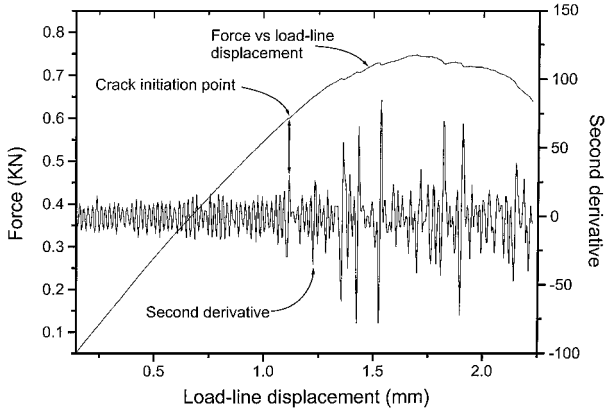

Figure 4 Typical load versus load-line displacement curve for a CSM glass fibre reinforced polyester composite, showing corresponding second derivative ($V_f = 0.2$).

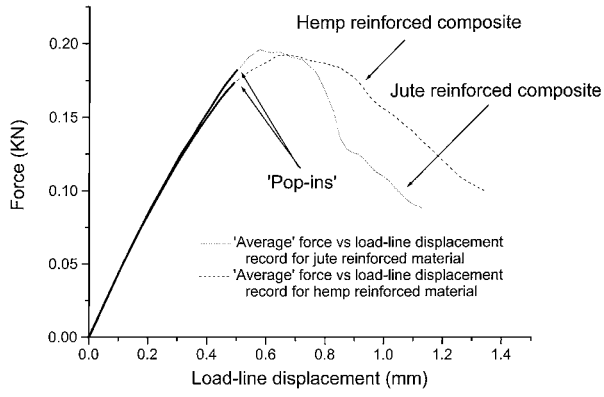

Figure 5 Average force versus load-line displacement curves for jute and hemp fibre reinforced polyester composites of 0.16 and 0.17 V_f respectively.

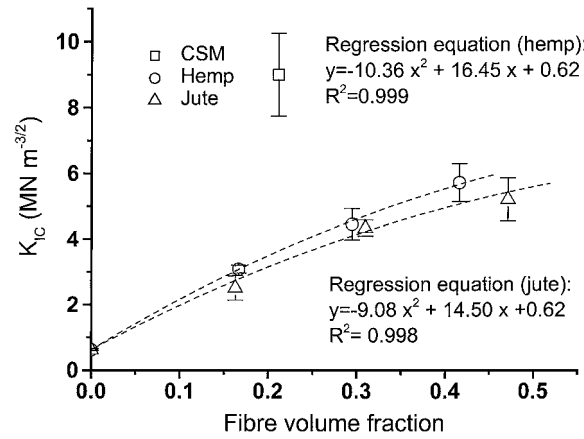

Figure 6 Variation of fracture toughness (K_{Ic}) with fibre volume fraction.

record, a method known as the 'offset procedure' may be adopted [13, 14]. This is designed to test whether any non-linear behaviour prior to 'pop-in' can be attributed to crack advance, or, whether it is due to plasticity effects. If possible, however, it is preferable to detect the onset of crack growth by some direct means [13]. If even small 'pop-ins' can be detected, then it should be possible to determine the onset of crack growth in the material. Essentially a 'pop-in' represents a change in the compliance of a specimen. Digital data acquisition enables computer numerical techniques, such as differentiation, to be performed on the force versus load-line displacement record. The second derivative of the load-deformation record represents the rate of change in stiffness of the specimen with respect to deformation; large changes in rate thus correspond to 'pop-ins' and can be used to detect the onset of crack growth in the material. This method, rather than the 'offset procedure' was used to determine the point of sudden crack advance in this work. A typical load-displacement record for a CSM glass fibre SEN test specimen along with the corresponding second derivative curve is shown in Fig. 4.

