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Jute and glass fibre hybrid laminates

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Hybrid laminates have been fabricated from randomly oriented jute fibre mats and woven glass fabrics with a common polyster resin matrix. Hand lay up techniques were used to simulate practical production methods in the field. A variety of laminate constructions were mechanically tested and some laminates were in addition assessed for environmental stability. Modified rule of mixtures expressions successfully predicted the tensile properties of the laminates and the jute plies were seen to control the failure of hybrid laminates at about 0.8% strain. Fracture toughness measurements of G_{IC} and K_{IC} indicate that hybrid laminates have maximum toughness ($G_{IC} \approx 12\,kJ\,m^{-2}$) when jute plies are sandwiched between glass fabric facings. All the hybrid laminates were found to be tough in impact, although here fabric plies used as the laminate core maximize the work of fracture at a value of approximately $45\,kJ\,m^{-2}$. Hybrid laminates with jute facings are, as expected, least able to withstand hot moist environments. However, significant moisture uptake by the polyester resin matrix was measured for all laminates. Optical and scanning electron microscopy have been used to explain the mechanical performance and environmental resistance of the hybrid laminates.

1. Introduction

A recent paper [1] reports the tensile properties of jute-reinforced polyster composites (JRP) containing uniaxially oriented raw jute fibre. The specific modulus (modulus divided by specific gravity) of jute fibre was found to be approximately $43\,GN\,m^{-2}$ compared with approximately $29\,GN\,m^{-2}$ for glass fibre. However, the specific strength of jute fibres, at $340\,MN\,m^{-2}$, is considerably lower than that for glass, at $1360\,MN\,m^{-2}$. Even when cost is taken into account the specific strength per unit cost of jute is only approximately 80% that of the more expensive glass fibre.

In order to better exploit the undoubtably attractive properties of jute, fibre mats of randomly oriented jute have been laminated with woven glass fabrics in a polyester resin matrix to form composite hybrid laminates. Jute is readily available as a fibre mat in the UK and woven glass fabrics are easy to handle and freely available in a variety of weaves. Plain and twill weaves were investigated in this work. A standard polyester resin was chosen because of its low cost and compatibility with both fibrous phases.

Research on jute composites has been reviewed [1] but little literature exists on the mechanical properties of jute hybrid laminates. Shah and Lakkad [2] fabricated jute and glass fibre hybrid composites in both epoxy and polyester resin matrices. Their test results showed that jute fibre would in most cases fail first at a strain of about 0.7% which could cause catastrophic failure depending on the volume fraction of glass fibre present. If the remaining glass could support the applied load then failure strains of about 1% were observed. They concluded that jute provides a reasonable core material laminated with glass fibre facings, where high strength applications are not being considered. In accelerated weathering tests the hybrid mechanical properties did not deteriorate as quickly as single fibre jute or glass laminates, although reasons for this are not proposed. Wells *et al.* [3] suggest the use of glass fabric skins in association with a surface gel coating to improve the environmental resistance of JRP.

The work reported here sets out to mechanically and environmentally test jute–glass fabric hybrid composites with a variety of laminate constructions. Optimum ply configurations are identified which offer respectable mechanical properties at an attractively low cost. The possibility of achieving a synergistic improvement in hybrid properties over properties predicted from laminates with single phase reinforcement is also investigated. Hybrid composites are fabricated by hand lay up which is intended to simulate practical production methods in the field.

2. Experimental methods

Jute fibre was supplied in the form of a randomly oriented chopped strand mat from Tayside Plastics Ltd (Dundee). The mat, type CFM 150, had a weight of $150\,g\,m^{-2}$, and contained a small percentage of impurities such as bark.

Two types of woven glass fabric were used, a twill weave (Marglass 254) and a plain weave (Marglass 7628), with the characteristics detailed in Table I.

Both fabrics were purchased coated with a methacrylato silane finish compatible with polyester resin. An air cure strand glass polyester resin A was chosen with a MEKP cataylst. The cure schedule was 24 h at room temperature followed by 2.5 h at 80° C. A variety of single, triple and five-ply laminates were constructed, the individual plies being labelled J(jute), T(twill) and P(plain). So a five-ply laminate with two

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TABLE I Glass fabric characteristics

Fabric	Thickness (mm)	Weight ($g\,m^{-2}$)	Threads (dm^{-1})		Filament diameter (μm)
			Warp	Weft	
Plain 7628	0.17	200	173 ×	122	9
Twill 254	0.19	186	142 ×	126	7

external plain weave layers and three internal jute layers is denoted P3JP. All the laminates containing glass fabrics were laid up with the warp fibres oriented parallel to the test direction.

Large laminated sheets were carefully laid up by hand and fed through a two-high rolling mill to achieve the desired thickness and hence fibre volume fraction. The gel state of the resin was ideal for this process as the intermediate viscosity of the resin prevented excessive resin flow, yet resisted expansion of the compressed jute fibre mat. The rolled laminate was then clamped between spaced glass plates and cured. Dumb-bell specimens for tensile testing were shaped with a router according to ASTM D638 [4].

