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Mechanical behaviour of bamboo and bamboo composite

SEEMA JAIN, RAKESH KUMAR
Instrument Design and Development Centre, Indian Institute of Technology, Hauz Khas, New Delhi 110 016, India

U. C. JINDAL
Mechanical Engineering Department, Delhi College of Engineering, Kashmiri Gate, Delhi 6, India

The tensile, flexural and impact strengths of bamboo and bamboo fibre-reinforced plastic (BFRP) composite have been evaluated. The high strengths of bamboo, in the fibre direction, have been explained by its anatomical properties and ultra structure. Bamboo fibres and bamboo orthogonal strip mats (bamboo mat) have been used to reinforce epoxy resin. BFRP composites with unidirectional, bidirectional and multidirectional strengths have been made. In bamboo mat composites, the fibre volume fraction, V_f, achieved was as high as 65%. The tensile, flexural and impact strengths of bamboo along the fibres are 200.5 MN m^{-2}, 230.09 MN m^{-2} and 63.54 kJ m^{-2}, respectively, whereas those of bamboo fibre composites and bamboo mat composites are 175.27 MN m^{-2}, 151.83 MN m^{-2} and 45.6 kJ m^{-2}, and 110.5 MN m^{-2}, 93.6 MN m^{-2} and 34.03 kJ m^{-2}, respectively. These composites possess a close to linear elastic behaviour. Scanning electron microscopy studies of the fractured BFRP composite specimens reveal a perfect bonding between bamboo fibres and the epoxy. Furthermore, high strength, low density, low production cost and ease of manufacturing make BFRP composite a commercially viable material for structural applications.

1. Introduction

Natural fibres have emerged as a renewable and cheaper substitute to synthetic fibres such as glass and carbon which are used as reinforcement in making structural components. These synthetic fibres are not suited to the common applications due to the high cost and high energy requirement in their production. Ligno-cellulosic based natural fibres are relatively inexpensive and these are abundantly available.

Some attempts have been made in the past to study the mechanical properties of natural fibres such as coir, banana, sisal, [1–4], etc. A little work has also been reported on natural fibre-reinforced (bagasse, jute, straw, etc.) plastic composites [5–7]. However, work reported on bamboo and bamboo fibre-reinforced plastic (BFRP) composites is very limited, and a thorough study is required in view of its high strength. Shah and Lakkad [8] have reported the tensile and compressive strength of Bamboo, and Jindal [9] studied some mechanical properties of the BFRP composite.

In the present paper we report the anatomical properties of bamboo in order to gain a better understanding of its mechanical properties. Using modified techniques we have developed BFRP composite with a fibre volume fraction, V_f, as high as 65%. To achieve a uniform strength in all directions we have also developed a BFRP composite with multidirectional orientation of the fibres.

Scanning electron microscopy of the reinforced and fractured samples of BFRP composites was performed.

2. Anatomical properties of bamboo

2.1. Bamboo fibres

Bamboo, belongs to the grass family *Bambusoideae.* It is a natural ligno-cellulosic composite, in which cellulose fibres are embedded in a lignin matrix. The average length of the bamboo fibres is about 2 mm, and average diameter between 10 and 20 μm. The hardness of the bamboo culm (Fig. 1) mainly depends on the number of fibre bundles and the manner of their scattering. The percentage of fibres increases from the bottom to the top of the culm.

2.2. Chemical constituents

The basic chemical constituents of bamboo are cellulose, hemicellulose and lignin. In bamboo, cellulose and hemicellulose are present in the form of holocellulose which amounts to more than 50% of the total chemical constituents. Most of the cellulose is present in the fibre.

The second most abundant chemical constituent of bamboo is lignin. This functions as a binder or works as a matrix for the cellulose fibres. Lignin is an energy storage system and it responds to the mechanical stresses as a composite material component.