3.2.2. Un-reinforced polymer

The suitability of the experimental technique used in this work to assess fracture toughness was demonstrated by considering fracture of the un-reinforced polymer alone. This material exhibited linear behaviour with no macroscopic evidence of plastic yielding prior to fracture. The value for plane strain fracture toughness (K_{Ic}) was found to be 0.62 MN m$^{-3/2}$. This figure is in excellent agreement with values published in the literature for thermosetting polyesters [18] and is in good agreement with the order of magnitude for other thermosetting resins such as epoxies [11]. Utilising the general relationship in Equation 3 [25], the value for E shown in Table I and the computed K_{Ic}, a value for the critical strain energy release rate under plane strain conditions (G_{Ic}) was calculated. This was found to be 0.09 kJ m^{-2} (assuming $\nu = 0.38$ [11]).

$$G = \alpha K^2 / E \tag{3}$$

where G is strain energy release rate, α is 1 in plane stress and $(1 - \nu^2)$ in plane strain, and where, ν is Poisson's ratio and, K is the stress intensity factor.

Again, this is in good agreement with reported values for the work of fracture of other organic glasses [28]. Of all the laminates studied, the polymer itself was nearest to an ideally elastic, isotropic and homogeneous material and as such might be expected to yield the most reliable results.

3.2.3. Fibre reinforced laminates

Fig. 5 shows 'average' force versus load-line displacement records for notched jute and hemp reinforced polyester SEN specimens of V_f 0.16 and 0.17 respectively. As may be observed, up to the points of 'pop-in', some departure from linearity occurs. This must raise some question over the validity of LEFM techniques in this instance. This issue will be explored further in Part II.

The variation of K_{Ic} with V_f for the jute, hemp and CSM reinforced materials is shown in Fig. 6. As with the tensile tests, curve fitting operations were performed and the results of these used to predict K_{Ic} at the desired volume fraction (0.2). Fracture toughness of the glass fibre reinforced material was evaluated at one fibre volume fraction (0.2) only. Table II provides a comparison of the plane strain fracture toughness (K_{Ic}) of the reinforced laminates with that of the un-reinforced polymer.

In addition, an estimate of the critical energy release rate (G_c) for the reinforced material was made utilising Equation 3 (the effect of ignoring the $(1 - \nu^2)$ term

TABLE II Comparison between the fracture toughness of laminates reinforced with jute, hemp and glass fibre and the un-reinforced polymer. ($V_f = 0.2$)

Laminate type	K_{Ic} (MN m$^{-3/2}$)	E (GN m^{-2})	G_c (kJ m^{-2})
CSM laminate	9.01	7.95	10.21
Jute laminate	2.56	6.79	0.97
Hemp laminate	3.51	6.70	1.84
Polymer	0.62	3.80	0.10

under plane strain conditions is negligible, and would not alter the order of magnitude of the differences between the laminate toughness figures). Young's modulus at 0.2 V_f was as shown in Table I. It must be noted that this is very much an estimate of the order of magnitude of G_c, since the materials are treated as being isotropic, with E being taken to be the experimentally determined value along one axis only. During the manufacture of the non-woven material, slight orthotropic properties are imparted to the felt and thus the natural fibre reinforcement cannot be treated as being truly planar random. These properties are imparted to the resultant composite and thus the value of E is, in reality, not independent of the test direction within the plane of the laminate. Nevertheless, these assumptions, whilst a simplification of the situation, are necessary in order to make the comparison.

4. Discussion

As noted, a value of 0.62 MN m$^{-3/2}$ for K_{Ic} for a thermosetting polymer is realistic. Likewise, the value for CSM reinforced material is in good agreement with other published data; a figure of 7.0 MN m$^{-3/2}$ being quoted for a similar laminate type, albeit at a higher (0.3) fibre volume fraction [18]. A slightly greater value for K_{Ic} might well be expected since the method used here to determine the load at crack initiation differs from the 'offset procedure', leading to somewhat higher values. At the time of writing, no figures could be found in the published literature for the K_{Ic} of plant fibre reinforced thermosetting PMCs. Nevertheless, these figures do not look unreasonable and are on a par with those quoted for a number of unreinforced thermoplastic polymers, for example Nylon 6.6 and polypropylene [18].

