Development and fracture mechanism of the bamboo/polyester resin composite

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Renewable natural fibres could be a potential substitute for the synthetic fibres in many applications, where low density, low cost, high strength and high modulus are required. Among the known natural fibres (jute, coir, straw, banana, etc.) [1–4], which are used as reinforcement in plastics, bamboo has low density [5] and high mechanical strengths [6, 7]. The incentive for partially or completely replacing glass fibres arises from the low specific gravity (approximately 0.9) of bamboo compared with that of glass (approximately 2.5). However, the specific tensile strength of bamboo fibres (about 0.28 GN m^{-2}) is considerably less than that of glass fibres (about 1.3 GN m^{-2}). Nevertheless, cost considerations (Table I) make bamboo an attractive fibre for reinforcement. Bamboo fibre is almost 10 times cheaper than glass fibre.

In a previous paper [7] we reported the development of bamboo fibre-reinforced plastic composite ($BFRP_{epoxy}$) by reinforcing bamboo fibres in epoxy resin. The cost of epoxy resin is very high. In this letter we report the successful reinforcement of bamboo fibres in commercially available unsaturated polyester (USP) resin, which is only approximately 20% of the cost of epoxy resin (Table I). A new bamboo fibres reinforced plastic composite ($BFRP_{USP}$) was developed. It was observed that the mechanical properties of $BFRP_{epoxy}$ and $BFRP_{USP}$ are comparable, whereas the cost has been drastically reduced in case of $BFRP_{USP}$ composite. $BFRP_{epoxy}$ and $BFRP_{USP}$ composite specimens were tested for their tensile and flexural strengths. Scanning electron microscopy (SEM) was conducted on the fractured $BFRP_{USP}$ samples to obtain a better understanding of the fracture mechanism.

Bamboo fibres in the form of orthogonal strip mat were procured from Tripura arts and handicrafts emporium, New Delhi, India. General-purpose resin, cobalt naphthalate accelerator and methyl ethyl ketone peroxide (MEKP) initiator were used as supplied.

TABLE I Cost of bamboo fibre, glass fibre and resins in India

Material	Cost ($ kg^{-1})
Bamboo mat	0.46
Glass fibre	4.32
Epoxy resin	9.36
USP resin	2.6

These bamboo mats were available in 4 ft × 4 ft (1220 mm × 1220 mm) size. The thickness of the mat was 0.5 mm and the cross-section of the strip was 4 mm × 0.3 mm. For the fabrication of BFRP composite, these mats were cut to the required size and the moisture content was removed by keeping them in an oven at 105 °C for 3 h. To make the BFRP composite, USP resin was mixed with cobalt naphthalate (1%) and MEKP (2%). The oven-dried mats were soaked in this resin mixture and kept in a stainless steel mould. A pressure of the order of 4 kN cm^{-2} was applied to the mould using a Carver laboratory moulding machine. The casting was cured at 80 °C for 120 min. The thickness of the composite could be controlled by keeping the spacers and by varying the number of mats. Using this technique a composite with a 70% volume fraction (v_f) was prepared. Details of the fabrication technique of $BFRP_{epoxy}$ composite are given in [7].

Seven-layered composites of $BFRP_{USP}$ and $BFRP_{epoxy}$ were made and tested for tensile and flexural strengths. The density of the composites was determined using a specific gravity bottle. The tensile and flexural properties were evaluated using an Instron machine (model 1122, capacity 2000 kg).

Tensile properties were evaluated according to American Society for Testing and Materials (ASTM) D638-82. The dog-bone shaped specimen had a gauge length of 90 mm. A crosshead speed of 5 mm min^{-1} and a chart speed of 50 mm min^{-1} were used. Flexural properties were measured according to ASTM D790-81. Three-point bend tests were performed. The outer rollers were 80 mm apart. A crosshead speed of 10 mm min^{-1} and a chart speed of 100 mm min^{-1} were used.

Specimens under tensile test were loaded until fracture. The strss–strain curve was plotted. To measure elongation two marks were made on the load axis and the change in the distance between the two marks was recorded for different loading conditions. Experimental results are tabulated in Table II.