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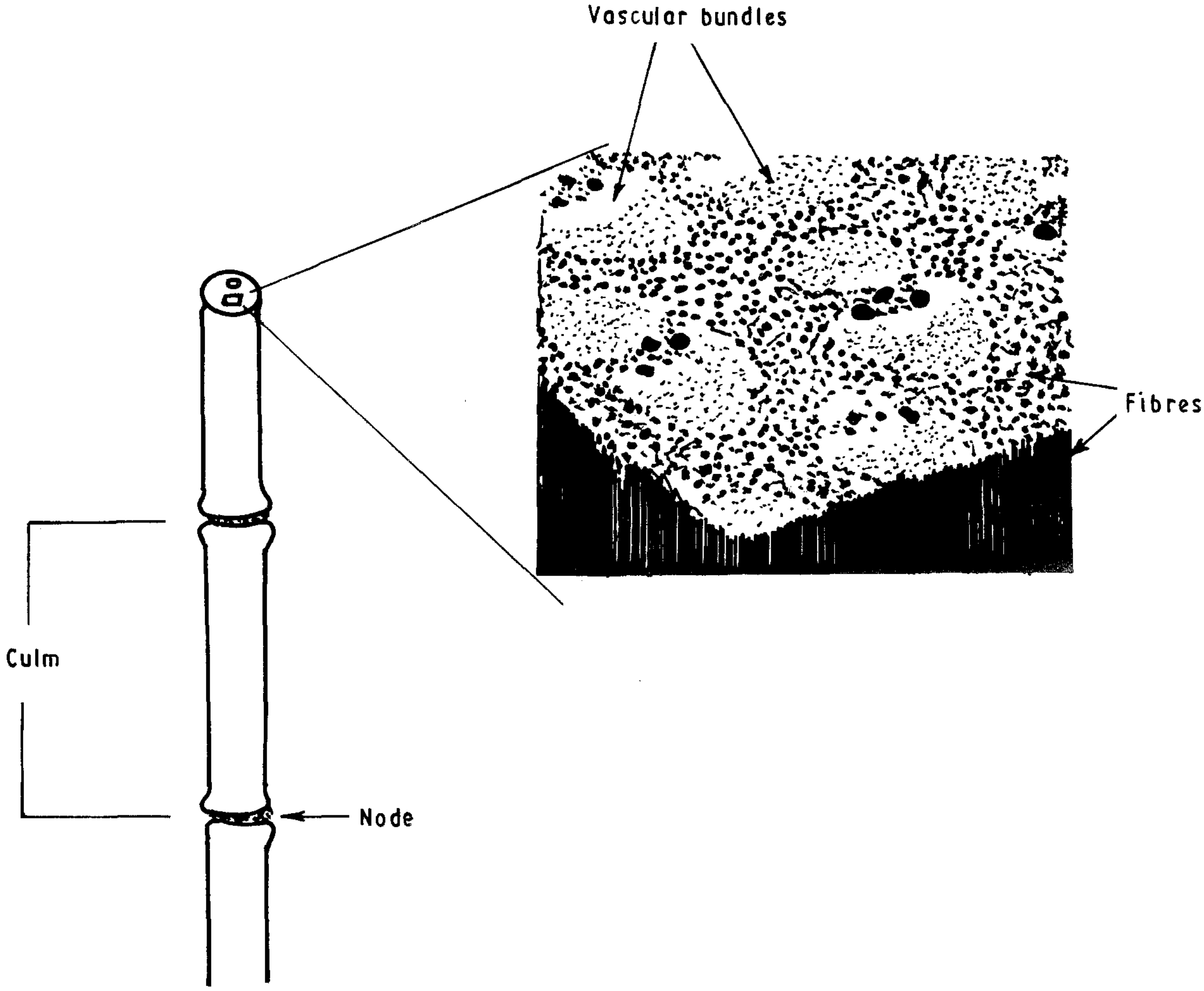

Figure 1 Bamboo culm and bamboo cross-section showing fibre bundles.

All ligno-cellulosic based natural fibres consist of cellulose microfibrils in an amorphous matrix of lignin and hemicellulose. These fibres consist of several fibrils which run along the length of the fibre. Each fibril exhibits a complex layered structure made up of a thin primary wall encircling a thicker secondary layer. In the secondary layer, parallel cellulose microfibrils are wound helically around the fibrils. The angle between the fibre axis and the microfibrils is termed the microfibril angle. Natural fibres themselves are cellulose fibre-reinforced materials and the microfibril angle and cellulose content determine the mechanical behaviour of the fibre.