Volume fractions of fibre were determined by weighing each component prior to lamination and then weighing the pore-free cured laminate such that,

$$V_f = \frac{W_j/\varrho_j + W_g/\varrho_g}{W_r/\varrho_r + W_j/\varrho_j + W_g/\varrho_g} \qquad (1)$$

where W_j is the weight of jute fibre, W_g is the weight of

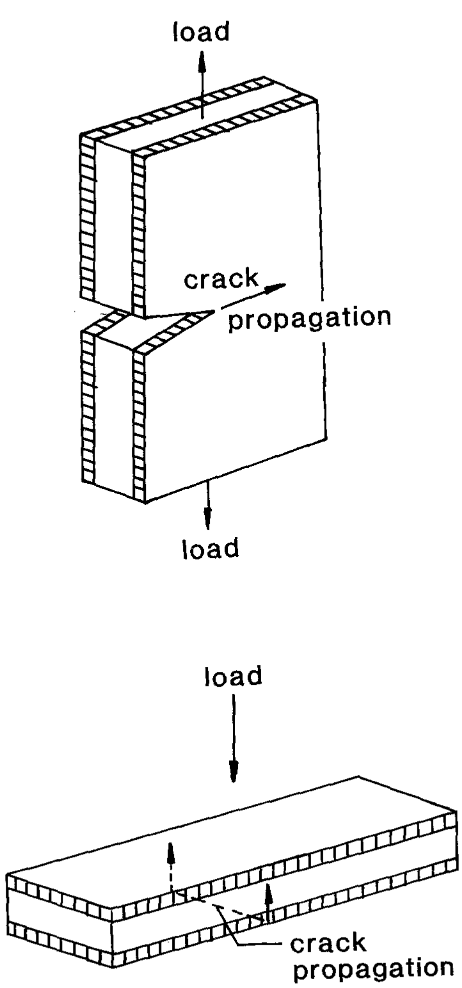

Figure 1 (a) Orientation of compliance specimens. (b) Orientation of Charpy impact specimens.

glass fibre and W_r is the weight of catalysed resin. The density ϱ_g of glass fibre ($2550\,kg\,m^{-3}$) and cured resin ϱ_r ($1148\,kg\,m^{-3}$) were obtained from the manufacturer's data sheets. The density of jute ϱ_j was obtained by a water immersion technique where a known weight of jute fibre was immersed in a known volume of water. Air was removed by agitation and by the use of a vacuum pump. Hence by measuring the jute volume a density for jute of $1300 \pm 110\,kg\,m^{-3}$ was obtained in agreement with other quoted values [3].

Dumb-bell specimens were tested in tension at a crosshead speed of $1\,mm\,min^{-1}$ with an extensometer attached to the necked portion of the sample. Fracture toughness measurements were made on edge-notched samples, Fig. 1a, using the compliance calibration technique. Specimens were parallel sided with dimensions 50 mm × 50 mm exposed between the grips. Cracks were cut with lengths between 2.5 and 25 mm and a scalpel blade was drawn across the saw cut to produce a constant crack tip radius.

Impact tests were performed in a Charpy machine to measure work of fracture. Samples were unnotched, Fig. 1b, because introducing a notch at right angles to the plane of the laminates involved cutting through one or more plies in the laminate. Impact loads were applied in a direction at right angles to the plane of the laminate and this orientation was chosen to represent lateral impact to a laminate panel in commercial use. Charpy impact test results are of course inherently inaccurate as some energy from the swinging pendulum is converted into heat, sound and kinetic energy imparted to the fractured sample. However, the test is a useful comparative method of assessing the efficiency of laminate construction.

Environmental tests were performed on two laminate constructions 3J and P3JP to investigate the effect of glass facings on the environmental resistance of the laminate. Tensile samples were immersed in water and weight changes noted with time. Some sample edges were sealed with resin. Accelerated tests were performed by boiling in distilled water for between 1/2 and 18 h. Specimens were dried out to constant weight before tensile testing. A less severe test was carried out for 21 days in an environmental cabinet with conditions switching every 12 h between 85° C/85% r.h. and − 10° C/low r.h. Finally scanning electron microscopy was used to examine the fracture surfaces of selected tensile, impact and environmentally exposed specimens, in conjunction with optical microscopy and visual examination.

3. Experimental results

3.1. Tensile properties

Measurements were made of the tensile stiffness and strength of three and five-ply laminates and those values were compared with properties predicted by summing the properties of glass and jute fibres in single ply composites. Simple rule of mixtures relationships for unidirectional composites are clearly not appropriate for predicting the properties of laminates containing bidirectional glass reinforcement and randomly oriented jute fibres. Hence the treatment of Krenchel [5] was used to account for the fibre

TABLE II The mechanical properties of jute and glass fibres

Fibre type	Experimental strength ($MN\,m^{-2}$)	Literature values [1, 6]	Experimental modulus ($GN\,m^{-2}$)	Literature values [1]
Twill	1040 ± 135	44.7 ($kN\,m^{-1}$)	51 ± 5	–
Plain	1140 ± 82	43.1 ($kN\,m^{-1}$)	66 ± 6	–
Jute	250 ± 37	422–442 ($MN\,m^{-2}$)	45 ± 4	53–66 ($GN\,m^{-2}$)

geometries. The Young's modulus for jute single ply material was predicted by,

$$E_c = 0.385\, E_f V_f + E_m(1 - V_f) \quad (2)$$

where the factor of 0.385 accounts for the random orientation of fibres. The single ply glass composite modulus was predicted by,

$$E_c = 0.5\, E_f V_f + E_m\,(1 - V_f). \quad (3)$$

where the factor of 0.5 accounts for the bi-directional weave. V_f is the fibre volume fraction and E_f and E_m the fibre and matrix moduli respectively. The equations for the composite strength are exactly analogous. The experimental strengths and moduli of glass and jute fibres derived from Equations 1, 2 and 3 are compared with literature values in Table II.

