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Reformed bamboo and reformed bamboo/aluminium composite

Part I *Manufacturing technique, structure and static properties*

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A new technique has been developed which aims at changing the form of bamboo from its natural circular cross-section into a plate for convenient use. The manufacturing technique covers three major processes: softening, compression and fixture. The microstructure of reformed bamboo was studied both qualitatively and quantitatively. The mechanical properties of reformed bamboo were tested and the results show a remarkable increase compared with normal bamboo. Although the reformed bamboo has many advantages, such as higher specific properties, inexpensive cost, etc., the composition of reformed bamboo with aluminium alloy sheets further improves the comprehensive performance.

1. Introduction

Bamboo, a traditional natural biomaterial, is attracting more and more attention from scientists and engineers owing to its unique biological structure and mechanical performance. In recent years, some work has been reported on the microstructure of bamboo fibre [1, 2] and its mechanical properties [3]. Literature has also appeared concerning bamboo in the field of biomimetics [4, 5]. In addition to these investigations, the use of bamboo as a structural material directly or as reinforcement of composite materials [6, 7] is also wide and competitive. Compared with synthetic composites, such as glass-fibre reinforced polymer (GFRP) and carbon-fibre reinforced polymer (CFRP), etc., bamboo composites have the advantages of high performance to cost ratio, and low energy consumption during the manufacturing process. Yet they also have some disadvantages; for example, in bamboo-fibre reinforced polymer (BFRP) [6], the manufacturing technique is very complex because bamboo should be split into many small strips and woven as a thin mat, and then adhered together with a resin. Much of the bamboo near the outer rind surface and the inner surface (pith-ring) are wasted because those parts of the bamboo are not suited to make strips or mats.

In the present work, a new technique to make reformed bamboo was developed in which there is no need to make bamboo strips, thus the process of making bamboo mats is unnecessary. Bamboo culm was separated into several parts longitudinally and was then compressed after certain treatment. According to the different uses, the mechanical properties and compressive ratio (which is defined as $r = (H_0 - H_1)/H_0$, where H_0 is the original thickness and H_1 the thickness after compression) of reformed bamboo can be designed beforehand and adjusted in the manufacturing process. As a new attempt, reformed bamboo was used to reinforce aluminium alloy for the purpose of protecting reformed bamboo itself and substituting some aluminium alloy. The structure and mechanical properties of reformed bamboo were studied.

2. General structure and property of bamboo

The anatomical structures and various properties of many species of bamboo have been investigated [1–3]. All bamboos share some common features: they are natural ligno-cellulosic composite and are composed of fibres (bast fibres in vascular bundles) and matrix (thin-walled cells around vascular bundles, vessels and sieve tubes in vascular bundles). Natural bamboo can be taken as unidirectional fibre-reinforced composite and its fibre volume fraction has an intimate relation with its mechanical property. The distribution of bast fibres of bamboo along the radial direction shows a gradient trend, and this undoubtedly influences its mechanical properties, as do synthetic fibre-reinforced composites. However, in previous works, when the mechanical properties of bamboo were concerned, average values across the thickness were more often used rather than those of a specific part of the bamboo culm. In fact, heterogeneity, porosity and anisotropy are important features of bamboo. Because the fraction of bamboo fibres is not constant along the radial direction (fibres

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are denser in the outer part than in the inner part), to make the measurement of mechanical properties more accurate, one bamboo culm was cut longitudinally into several beams, with the width of each beam being about 15 mm; then each beam was separated into several strips of increasing thickness from the outer surface to the inner surface, and the tensile strength and effective modulus of each layer were measured experimentally. Owing to the gradient of fibre volume fraction in the radial directions, strictly speaking, there will be a coupling between stretching and bending under tension. To weaken the unexpected effect of coupling, each strip was made very thin; therefore, within the thickness of each strip, the modulus can be assumed to be a constant, which is the factual tested data of the effective modulus. End-taped specimens were made for testing tensile strength and effective modulus, of size 120 mm × 12 mm × h mm (h is the thickness of the specimens). The flexural strength was measured in three-point bending with a span of 40 mm for bamboo strip specimens. Fig. 1 shows the changing trends of the major mechanical properties of bamboo (*Phyllostachys pubescens*) along the radial direction.