With regard to K_{Ic}, the addition of reinforcing fibre to the polymer results in an order of magnitude improvement in fracture toughness, with an approximately three-fold difference between natural and synthetic fibre types being observed (see Table II). The stress intensity factor, in essence, provides a measure of the severity of the stress field ahead of a sharp crack. Simplistically, therefore, K_{Ic} can be viewed as providing a measure of the strength of the material in the presence of a notch. The lower fracture toughness observed in the natural fibre reinforced material compared with the glass fibre material, may thus, in part at least, be attributed to the lower tensile strengths reported for these fibres [29].

As may be seen from Table II (at 0.2 V_f), the addition of both natural fibre types resulted in an order of magnitude improvement in the values of G_c of the laminates over that of the unreinforced polymer, hemp possibly providing a somewhat greater improvement. However, the value of G_c for CSM glass fibre reinforced polyester exceeded that of the natural fibre reinforced composites by between five and ten fold. This order of difference is more or less the same as that observed between the Charpy impact strengths of the natural and glass reinforced fibre laminates noted in Section 1.1. The implications of this are that the energy dissipative processes involved in the toughening of the bast fibre reinforced composites are not as effective as those seen in their glass fibre reinforced counterparts.

One of the advantages of fracture mechanics is that macroscopic material behaviour can be linked to conditions at the crack-tip. Provided non-linear behaviour is confined to a small region in the vicinity of the crack-tip (the so called 'plastic zone') and that macroscopically a material responds elastically, Equation 4 [11] provides a link between the radius of the plastic zone (r_y), K_{Ic} and σ_{ys}.

$$r_y \approx \frac{1}{2\pi}\left(\frac{K}{\sigma_{ys}}\right)^2 \tag{4}$$

If it is considered that in fibre reinforced composites, this 'plastic zone' corresponds to a region where the majority of irreversible microstructural damage occurs then it should be possible to estimate the extent of microstructural damage in laminates by considering the 'size' of the plastic zone. Furthermore, if it is assumed that most of the energy absorbing processes associated with the toughness of these materials occur within this damage, or plastic, zone then an estimate of the 'energy absorbing capacity' of the material should be possible by considering the 'size' of the plastic zone. Fig. 7 shows an idealised representation of the 'plastic zone' ahead of the crack-tip.

The composites under investigation were, however, at the scale of this investigation heterogeneous, anisotropic and exhibited a degree of non-linear behaviour and would, therefore, have contravened LEFM

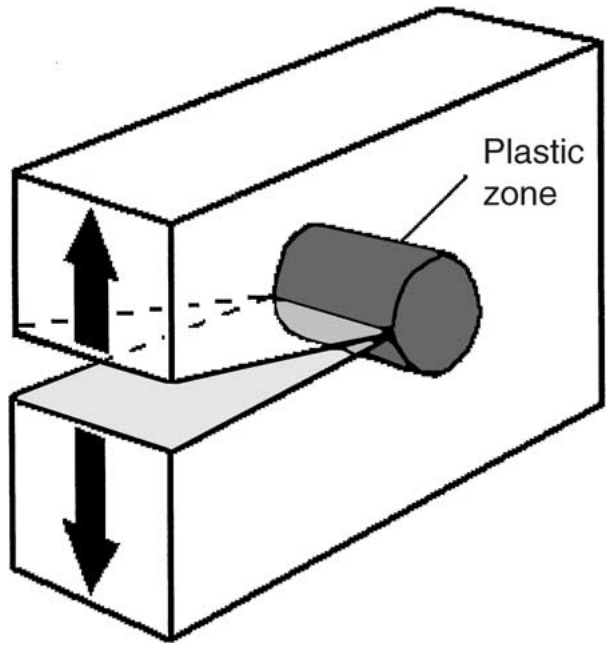

Figure 7 Schematic representation of the crack-tip 'plastic zone' under opening mode conditions.

TABLE III Computed crack-tip plastic zone radii ($V_f = 0.2$)

Laminate type	r_y (mm)	r_y^2 (mm^2)
CSM reinforced laminate	3.64	13.25
Jute reinforced laminate	0.52	0.27
Hemp reinforced laminate	1.44	2.07
Polymer	0.03	9×10^{-4}

assumptions. Nevertheless, if the situation is idealised and it is assumed that *the materials were homogeneous, isotropic and that macroscopically they behaved in a linear-elastic fashion and, furthermore, that they possessed* K_{Ic} and σ_{ys} *values equal to those determined for the 'real' laminates, then for these 'equivalent', hypothetical, materials* r_y *may be computed*. It must be appreciated that this is very much a simplification of reality, but the exercise was conducted in order to *estimate* the relative 'sizes' of the laminate 'plastic zones'.