The ultra structure of bamboo fibres, proposed by Liese [10], is shown in Fig. 2. The lamellation consists of alternating broad and narrow layers with different fibrillar orientation. In the broader lamellae, the fibrils are oriented at a smaller angle to the fibre axis, whereas the narrow ones show mostly a transverse orientation. The narrow lamellae exhibit a higher lignin content than the broader ones. The polylamellate wall structure of the fibres leads to an extremely high tensile strength. The polylamellate structure does not exist in the cell wall of the fibres of normal wood.

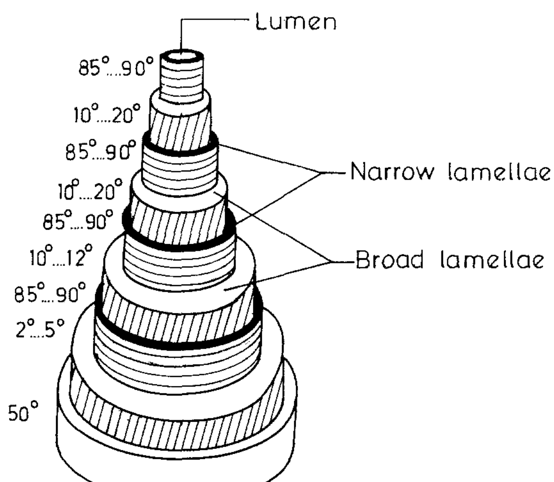

Figure 2 Model of the polylamellate wall structure of a bamboo fibre (after Liese [10]).

McLaughlin and Tait [11] have carried out extensive studies on various plant species and presented a physical description of the mechanism of failure in tension of cellulose-based fibres. They predicted that tensile strength and mean Young's modulus increase with increasing cellulose content and decreasing micro-fibrillar angle. In Table I, chemical constituents, density, microfibrillar angle, of a few plant species are tabulated. From the table it can be observed that bamboo has 60% cellulose and with a considerably higher percentage of lignin ($\simeq 32\%$), its micro-fibrillar angle is relatively small (10°–12°). These facts about bamboo support its high tensile strength.

TABLE I Composition of a few natural fibres

	Density (10^{-3} kg m^{-3})	Microfibril angle (deg)	Cellulose (%)	Lignin (%)
Coir	1150	30–49	43	45
Banana	1350	11	65	5
Sisal	1450	20–25	70	12
Jute	1450	8.1	63	11.7
Bamboo	600–800	2–10	60.8	32.2

TABLE II Mechanical properties of bamboo

	Density (10^3 kg m^{-3})	Tensile strength (CoV)[a] (MN m^{-2})	Elongation (mm)	Flexural strength (CoV)[a] (MN m^{-2})	Deflection (mm)	Impact strength (CoV)[a] (kJ m^{-2})
Bamboo (across the fibre)	0.802	8.6 ($\pm$ 1.02)	0.10	9.04 ($\pm$ 0.3)	Fibres split	3.02 ($\pm$ 1.08)
Bamboo (along the fibres)	0.802	200.5 ($\pm$ 7.08)	10.2%	230.09 ($\pm$ 9.06)	6.3	63.54 ($\pm$ 4.63)

[a] Coefficient of variance.

By considering these important properties of bamboo, a new composite material has been developed. A series of experiments has been conducted on samples of raw bamboo. It was found that bamboo has a maximum strength along the fibres and a minimum strength across the fibres (Table II). A multilayer composite, with different fibre orientations, was made to achieve a uniform strength in all directions.

3. Experimental procedure

Bamboo fibres in the form of mattings (bamboo fibres woven with the help of cotton thread) (Fig. 3a) and orthogonal bamboo fibre strip mats (Fig. 3b) were procured from the Tripura Government Arts and Handicrafts Emporium, New Delhi, India.

3.1. BFRP composite from bamboo fibres

Fibres were obtained by removing the cotton threads; fibres of 0.1–0.3 mm diameter and 40 cm length were chosen. The moisture content of these fibres was removed by drying in an oven at 105 °C for 3 h. After removing air bubbles and moisture, araldite resin CIBA Cy-230 was mixed with hardener CIBA CY-951 10% by weight of the resin. Dried fibres were soaked in the resin and hardener mixture and kept unidirectionally adjacent to each other in an acrylic perspex mould. The excess resin was squeezed out by applying pressure to the mould. A composite plate of uniformly distributed bamboo fibres in a resin matrix was obtained after curing the resin for 24 h. This composite plate was inspected for any voids. Using the above technique, none of the plates had more than 0.5% voids.