Fig. 2 shows an optical photograph of the cross-section of *Phyllostachys pubescens*. It is obvious that there are many voids inside and outside the vascular

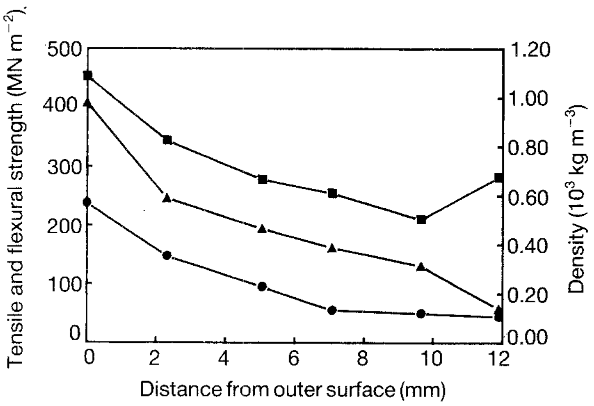

Figure 1 The radial changing trends of (▲) tensile and (●) flexural strength and (■) density of *Phyllostachys pubescens*.

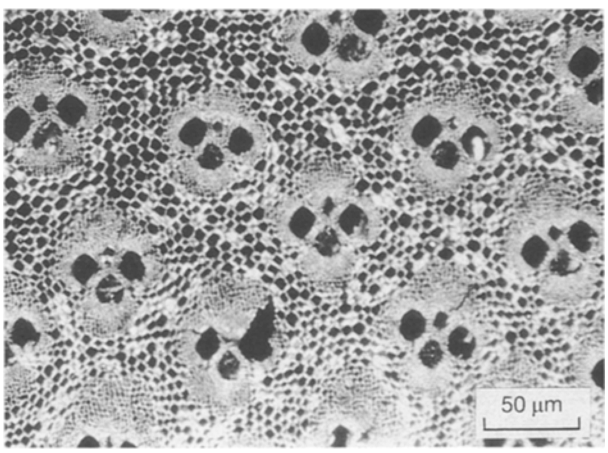

Figure 2 Optical photographs of the cross-section of *Phyllostachys pubescens*.

bundles, and the number of voids in the inner part of bamboo is greater than that in the outer green bamboo. The gradient structure of bamboo is optimum to adapt to the living environment, because this structure (a thick-walled circular cylinder with one end fixed), can provide optimum strength distribution and maximum structural stability with minimum material weight [4]. However, while bamboo is used as a structural material, i.e. bamboo fibre-reinforced polymer (BFRP), the inhomogeneity of bamboo is usually an unexpected feature. To make the use of natural bamboo more convenient and more abundant, the microstructure of bamboo is redesigned and reformed to enhance the homogeneity of structure and property distribution.

3. Reformed bamboo

3.1. Manufacturing technique

Bambusa pervaribilis, a kind of abundant bamboo in China, was chosen as the experimental material in this experiment. The manufacturing procedure consists of three steps: softening, compression and fixture. First, natural bamboo culm was separated longitudinally into several parts (usually two to four parts) and the diaphragms in the nodes were cut off roughly. Then the bamboo strips were heated in a container to adjust the moisture content to certain value. The strips were then compressed with a compressor to obtain the required compressive ratio. Finally, under certain pressure, strips were pressed for 3 h for the purpose of fixture. During the process, the moisture content of the bamboo is very important. The technological conditions can be determined according to Fig. 3, which shows the relationships between moisture content, compressive ratio and pressure.

If the moisture content of bamboo is too low (such as 8.5%), as illustrated in Fig. 3, the bamboo is too rigid and brittle to be compressed rapidly; the other two curves show similar trends. It should be noticed that when the moisture content reaches 30%, the saturation content, the water in bamboo will damage cell tissues during the compression process, and this will deteriorate the mechanical performance of reformed bamboo.