The literature values for the twill and plain weave fabric strengths are for the warp direction expressed as failure force per unit width. No literature values are available for the modulus of elasticity. However, glass fibres generally have a Young's modulus of approximately $70\,GN\,m^{-2}$. The calculated values for the experimental moduli of the glass fibres in the twill and plain weave fabrics is rather lower because of the crimp in the woven yarns. The range of error given for the experimental values represents the standard deviation for at least eight samples. All the hybrid laminates were tested with the glass weave oriented with the warp fibres in the test direction.

Table III summarizes the tensile test results for a variety of single, three and five-ply laminates. The predicted failure strengths and elastic moduli of the hybrid laminates were calculated using the derived fibre strengths and moduli from the single ply results. Simple rule of mixtures expressions were again used to calculate the composite strengths and moduli, and these values were used as a baseline from which any possible synergistic effects could be assessed. The volume fractions of fibre in all the composite laminates is low, ranging from 0.145 for jute alone to 0.31 for the plain weave fabric. However, these values reflect practical figures that might be obtained by hand lay up. The addition of jute fibres to polyester resin raises the modulus and strength significantly, as expected, and the strain to failure is approximately double that of the resin alone. The stress–strain characteristic for jute–polyester(J) is linear to about 0.3% strain, but becomes nonlinear at approximately half the failure stress. This plastic deformation is a result of fibres shearing in the matrix and the inherent ductility of the fibre itself.

Uncrimping of the glass fabrics in the four glass–polyester (P and T) composites results in failure strains of about 2%. The properties are considerably superior to the jute composite because of the higher glass fibre stiffness and the larger fibre volume fraction. At about 75% of the failure stress, whitening of the surface of the glass laminates occurred, especially in the more highly crimped plain weave fabric composites, due to microcracking of the resin.

The hybrid laminates all failed at about 0.8% strain or less, indicating that failure of the laminate initiates from the jute ply. This normally causes catastrophic failure of the laminate unless there is a substantial

TABLE III Summary of tensile testing results (values are quoted ± one standard deviation)

Laminate	V_f	Strain to failure (%)	Experimental tensile strength ($MN\,m^{-2}$)	Predicted tensile strength ($MN\,m^{-2}$)	Experimental elastic modulus ($GN\,m^{-2}$)	Predicted elastic modulus ($GN\,m^{-2}$)	Deviation between experimental and predicted values
Jute	0.145	0.74 ± 0.1	31 ± 4.6	–	5.1 ± 0.4	–	–
P (warp)	0.31	1.71 ± 0.2	191 ± 14.0	–	12.3 ± 1.2	–	–
P (weft)	0.31	1.81 ± 0.12	129 ± 8.8	–	7.6 ± 0.4	–	–
T (warp)	0.2	1.61 ± 0.3	120 ± 16.1	–	7.5 ± 0.7	–	–
T (weft)	0.2	2.13 ± 0.37	107 ± 11.0	–	5.8 ± 0.8	–	–
Resin A	–	0.43 ± 0.07	20 ± 3.1	–	3.0 ± 0.3	–	–
JJJ	0.16	0.73 ± 0.11	38 ± 5.8	34.2 ± 4.9	5.2 ± 0.5	5.3 ± 0.8	σ + 11% E − 3%
JPJ	0.16	0.72 ± 0.09	42 ± 5.5	37.4 ± 6.2	5.9 ± 0.6	5.8 ± 1.0	σ + 12% E − 2%
TJT	0.19	0.85 ± 0.08	64 ± 4.4	51.5 ± 10.7	8.0 ± 0.6	6.6 ± 1.1	σ + 24% E + 21%
PJP	0.20	0.80 ± 0.05	60 ± 7.0	52.7 ± 10.3	7.9 ± 1.0	7.2 ± 1.0	σ + 10% E + 10%
PJPJP	0.21	0.82 ± 0.12	60 ± 6.8	52.7 ± 10.1	8.3 ± 0.6	7.3 ± 1.3	σ + 15% E + 14%
P3JP	0.18	0.64 ± 0.19	42 ± 9.8	37.2 ± 7.3	6.9 ± 1.0	6.1 ± 0.9	σ + 12% E + 13%
J3PJ	0.20	0.58 ± 0.19	47 ± 10.3	42.1 ± 8.2	7.9 ± 0.9	7.1 ± 1.0	σ + 12% E + 11%

volume fraction of glass fibre in the laminate. For instance the glass core in the J3PJ laminate frequently withstood fracture of the outer jute plies. Stress whitening of the glass plies often manifested itself as ply separation at the glass–jute interface, although twill weave fabrics were less likely to delaminate because of their lower degree of yarn crimp.