In this instance, σ_{ys} is taken to be the 0.2% proof stress (Table I). The radii of the computed plastic zones, are presented in Table III. As may be noted, the value of y for the un-reinforced polymer is significantly less than that of the reinforced laminates. Its value of $\sim$30 μm is probably realistic, denoting a very small region of plastic flow and consistent with other predominantly brittle materials in which the main energy absorbing process is through the creation of new crack surfaces. Of all the materials studied, the un-reinforced polymer is nearest to the idealised 'equivalent' material; being essentially elastic, homogeneous and isotropic. Similarly, the r_y values for the 'equivalent' reinforced materials do not appear unreasonable.

A visual inspection of the failed bast fibre reinforced specimens revealed that damage extended approximately 1 mm beyond the apparent crack face into the laminate itself. In other words the advancing crack left a 'wake' of micro-damaged laminate, analogous to the plastic wake left behind an advancing crack in metals [25]. This would seem to be consistent with calculated values for r_y which fell in the range of $\sim$0.5–1.5 mm. The radius of the 'plastic zone' determined for the glass fibre reinforced 'equivalent' laminate was approximately 5 times that of the natural fibre reinforced 'equivalent' material. Again, this prediction was supported by visual inspection of the ruptured laminate.

If it is assumed that most energy dissipation occurs in the damage region ahead of the advancing crack-tip, then it is reasonable to assume that the amount of energy absorption is dependent upon the 'volume' of the damage zone. Thus, for a crack of unit width, the 'volume' of the damage zone would be proportional to r_y^2. Table III also shows a comparison of the computed r_y^2 values. As may be seen, the estimated 'volume' of the damage zone observed in the 'equivalent' natural fibre reinforced composites is approximately an order of magnitude lower that that seen in the 'equivalent' glass fibre reinforced material at equal fibre volume fractions. This would seem to point to a possible explanation for the lower toughness observed in the bast fibre reinforced materials, in that energy dissipative processes are simply not stimulated in the crack-tip region to the same extent as they are in their glass fibre reinforced equivalents. The order of magnitude difference seen in r_y^2 is also consistent with the measured works of fracture of the natural and synthetic fibre reinforced composites that also differ by approximately an order of magnitude.

Previously, it has been postulated [8] that the relative lack of toughness in bast fibre reinforced polyester composites can be attributed (amongst other factors) to the lack of fibre pull-out exhibited by these materials, when compared to the extensive fibre pull-out observed in glass fibre reinforced material. Fibre pull-out is a mechanism which can account for significant energy absorption in fibre reinforced composites [11]. This would seem to be consistent with the findings of the present work, namely that the size of the 'plastic zone' in bast fibre reinforced material is significantly smaller than in glass fibre reinforced equivalent materials.

5. Conclusions

LEFM has been used to assess the toughness of natural (and synthetic) fibre reinforced polyester laminates. However, since the materials' properties deviate from that which is normally acceptable, the validity of this analysis must be treated with caution. Nevertheless, it may be observed that K_{Ic} for the natural fibre reinforced composites were around 3 times lower than the volume equivalent (0.2 V_f) glass fibre reinforced materials. When converted to G_c values, this difference approximates to an order of magnitude. An extension of this approach yields a possible explanation, in that the various micro-structural toughening mechanisms are not being stimulated to the same extent in the natural fibre reinforced materials as they are in their glass fibre counterparts.

The use of fracture mechanics to characterise the toughness of these materials has, it is to be hoped, provided a more quantitative assessment of the relative toughness of bast fibre reinforced unsaturated polyester laminates. It would appear to have confirmed that initial concerns regarding the toughness of the materials are, indeed, valid. Although the applicability of fracture mechanics techniques to characterise toughness in this class of material is open to some criticism, it is believed that this approach has provided some further insight into the mechanisms involved in the toughness of these materials. Further, it has highlighted the fact that the micromechanics of fracture of these composites should be investigated more closely.

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