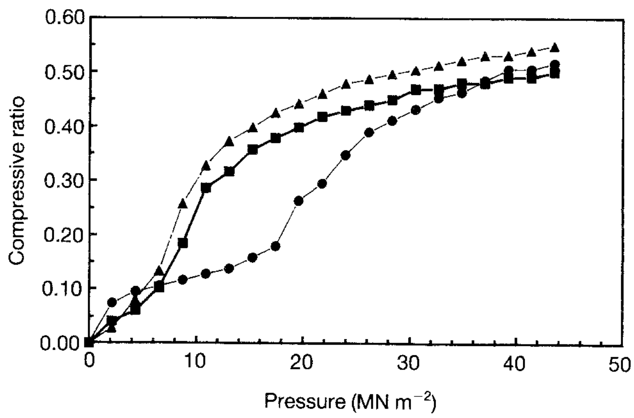

Figure 3 Relationships between moisture content, compressive ratio and pressure of bamboo. Moisture content: (●) 8.5%, (■) 22.6%, (▲) 28.9%.

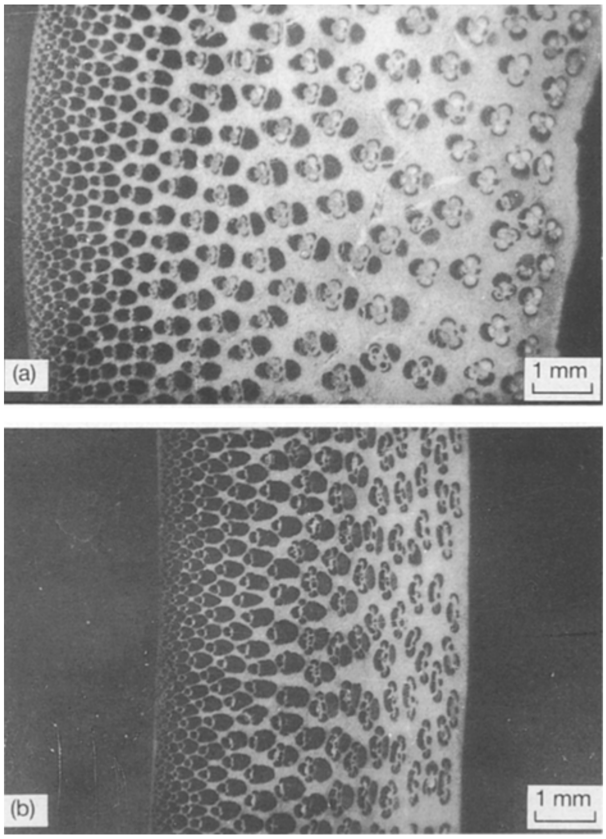

Figure 4 Optical photographs of cross-sections of (a) normal bamboo, and (b) reformed bamboo.

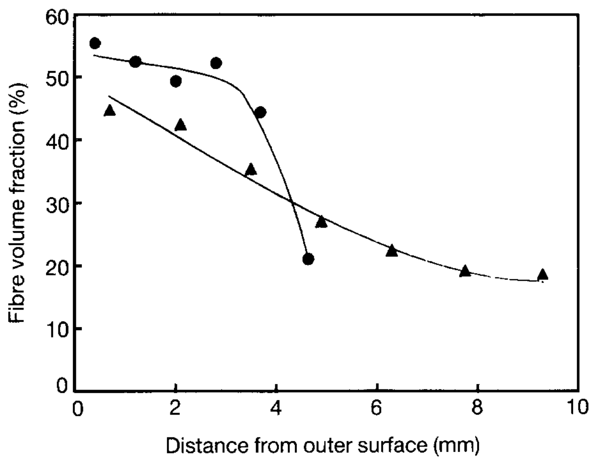

Figure 5 Fibre volume fraction of bamboo (▲) before and (●) after compression (compressive ratio is 0.49).