For $BFRP_{USP}$ as well as for $BFRP_{epoxy}$ the stress–strain curve (Fig. 1) shows a uniform increase in stress with strain, followed by immediate fracture at maximum load. This predicts, in general, linear-elastic behaviour of the BFRP composite with a brittle fracture. Specifically, the $BFRP_{epoxy}$ composite shows more elongation and 10% higher tensile strength. The detailed fracture mechanism of $BFRP_{epoxy}$ was reported in [7], and shows fibre

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TABLE II Various properties of the BFRP composite

	$BFRP_{USP}$	$BFRP_{epoxy}$
Specific gravity	0.924	0.930
Number of samples tested	5	5
Fibre volume fraction, v_f (%)	68	63
Tensile strength (MN m^{-2}) (cov[a])	102.6 ± 4.86	112.5 ± 3.76
Flexural stress (MN m^{-2}) (cov)	106.9 ± 6.41	122.47 ± 5.84
Flexural modulus (GN m^{-2}) (cov)	7.52 ± 5.82	8.37 ± 3.49

[a]cov, Coefficient of variation.

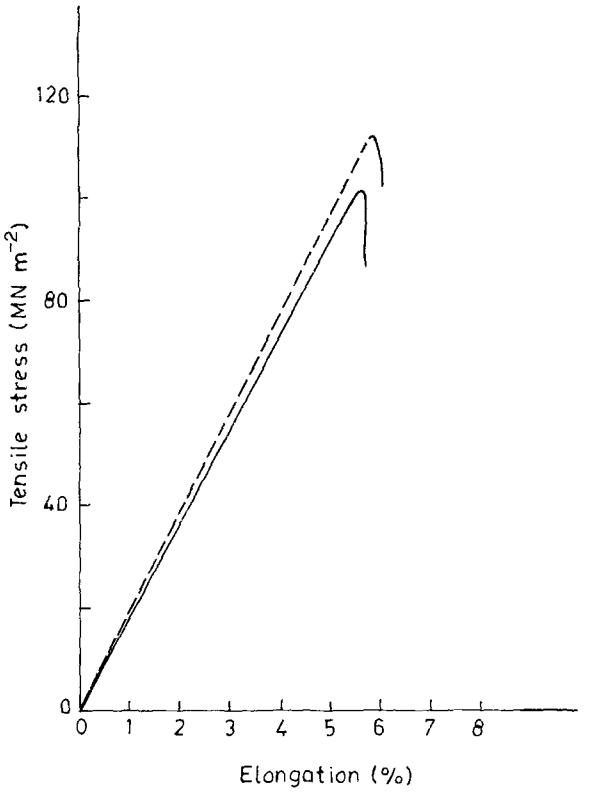

Figure 1 Tensile stress versus elongation curves of BFRP composite: (——) $BFRP_{USP}$ and (– – –) $BFRP_{epoxy}$.

pull-out from the matrix and good fibre matrix bonding. In $BFRP_{USP}$ composite, on the macroscopic level, the fracture mechanism and appearance is dominated by delamination, matrix fracture and fibre–matrix separation. From SEM micrographs on a microscopic level it was observed that the delamination or interlaminal fracture of BFRP composite is dominated by fibre–matrix debonding (Fig. 2), resin deformation and fracture (Fig. 3) and fibre pull-out. The fracture exhibited large amounts of fibre–matrix separation and small finely spaced areas of cohesive matrix fracture. The regions of matrix fracture found in these specimens exhibited a relatively rough topography. Detailed inspection of these areas (Fig. 3) revealed numerous inclined platelets of fractured resin.

Due to the presence of hydroxy and other polar groups in various constituents of bamboo fibres, the moisture regain is high, which leads to poor wettability with resin and weak interfacial bonding between fibres and relatively more-hygroscopic matrices.

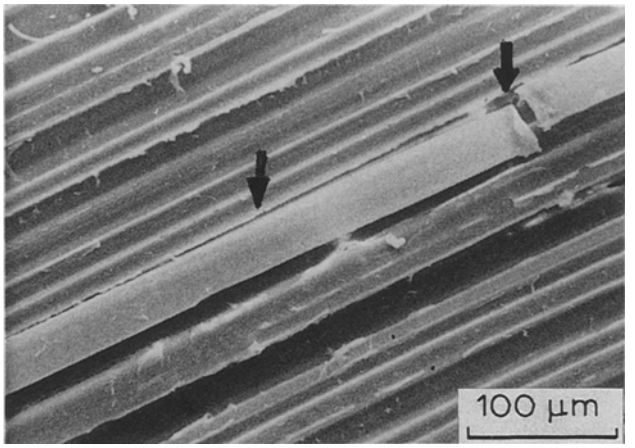

Figure 2 Tensile fracture of $BFRP_{USP}$ composite showing fibre–matrix debonding.