The tensile strength of the hybrid laminates varied depending on the construction. An example of this is the data for the PJPJP and J3PJ construction, the former having an average strength approximately 30% greater than the latter construction. It is thought that three factors account for this difference:

1. The surface of tensile specimens are subject to greater strains than the sample centres.
2. Glass plies have a greater extensibility than the jute plies.
3. Glass plies are resistant to the propagation of microcracks, whereas jute plies are not.

Thus by placing a more extensible, flaw-tolerant ply at the surface, the probability of failure at surface stress concentrations is reduced. As expected the modulus of elasticity is independent of the laminate construction. Measured values of composite strength and modulus are about 10% greater than those predicted. This is not in itself evidence for any synergistic effect as no account is taken of transverse fibre contributions, the simple rule of mixtures expressions (Equations 2 and 3) are approximations and experimental error could be as high as $\pm 10\%$. Nevertheless theoretical predictions give a reasonably accurate estimate of the properties of the hybrid laminates.

3.2. Fracture toughness tests

Values for the Mode I critical strain energy release rate, G_{IC}, were calculated using the compliance calibration technique and the formula,

$$G_{IC} = \frac{P^2}{2B}\frac{dc}{da} \quad (4)$$

where P is the load at failure, B is the specimen thickness and dc/da is the rate of change of compliance with crack length. G_{IC} is expected to be a materials constant which is independent of crack length. Fig. 2 for P3JP demonstrates that some variation in G_{IC} with

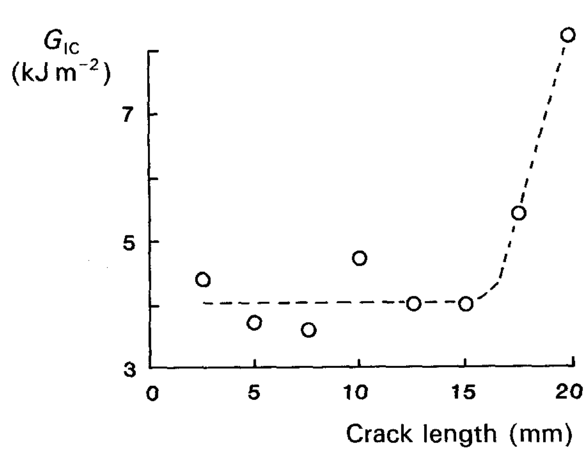

Figure 2 Plot of G_{IC} against crack length for a P3JP five-ply laminate.

TABLE IV Summary of fracture toughness results

Sample	G_{IC} (kJ m^{-2})	K_{IC} (MN m$^{-3/2}$)
Plain weave (warp)	34.3 ± 5.0	20.6 ± 2.5
Plain weave (weft)	18.1 ± 1.2	11.7 ± 0.7
Twill weave (warp)	23.5 ± 3.7	13.3 ± 1.7
Twill weave (weft)	18.1 ± 2.0	10.2 ± 1.0
Jute single-ply	1.2 ± 0.1	2.5 ± 0.2
Jute three-ply	3.9 ± 0.4	4.5 ± 0.5
JPJ	3.7 ± 0.5	4.6 ± 0.5
TJT	9.5 ± 1.8	8.7 ± 1.1
PJP	5.9 ± 1.0	6.8 ± 1.0
PJPJP	12.2 ± 2.3	10.1 ± 1.3
P3JP	4.2 ± 0.4	5.4 ± 0.7
J3PJ	9.6 ± 0.9	8.7 ± 0.9

crack length is found. At long crack lengths some deviation from plane stress conditions occurs as the sample tends to buckle under load. Using the plane stress relationship for the critical stress intensity factor,

$$K_{IC} = (EG_{IC})^{1/2} \quad (5)$$

values of G_{IC} and K_{IC} were calculated for the laminates of Table III and these are presented in Table IV. The values of G_{IC} and K_{IC} for the single-ply plain and twill weave glass fabrics agree with literature values of between 10 and 100 kJ m^{-2} for G_{IC} and 20 to 60 MN m$^{-3/2}$ for K_{IC}, depending on fabric construction and fibre volume fraction. In both these fabrics a region of delamination (whitening) running ahead of the crack front was observed although the crack propagated stably, fibre tows breaking in turn. In contrast the jute single-ply exhibited unstable crack propagation especially at small crack lengths where the stored elastic strain energy was large enough to cause rapid and catastrophic failure of the sample via the propagating crack. This is reflected in the values of G_{IC} and K_{IC}, these values being an order of magnitude less than those for the glass fabrics. It must be remembered that jute laminate has a low fibre volume fraction with random fibre orientation so the two types of laminate cannot strictly be compared.

Turning to the hybrid constructions a number of results are worthy of discussion. Firstly the fracture toughnesses of the JPJ and 3J constructions are very similar and the fibre phase of the central core has little influence on G_{IC} as might be expected from the single-ply results. The outer jute plies appear to control crack propagation and cracks grow rapidly. However, the thicker glass core of the J3PJ construction restrains crack propagation in the jute surface plies, resulting in slow, controlled crack growth. The G_{IC} value for PJPJP is 25% greater than J3PJ despite the fibre volume fraction being identical (Table III). Evidently the laminate construction does affect the mode of failure as discussed for the tensile results of Section 3.1. During compliance testing of J3PJ samples the crack propogates further in the jute plies than in the glass, whereas for the PJPJP construction the crack front was roughly straight indicating the controlling influence of the outer glass plies.