3.2. The structure of reformed bamboo

The structural changes of reformed bamboo derive from the distribution of vascular bundles and the vascular bundles themselves. Fig. 4 shows optical photographs of cross-sections of normal bamboo (a) and reformed bamboo (b). From a comparison of Fig. 4a and b, it can be seen that the vascular bundles, or exactly speaking, the bast fibres in the inner part near the pith-ring, became denser, and many voids in the vascular bundles (vessels and sieve tubes) disappeared after compression; the shape of the vascular bundle also changed from circular to elliptical.

To analyse the fiber volume fraction precisely, an Automatic Image Analyzer (Kontron IPS 500) was used to measure the area fraction of bast fibres over the total area. The specimen was divided into six or seven parts along the circumferential direction. The voids in the vascular bundles were taken to be matrix, thus the fibre area fraction of each small divided part can be measured and the fibre area fraction along the radial direction was available. Because bamboo is strict unidirectional fibre-reinforced composite material, the fibre volume fraction was also calculated, and is shown in Fig. 5.

The fibre volume fraction, V_f, of normal bamboo decreases gradiently along the radial direction; after compression (cf. Fig. 5), the V_f of most parts of bamboo is in the vicinity of 50%, but the fibre fraction near the pith-ring (the inner surface of bamboo culm) remains the same. The mean value of fibre volume fraction of both kinds of bamboo are listed in Table I.

3.3. Mechanical properties of reformed bamboo

To obtain a comprehensive evaluation of reformed bamboo, tests were made of its density, static properties such as tensile modulus and strength, flexural modulus and strength, and shear strength along the fibre direction. The sizes of the bamboo specimens were determined by referring to the testing standards of wood [3] and fibre-reinforced composites, or according to previous work [8]. Experimental material was purchased from Guangdong province in South China. All tests were performed on a Shimadzu-DCS testing machine at room temperature. The geometric

TABLE I Comparison of the mechanical properties of reformed bamboo and normal bamboo

	Reformed bamboo		Normal bamboo	
	Mean	Dev.	Mean	Dev.
Fibre volume fraction (%)	43.6	13.4	29.2	12.8
Shrinkage coefficient:				
radial	0.252	0.005	0.299	0.020
tangential	0.184	0.057	0.319	0.076
bulk	0.446	0.083	0.663	0.132
Density (10^3 kg m^{-3})	0.87	0.17	0.66	0.07
Tensile strength (MN m^{-2})	271.5	60.6	206.2	24.7
Tensile modulus (GN m^{-2})	29.0	5.6	20.1	3.2
Flexural strength (MN m^{-2})	276.6	22.7	210.3	25.3
Flexural modulus (GN m^{-2})	23.2	4.7	13.1	3.0
Compressive strength (MN m^{-2})	104.7	28.4	78.7	7.6
Shear strength (MN m^{-2})	14.5	2.2	15.1	4.6

configuration and sizes of the specimens are shown in Fig. 6.

For tensile experiments, because the longitudinal shear strength is much lower than the tensile strength, the side-curved specimens were often found to be damaged by shear fracture at the specimen end rather than tensile fracture in the working length, so in our experiments, end-taped specimens were used instead of side-curved ones. Owing to the gradient of bamboo structure, the strength and modulus are very different in the radial direction, so measurements should be thought of as "effective" or "apparent" properties or, in other words, they are the average values across the thickness of the specimens.

During the tensile procedure, the process of the accumulation of damage was accompanied by sound emission. The pull-out of fibres is significant in fracture, as shown in Fig. 7. In all the bending tests, the side with the higher strength was loaded in tension. For shear tests, the direction of the loads is shown in Fig. 6; the shear test was performed on the basis of the test standard using the method for wood. The test results are summarized in Table I.

The data in Table I reveal that many mechanical properties of reformed bamboo are obviously increased, for example, the tensile strength is increased by 31.7%, tensile modulus 44.0%, and flexural strength 31.5%, at the expense of 32.2% increase of density.