A multilayered composite was made by cutting laminates of the required fibre orientation from this unidirectional plate and fixing them in a specific manner, one over the other, by applying resin hardener mixture between every two consecutive laminates.

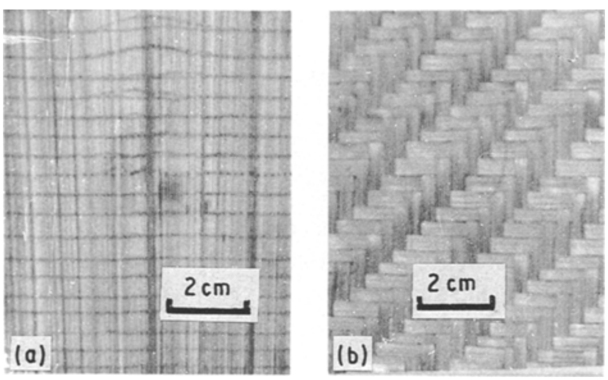

Figure 3 (a) Bamboo fibre mat and (b) bamboo orthogonal strip mat.

3.2. BFRP composite from bamboo orthogonal mat

These mats are available in 60 cm × 60 cm × 0.05 cm size. The cross-section of the strips is 4 mm × 0.3 mm. For a single-layered composite, a hand lay-up method was used; the composite was cured under pressure in the mould used earlier.

For the multilayered composites with different fibre orientations, the mat was cut according to the required fibre orientation and then the composite was made by stacking these one over the other and using the hand lay-up method. A composite with 65% fibre volume fraction was obtained by applying a pressure of the order of 3.2 kN cm^{-2} to the mould.

3.3. The mechanical properties of bamboo and BFRP composites

Bamboo is a natural composite material in which cellulose fibres are reinforced in the lignin matrix along the length of the bamboo culm, providing it with maximum strength in that direction. Because bamboo has minimum strength across the fibres, multilayered composites of different fibre orientations, with a view to improving strength in all directions, have been developed. Experiments were conducted to determine the tensile, flexural and impact strengths on samples made of (i) raw bamboo, (ii) unidirectional composite (fibres) (0°), (iii) bidirectional composite (mats) (0°/90°), and (iv) multidirectional composites from bamboo fibres (B_{nf}) and orthogonal mats (B_{nm}), where n corresponds to the number of layers, with the following orientations: (a) B_{5m} and B_{5f} ($0^{\circ}_{2}/\pm 45^{\circ}/90^{\circ}$), (b) B_{7m} and B_{7f} ($0^{\circ}_{2}/\pm 30^{\circ}/\pm 60^{\circ}/90^{\circ}$), (c) B_{9m} and B_{9f} ($0^{\circ}_{2}/\pm 22.5^{\circ}/\pm 45^{\circ}/\pm 67.5^{\circ}/90^{\circ}$).

3.3.1. Tensile and flexural tests

Tensile and flexural tests were performed according to ASTM D638 and ASTM D790, respectively. Three-point bend tests were performed to measure flexural strength. Outer rollers were 80 mm apart.

Tensile and flexural specimens of bamboo were in the form of rectangular strips. The samples were 150 mm long and 25 mm wide, with a thickness between 2 and 4 mm. Ten samples of raw bamboo were tested and five samples each of unidirectional, bidirectional and multidirectional (B_5, B_7, B_9) BFRP composites were tested on an Instron 1121 (1000 kg load capacity) universal testing machine at a crosshead speed of 0.5 mm min^{-1}. Load–displacement curves were generated for each sample. For measuring the elongation, two marks along the central load axis were made, at a distance of 15 mm, on either side, from the centre of the sample. Changes in the distance between the two marks were measured using a divider for different loads, and the corresponding elongations were calculated. The results of the tests are given in Tables II and III.

3.3.2. Impact test specimen

Test specimens were 75 mm long and the cross-section was 10 mm × 10 mm. Tests were performed on notched and unnotched bamboo fibre- and bamboo mat-reinforced plastic composites. Notched specimens had 2 mm deep 45° notch angle at a distance of 28 mm from the top end. The samples were fractured in a Hounsfield plastic impact testing machine. Impact toughness was calculated from the energy absorbed and the cross-sectional area without notch/cross-sectional area at the notch.