Finally the TJT construction is seen to be tougher than the PJP. The glass ply can only exert a constraint

TABLE V Work of fracture of laminates in un-notched Charpy impact tests

Laminate construction	Fibre volume fraction	Work of fracture ($kJ m^{-2}$)
Resin A	–	3.1 ± 0.6
3J	0.16 jute	2.9 ± 0.3
JPJ	0.13 jute 0.03 glass	20.2 ± 1.7
P3JP	0.13 jute 0.04 glass	10.1 ± 1.3
PJPJP	0.13 jute 0.08 glass	24.5 ± 2.4
J3PJ	0.12 jute 0.08 glass	44.0 ± 3.6

on the jute ply as long as they are in contact. The twill weave is crimped less than the plain weave and as a result it maintains contact with the jute ply for longer, constraining crack propagation through the jute ply. In conclusion it has been demonstrated that the best way of maximizing the toughness of the hybrid laminates is to sandwich jute plies between glass facings.

3.3. Impact tests

The results of impact testing of selected three and five-ply laminates are summarized in Table V.

A result for the resin matrix alone is included providing a baseline measurement from which the toughening effects of fibre additions can be assessed. Somewhat surprisingly the addition of jute fibres (3J) has no beneficial effect on work of fracture, probably due to the low volume fraction of randomly oriented jute fibre.

The hybrid laminates all produced values of impact toughness of greater than $10^4 J m^{-2}$ which is high for these low fibre volume fractions. Although the JPJ and P3JP samples contain approximately the same fibre volume fractions, the fabric used as a core is a much more efficient barrier to crack propagation than as a facing. Interestingly this is the reverse of the effect noted in the fracture toughness results. Here the difference must be due to interfacial delamination between jute and glas plies and the trend is again seen in the J3PJ and PJPJP construction of equivalent volume fraction where the glass placed as a core improves the work of fracture significantly. Fracture mechanisms are described in Section 3.5 but it can be said briefly that greater interfacial ply delamination accounts for the high work of fracture of the J3PJ construction.

3.4. Environmental tests

Jute and P3JP laminates were immersed in water at room temperature with sealed and unsealed edges and the rate of water uptake was measured, Fig. 3. The parabolic curve shape is typical of permeation controlled processes. The figure illustrates that glass fabric facings and sealed sample edges are beneficial in preventing water permeation.

After a period of only 7 days the unsealed 3J sample showed visible darkening around the edges and after 14 days this had spread across the whole sample. This effect occurred to some extent in P3JP material but not at all in the sealed laminates. Sealing of edges prevents diffusion of water through jute fibres which have hollow central channels. Sealed P3JP laminates are most effectively protected from water ingress but nevertheless a weight increase of over 2% is experienced demonstrating that the polyester resin itself absorbs a significant amount of moisture.

P3JP and 3J laminates were also exposed to boiling water in an accelerated test and dried to constant weight for testing. The effect of exposure time on the modulus of elasticity and strain to failure are demonstrated in Fig. 4. In both cases the Young's modulus, measured in tension, falls by about 50% and the strain to failure increases. Little change was measured in the tensile strength.

Water is expected to have disrupted glass and jute fibre to matrix bonds and plasticized the resin matrix. As a result the strain to failure increases as the modulus falls sharply in the first few hours of exposure. Further boiling reduces the modulus moderately but this is now associated with a decreasing strain to failure suggesting matrix embrittlement. However the strength of the 3J laminate falls to only about $30 MN m^{-2}$ after 18 h of immersion which is approximately 75% of the initial strength.

This contrasts with a greater than 50% reduction in the modulus of elasticity. It is proposed that a probable reduction in the frictional bond between fibres and matrix has a greater effect on stiffness than strength.

To alternate heating and freezing of laminates is potentially more destructive than the boiling test since the water that permeates into the laminate at high temperatures (85° C/85% r.h.) will freeze and cause internal damage during the cold cycle (−10° C/low r.h.). After 21 days of cycling the P3JP laminates showed a fall in elastic modulus from $6.9 \pm 1.0 GN m^{-2}$ to

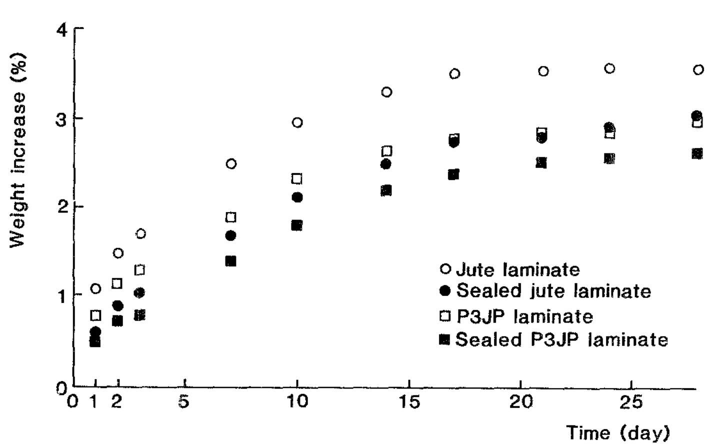

Figure 3 Percentage weight increase against time for jute laminates immersed in water at room temperature.