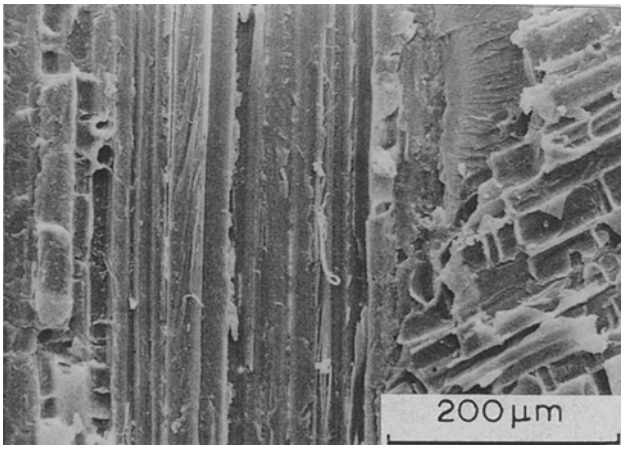

Figure 3 Tensile fracture of $BFRP_{USP}$ composite showing matrix fracture.

In flexural tests the stress–deflection curves (Fig. 4) for $BFRP_{epoxy}$ and $BFRP_{USP}$ showed a linear segment and then a curved portion from the middle of the curve until the fracture load was reached. The fracture showed a staggered decrease in the load (Fig. 4).

The flexural stress is given by

$$S = 3PL/2bd^2$$

and the flexural modulus by

$$E_B = L^3m/4bd^3$$

where P is the maximum load at rupture (N), L is the span length (m), d is the thickness of the specimen (m) and m is the slope of the tangent to the initial straight-line portion of the load–deflection curve (N m^{-1}). Experimental results are tabulated in Table II. For $BFRP_{USP}$ the flexural strength was about 12% less than for $BFRP_{epoxy}$ and the maximum deflection approximately 6% higher.

A new composite material made by reinforcing bamboo fibres in USP resin has been successfully developed. $BFRP_{USP}$ composite has marginally lower mechanical properties than $BFRP_{epoxy}$ composite. However, the cost of the composite has been

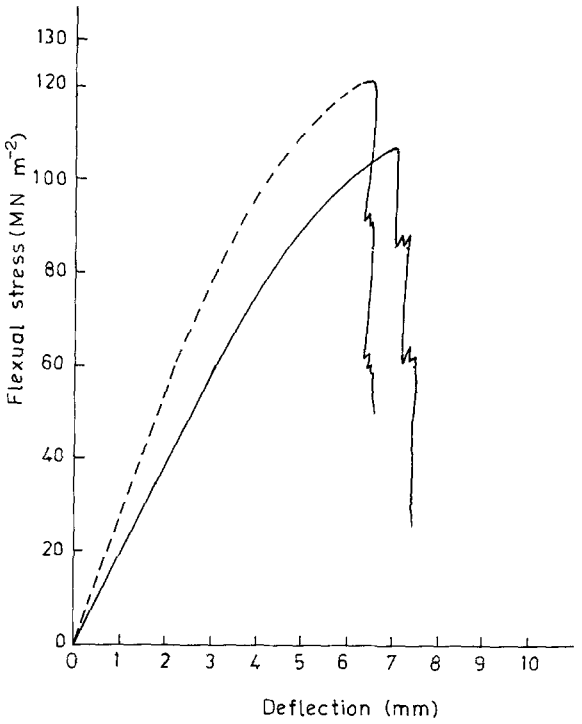

Figure 4 Flexural stress versus deflection curves of BFRP composite: (—) $BFRP_{USP}$ and (– – –) $BFRP_{epoxy}$.

greatly reduced. This material can be used for common commercial applications, such as crash helmets, low-cost housing and windmill fins. The poor interfacial bonding due to the hygroscopic nature of the bamboo fibres can be overcome by using suitable coupling agents.

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