4. Results and analysis

The percentage of cellulose (fibres) and lignin (binding material) in bamboo fibres is higher than in other natural fibres. The microfibril angle of the cellulose fibres is very small and bamboo has a polylamellate wall structure. These are the factors responsible for the higher tensile, flexural and impact strengths of bamboo in the fibre direction. Perpendicular to the fibre direction, bamboo has minimum strength. The

TABLE III Tensile and flexural strengths of bamboo fibre and bamboo mat composites

Type of sample	Bamboo fibre composite							Bamboo mat composite					
	Orientation of fibres (deg)	Density of the composite (10^3 kg m^{-3})	Fibre volume, V_f (%)	Tensile strength (CoV) (MN m^{-2})	Elongaation (%)	Flexural strength (CoV) (MN m^{-2})	Deflection (mm)	Density of composite (10^3 kg m^{-3})	V_f (%)	Tensile strength (CoV) (MN m^{-2})	Elongation (%)	Flexural strength (CoV) (MN m^{-2})	Deflection (mm)
Unidirectional (single layer)	(0)	0.975	50	175.27 (± 4.29)	8.9	151.83 (± 3.86)		–	–	–	–	–	–
Bidirectional (single layer)	(0/90)	–	–	–	–	–		0.908	70	110.5 (± 2.49)	7.0	93.6 (± 4.98)	
Multidirectional (5 layer)	(O_2/ ± 45 + 90)	1.030	35	99.34 (± 3.96)	6.2	130.23 (± 5.28)	2.5	0.936	60	80.5 (± 1.40)	4.09	108.56 (± 1.52)	5.4
Multidirectional (7 layer)	(O_2/ ± 30/ ± 60/90)	1.010	35	82.2 (± 1.72)	7.5	161.1 (± 2.85)	1.75	0.930	63	87.99 (± 0.31)	5.55	124.52 (± 2.86)	3.6
Multidirectional (9 layer)	(O_2/ ± 22.5/ ± 45/ ± 67.5/90)	1.003	35	70.13 (± 1.65)	8.0	186.38 (± 2.53)	1.25	0.925	65	92.65 (± 0.70)	6.59	134.59 (± 3.78)	3.2

tensile, flexural and impact strengths of the bamboo are given in Table II.

4.1. Tensile and flexural tests of bamboo fibre and bamboo mat composites

The values of tensile strength and elongation are given in Table III. Unidirectional BFRP composite with 50% V_f has 60% greater strength than that of bidirectional BFRP composite with 70% V_f. In unidirectional BFRP composite, V_f is low and the density of the composite is higher as also is its cost, whereas in bidirectional BFRP composite, V_f is 70% but only 50% of the fibres which are in the tensile load direction (y) contribute to the tensile strength, the remaining 50% of the fibres are just working as reinforcement in the x-direction, thus giving a bi-axial strength. At the same time, the x-directional reinforcement reduces the density and also the cost of the composite.

The tensile strength of the multidirectional bamboo fibre composites decreases with increasing number of layers, $B_{5f} > B_{7f} > B_{9f}$, whereas the trend of tensile strength is opposite in the bamboo mat composite. With increasing number of layers, the volume fraction of fibres continues to increase, as does its tensile strength: $B_{9m} > B_{7m} > B_{5m}$.

In mat composite (B_m), shearing stresses in 45° ply are very dominant, whereas in bamboo fibre (B_f) composite shearing stresses are not prominent. However, in nine-layered fibre (B_{9f}) composite the additional araldite poured in between the laminates does not give as much strength as araldite composited with mats and cured in one solid block. In the former case, the cross-linking of the polymer is not continuous over the surface of the laminate, whereas the cross-linking is continuous in the case of bamboo mat composites.

The load–extension curves are shown in Fig. 4. The general trend of these graphs shows a straight line upto the breaking load. The elongation of bamboo fibre composite is between 6.2% and 8.9%, whereas for bamboo mat composites it is between 4.09% and 7.0%.

From the graphs it is observed that the behaviour of these composites is close to linear elastic, and also that at the breaking load the fracture is brittle. This material is not homogeneous; it has an orthotropic property due to which fibres are pulled out from the matrix.