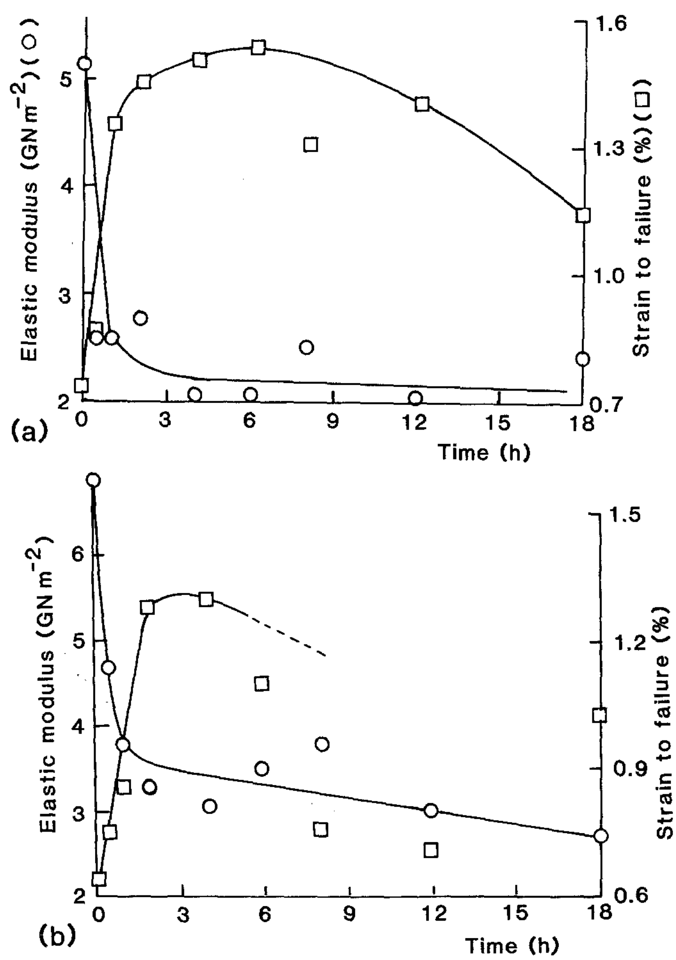

Figure 4 Modulus of elasticity and strain to failure against exposure time in boiling water. (a) three-ply jute laminate (3J) and (b) P3JP laminate.

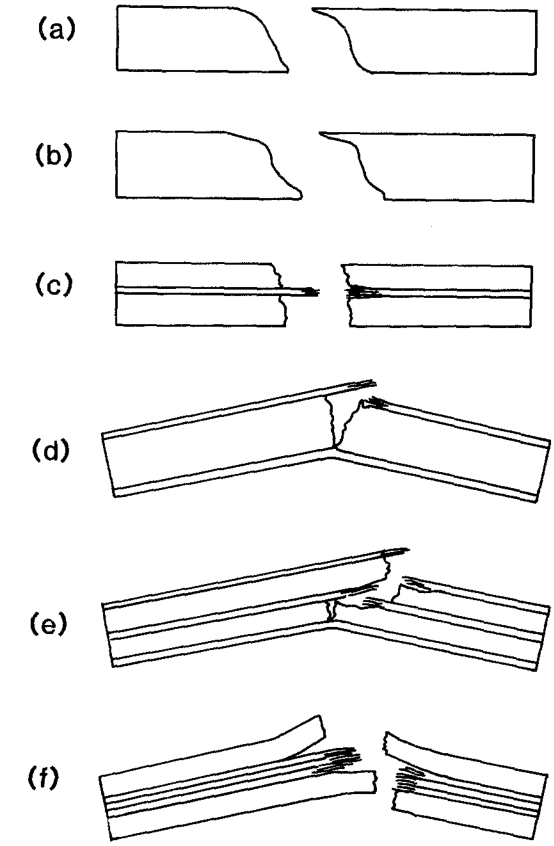

Figure 6 Fracture of un-notched specimens tested by Charpy impact. (a) Resin A, (b) three-ply jute, (c) JPJ, (d) P3JP, (e) PJPJP and (f) J3PJ.

$5.0 \pm 1.0\,\mathrm{GN\,m^{-2}}$ with a smaller change than for the boiled material. However, the change in strength was similar to the boiled material, namely a fall from 41.5 ± 9.8 to $31.1 \pm 2.5\,\mathrm{MN\,m^{-2}}$ with an increase in failure strain from 0.64 ± 0.2 to 0.78 ± 0.2. All figures quoted here are plus or minus one standard deviation over at least eight samples.

Clearly total immersion in boiling water has a more dramatic effect on the laminate stiffness than the cyclic test. But 21 days of hot/cold testing produces a similar change in strength to 18 h of boiling, so cyclic freezing appears to increase the flaw density in the laminate reducing the strength more rapidly than the modulus of elasticity.

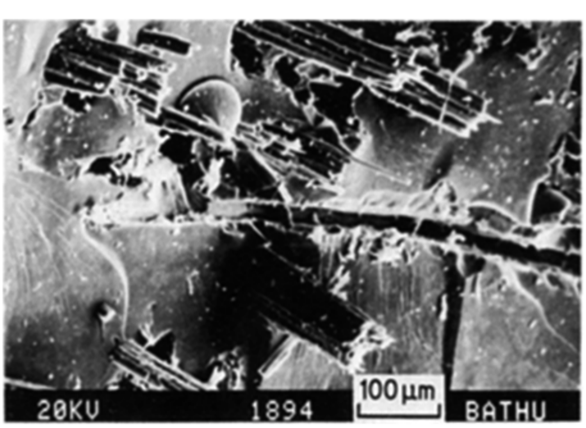

Figure 5 Tensile fracture of a single-ply jute laminate.