For bamboo fibre and mat composites, the flexural strength increases from the five-layered to the nine-layered composites (Table III). In the flexural test it was observed that as the number of layers of BFRP lamina/mats increases, the strength also continues to increase due to the fact that specimens have also been tested to failure in the flexural test. In the tensile test the stress distribution across the section is uniform, but in the case of the flexural test, the stress distribution across the depth is linear during the elastic stage and nonlinear in the plastic stage. The effect of this nonlinearity is that as the depth of the flexural specimen increases, flexural strength also increases.

The stress–deflection curve shows a linear segment and then a curved segment from the middle of the curve up to the fracture load. The fracture shows a staggered decrease in load (Fig. 5).

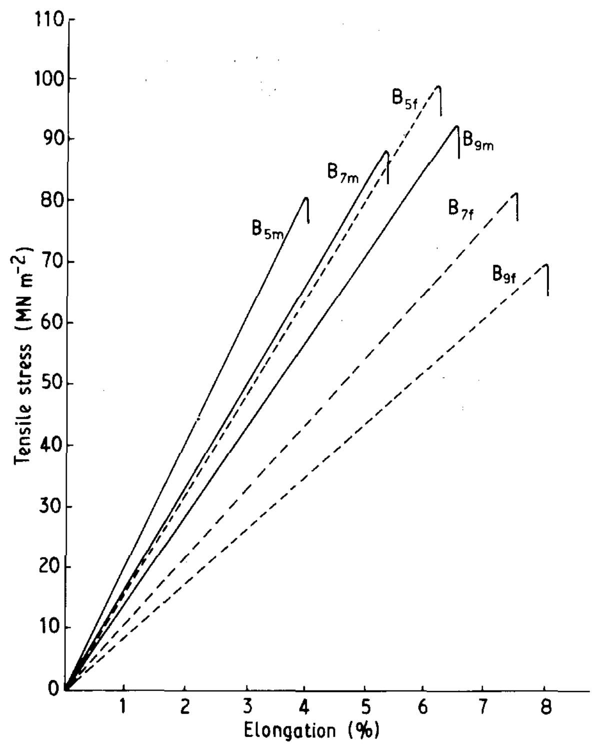

Figure 4 Tensile strength–elongation curves of bamboo fibre and bamboo mat composites.

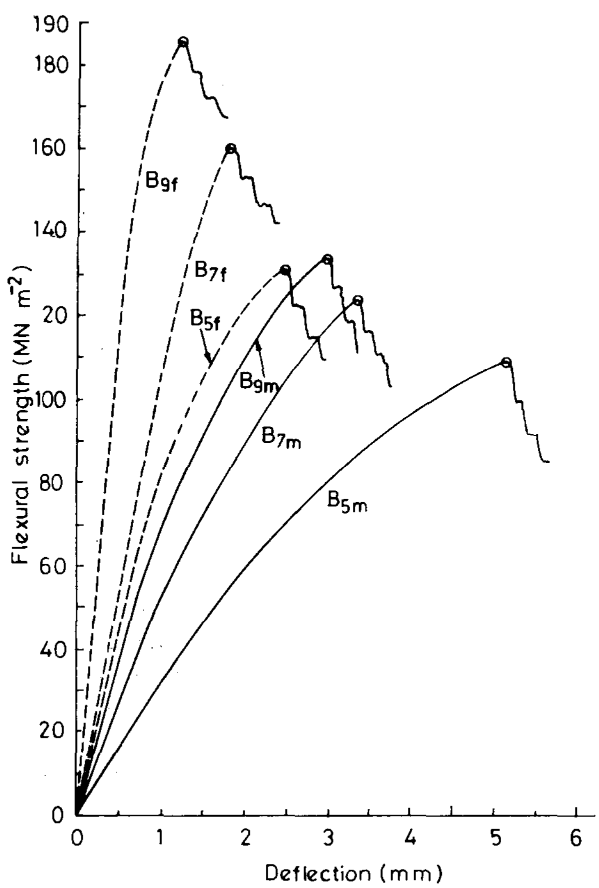

Figure 5 Flexural strength–deflection curves of bamboo fibres and bamboo mat composite.

For the bamboo fibre composite, tensile strength decreases as the number of layers increases. However, it is seen that for the same composite with increase in

TABLE IV Impact strength of BFRP composite

	V_f (%)	Impact strength of notched specimen (CoV) (kJ m^{-2})	Impact strength of unnotched specimen (CoV) (kJ m^{-2})
Fibre composite	35%	43.71 (± 2.92)	45.62 (± 3.01)
Mat composite	65%	33.87 (± 2.20)	34.03 (± 1.26)

the number of layers the flexural strength increases. According to the Tsai–Hill failure criterion [12] the strength continuously decreases as the angle of orientation of the fibres increases from 0°. In B_{5f}, B_{7f} and B_{9f} the fibre volume fraction is constant but the angle of orientation of the fibres increases with the number of layers. The decrease in the tensile strength as the number of layers increases is in agreement with the Tsai–Hill failure theory.

For the flexural strength tests of the bamboo fibre composite, the span length, L, is constant for B_{5f}, B_{7f} and B_{9f}, but the thickness, t, increases from B_{5f} to B_{9f}. Thus it is seen that the ratio, S, of the span length to thickness ($S = L/t$) is reduced from B_{5f} to B_{9f}. As the value of S falls, so does the effect of transverse shear stress [12]. Similarly, for a higher S ratio, the transverse shear effect increases. Thus, as the number of layers in the bamboo fibre composite increases from B_{5f} to B_{9f} the flexural strength also increases. On the other hand, bamboo mat composites follow the rule of mixtures: as the fibre volume fraction increases the tensile and flexural strengths also increase.

4.2. Impact test

The results of pendulum impact tests are shown in Table IV. Fibre composites have a higher impact strength than mat composites. This can be explained by 50% of the fibres in mat being in the direction of impact, and the other 50% being perpendicular to the impact. Only perpendicular fibres are capable of arresting and diverting the propagation of the notch by delamination.

Another important fact which has emerged is that the notch does not affect the strength of BFRP composite. The high impact strength of BFRP composite puts it in the category of tough engineering materials.

4.3. SEM studies

The cross-section and longitudinal sections of bamboo are shown in Figs 6 and 7. The cross-section shows the porosity of bamboo. Epoxy impregnates

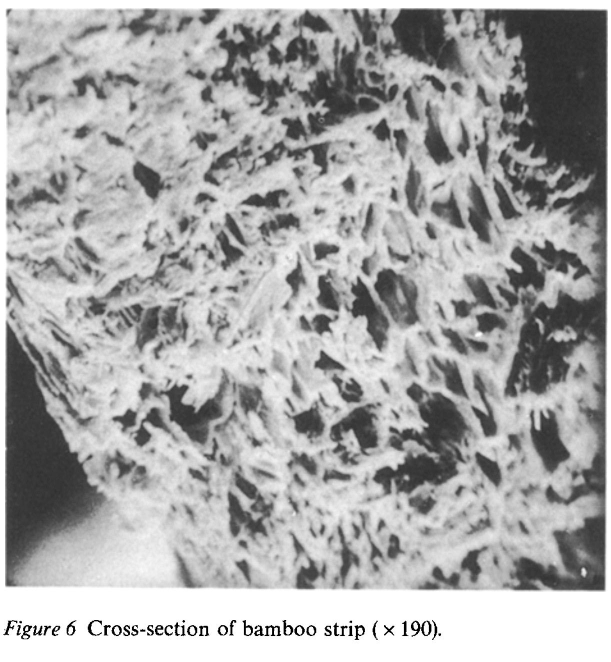

Figure 6 Cross-section of bamboo strip (× 190).