3.5. Fractography

Jute fibre reinforced composites fracture in tension in very much the same way as glass reinforced plastics, GRP, [1], although the fibres are coarser, hollow and less evenly spaced. Matrix fracture is essentially brittle, Fig. 5, although some evidence for plastic deformation can be observed in the form of micro-rugosity and yield lines. The length of jute fibre pull out depends on the relative orientation of the fibre to the fracture surface. Fibre surfaces are quite smooth and fibre fractures are brittle, similar to the glass fibre fractures in the woven glass plies. Stress whitening at the surface of glass plies is observed to be due to microcracking in a direction at right angles to the applied stress, a feature commonly seen in glass fabric reinforced composites. Hybrid laminates of glass and jute plies typically delaminate at the jute to glass interface when tested in tension. This effect is more pronounced in the plain weave than the twill weave material as has been described in Section 3.1.

The impact results of Section 3.3 demonstrated the effectiveness of placing the fabric plies at the core of jute/glass hybrid laminates. The mode of fracture of various laminates tested in impact are sketched in Fig. 6. The similarity between the resin, (a), and three-ply jute, (b), fractures accounts for the similarity in the work of fracture results, and the jute fibre contributes negligibly to the work of fracture because of the low fibre volume fraction. The principal contribution to work of fracture in the hybrid laminates must result from glass fibre fracture and pull-out, and interfacial ply separation associated with blunting of rapidly propagating cracks.

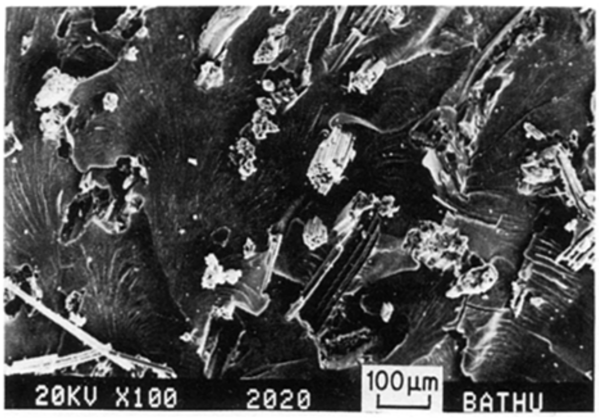

Figure 7 Fracture surface of a three-ply jute laminate exposed to boiling water for 12 h.

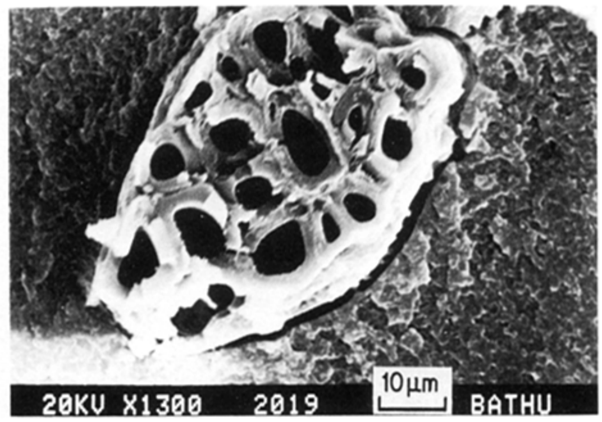

Figure 8 Jute fibre fractured in a polyester resin matrix after 12 h exposure to boiling water.

The JPJ laminate, (c) is tougher in impact ($\approx 20\,\mathrm{kJ\,m^{-2}}$) than the P3JP laminate, (d), ($\approx 10\,\mathrm{kJ\,m^{-2}}$). In the JPJ material two jute/glass interfaces must delaminate and the glass fabric layer must break before the laminate fails. In the P3JP material typically only one glass fabric layer fractures and only one jute/glass interface is effective in blunting the advancing crack. This effect is observed again in the PJPJP, (e), and the J3PJ, (f), constructions. The addition of glass facings to the JPJ laminate only raises the work of fracture from about 20 to $25\,\mathrm{kJ\,m^{-2}}$. However the addition of two glass plies to increase the size of the core raises the work of fracture from 20 to $44\,\mathrm{kJ\,m^{-2}}$. There is more interfacial ply delamination in J3PJ laminates than PJPJP laminates reflecting its higher work of fracture. The geometrical arrangement of a thick glass core with jute facings undoubtably contributes to the high work of fracture and the J3PJ laminates often disintegrate when loaded in impact.

Turning to the effect of environment on fracture, the severe boiling water environment has the most obvious effect on the fracture topography. There are pronounced ridges on the resin surface, Fig. 7, characteristic of a more plastic fracture mode. The laminates subjected to the hot/cold controlled environment and the as-manufactured laminates exhibit relatively smooth resin fractures. The surface roughness of the fractured resin in the boiled samples, Fig. 8, is of a fine-scale, and this roughness is absent in the other test conditions. There is also clear evidence of de-bonding at the fibre–matrix interface.