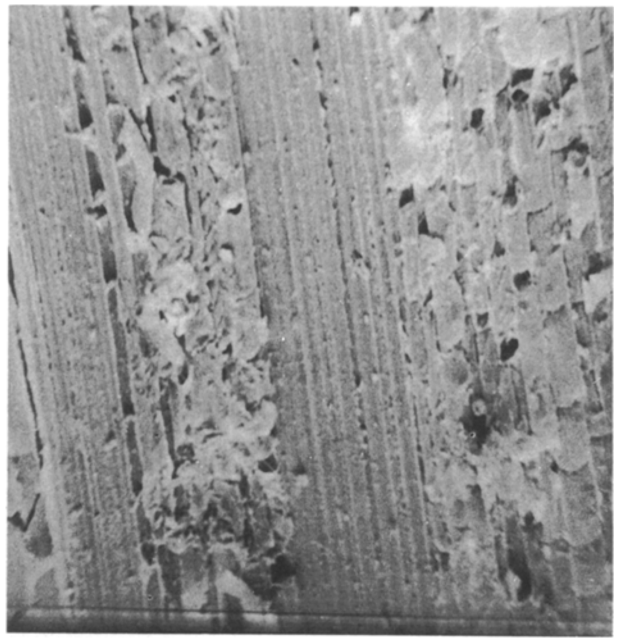

Figure 7 Longitudinal section of bamboo (× 70).

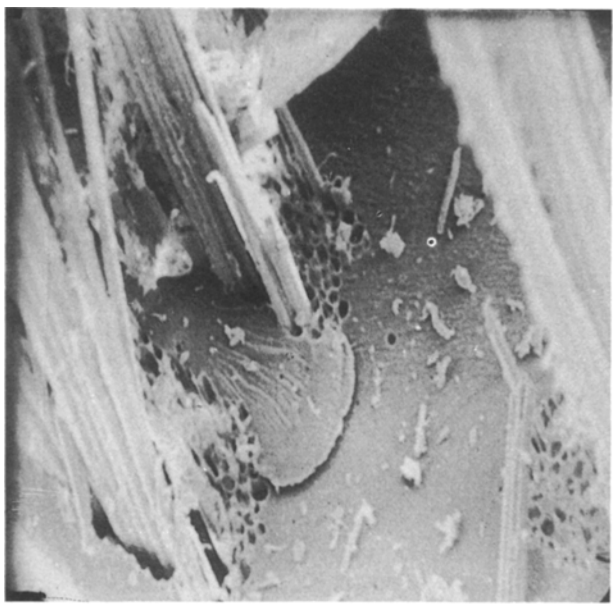

Figure 8 Tensile fracture mode of BFRP composite with fibre pull out (× 55).

these cavities and makes a good bond with the bamboo. In Fig. 8 the tensile fracture mode of bamboo–epoxy is shown: fibres are seen to have pulled out from the resin matrix. This fibre pull-out indicates perfect bonding between bamboo and epoxy.

5. Conclusion

Bamboo, a natural composite, has been shown to have maximum strength along the fibres and minimum strength across the fibres.

A composite with good strength in all directions has been successfully developed using bamboo fibres and bamboo mats. The fibre volume fraction achieved was 65%. This high fibre volume reduces the density and the cost of the composite. Owing to the reinforcement of fibres in the orthogonal directions (in the form of a mat) the BFRP composite possesses useful biaxial strengths.

This composite is non-corrosive in nature and the layer of epoxy on the surface prevents the natural decay of the bamboo. It has been observed that the mechanical properties of BFRP composite are superior to other known natural fibre-reinforced plastic composites, as reported in the literature.

References

1. A. G. KULKARNI, K. G. SATYANARAYANA, K. SUKUMARAN and P. K. ROHTAGI, *J. Mater. Sci.* **16** (1981) 905.
2. *Idem, ibid.* **18** (1983) 2390.
3. P. S. MUKHERJEE and K. G. SATYANARAYANA, *ibid.* **19** (1984) 3925.
4. *Idem, ibid.* **21** (1986) 51.
5. E. C. McLAUGHLIN, *ibid.* **15** (1980) 886.
6. P. J. ROE and M. P. ANSELL, *ibid.* **20** (1985) 4015.
7. N. M. WHITE and M. O. ANSELL, *ibid.* **18** (1983) 1549.
8. A. N. SHAH and S. C. LAKKAD, *Fibre Sci. Technol.* **15** (1981) 41.
9. U. C. JINDAL, *J. Compos. Mater.* **20** (1986) 19.
10. W. LIESE, "Recent Research on Bamboo", Proceedings of the International Bamboo Workshop, Hangzhon, People's Republic of China (IDRC, Canada, 1986) p. 196.
11. E. C. McLAUGHLIN and R. A. TAIT, *J. Mater. Sci.* **15** (1980) 89.
12. ROBERT M. JONES, "Mechanics of Composite Materials" (McGraw-Hill, New York, 1975) pp. 73–83, 301–3.

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