Little apparent change occurs at the surface of weathered fibres, both glass and jute, so the environment most importantly affects the plasticity of the resin and the fibre–resin interface. The volume of samples was not observed to have increased when dried after weathering, within experimental error, and the ply to ply interface remains intact. The peel energy of the glass fabric from jute plies is reduced from approximately 300 to $250\,\mathrm{J\,m^{-2}}$. Hence in general the laminates show a fairly good resistance to the weathering environments for a short period of time but preventative measures such as sealing with a hydrophobic gel may be required to protect laminates against long term exposure.

4. Discussion and conclusions

There is little point in comparing the properties of the various hybrid laminates without making reference to the cost per unit property. The costing made in Table VI is based on manufacturer's figures for 1983. The glass fabrics are sold in a roll width of 130 cm [6] and the plain weave fabric was priced at £1.04 $\mathrm{m^{-1}}$ length and the twill weave at £2.71 $\mathrm{m^{-1}}$ length. Jute mat was supplied in a 100 cm wide roll [7] and cost £0.28 $\mathrm{m^{-1}}$ length. The polyester resin was marketed in 1983 at £1.24 $\mathrm{kg^{-1}}$.

The values of cost per $\mathrm{m^2}$ of laminate in Table VI are clearly greater for the five-ply constructions than the three-ply, simply because they are thicker. The cost per unit property columns are normalized with respect to cross-sectional area. The TJT construction is disadvantaged because of the high cost of the twill weave fabric and 3J laminates are more expensive than the PJP laminates because of the low volume fraction of the cheap jute fibre in the resin matrix. From the tensile property viewpoint the PJP laminate is the most cost effective construction.

Comparing the five-ply laminates it can be seen that the P3JP construction is uneconomic. The cost per $\mathrm{kJ\,m^{-2}}$ of G_{IC} for PJPJP is lower than for J3PJ but J3PJ offers an exceptionally low cost per $\mathrm{kJ\,m^{-2}}$ of

TABLE VI The cost per unit property for selected laminate constructions

Laminate	V_f	Cost per $\mathrm{m^2}$ of laminate (£)	Cost per $\mathrm{GN\,m^{-2}}$ of stiffness (£)	Cost per $\mathrm{MN\,m^{-2}}$ of strength (£)	Cost per $\mathrm{kJ\,m^{-2}}$ of G_{IC} (£)	Cost per $\mathrm{MN\,m^{-3/2}}$ of K_{IC} (£)	Cost per $\mathrm{kJ\,m^{-2}}$ of impact energy (£)
3J	0.16	5.64	1.10	0.16	1.45	1.26	1.95
JPJ	0.16	6.17	1.05	0.15	1.67	1.34	0.31
PJP	0.20	5.05	0.64	0.085	0.85	0.74	–
TJT	0.19	8.33	1.05	0.13	0.88	0.96	–
J3PJ	0.20	8.31	1.05	0.18	0.87	0.96	0.19
PJPJP	0.21	8.09	0.97	0.135	0.66	0.80	0.33
P3JP	0.18	8.51	1.40	0.20	2.03	1.58	0.84

impact energy explained by the results of Sections 3.3 and 3.5. Impact test samples are un-notched and the orientation of the plies in the impact and fracture toughness tests, Fig. 1, are different. However, it is clear that the addition of a glass core seems a very good way of increasing the work of fracture perpendicular to the laminate, but a less effective way of utilizing the fibre for toughening in the other directions. (The J3PJ laminate has a work of fracture in impact of about $44\,kJ\,m^{-2}$ but the critical strain energy release rate is less than $10\,kJ\,m^{-2}$. Conversely the PJPJP laminate has a work of fracture in impact of about $24\,kJ\,m^{-2}$ and a G_{IC} value of about $12\,kJ\,m^{-2}$).

Unfortunately the excellent work of fracture of the J3PJ laminate is offset by its inferior environmental stability and so the PJPJP laminate with its protective outer glass plies has the most balanced set of properties when compared on a cost basis with the other laminates of Table VI.

Clearly improvements in laminate properties are possible by increasing the volume fraction of inexpensive fibre in the jute plies. However, in this work the intention was to compare the properties of hybrid jute/glass laminates fabricated by inexpensive hand lay up techniques.

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References

1. P. J. ROE and M. P. ANSELL, *J. Mater. Sci.* **20** (1985) 4015.
2. A. N. SHAH and S. C. LAKKAD, *Fibre Sci. Technol.* **15** (1981) 41.
3. H. WELLS, D. H. BOWEN, I. MACPHAIL and P. K. PAL, "The Potential of Jute and Similar Bast Fibres as High Specific Stiffness Reinforcements". In the Proceedings of the 35th Annual Technical Conference of the Reinforced Plastics and Composites Institute (The Society of Plastics Industry Inc, 1980).
4. ASTM D638 Standard Test Method for Tensile Properties of Plastics (American Society for Testing and Materials, Philadelphia, Pennsylvania, 1980).
5. H. KRENCHEL "Fibre reinforcement" (Akademick Forlag, Copenhagen, 1964).
6. "Marglass Handbook" (Marglass, Sherborne, undated).
7. Tayside Plastics Technical Data Sheet (Tayside Plastics Ltd, Dundee, 1983).

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