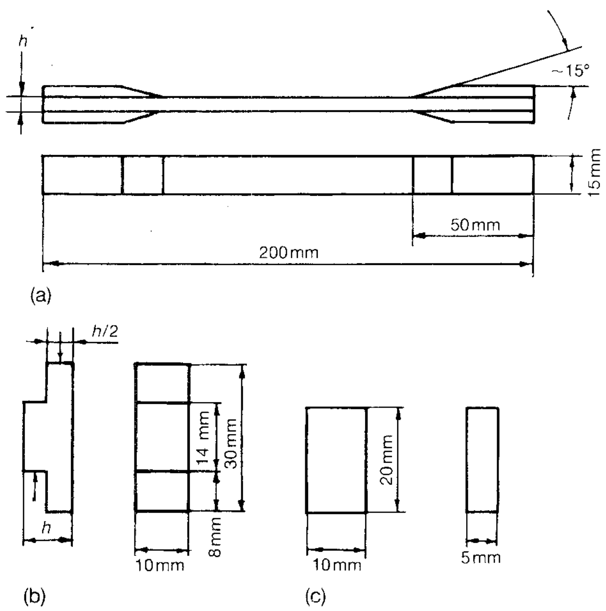

Figure 6 The shape and size of the bamboo specimens (*h* is the thickness of the bamboo culm). (a) Tensile, (b) shear, (c) compressive specimens.

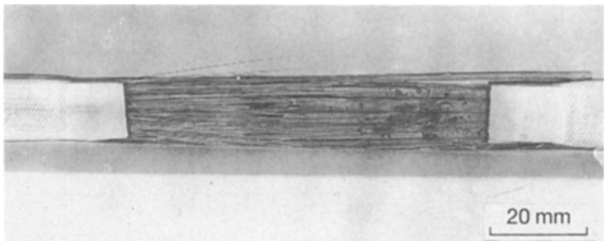

Figure 7 Photograph of a tensile fractured specimen of reformed bamboo.

The increase in the static mechanical property of reformed bamboo compared with the normal one can be explained by the following four aspects.

(a) Density. It is well known that the mechanical properties of a biomaterial have a close relationship with the density of the material. For wood, usually the wood possesses a higher density, and has higher strength; such a correlation also exists in bamboo. Fig. 8 shows the correlation between the flexural strength and density of bamboo.

(b) Compressive ratio. For the same bamboo, the higher the compressive ratio, the denser will be the reformed bamboo. The total number of bast fibres in bamboo, which bear most of the load to which the bamboo is subjected, remains the same, so the strength and modulus per unit area will be increased, as shown in Figs 9 and 10.

(c) Fibre volume fraction. According to the mixture principle, $\sigma_c = \sigma_f V_f + \sigma_m V_m$, for bamboo, σ_f is much higher than σ_m, thus the relationship between σ_c and V_f approaches a linear form; the increase of V_f of reformed bamboo will undoubtedly increase its strength.

(d) Microfibril angle. The microfibril angle of the plant can dominate substantially its mechanical property. During compression, the length and width of a

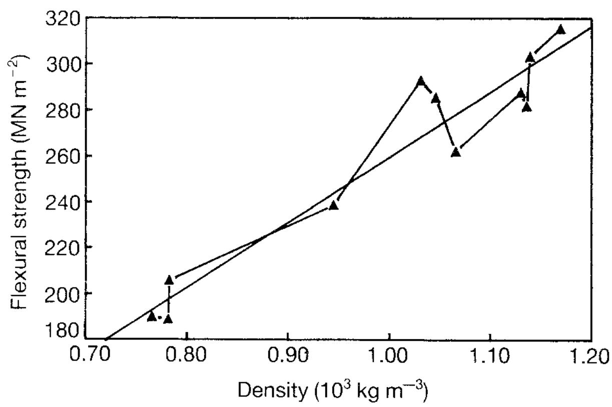

Figure 8 The correlation between the flexural strength and density of bamboo.

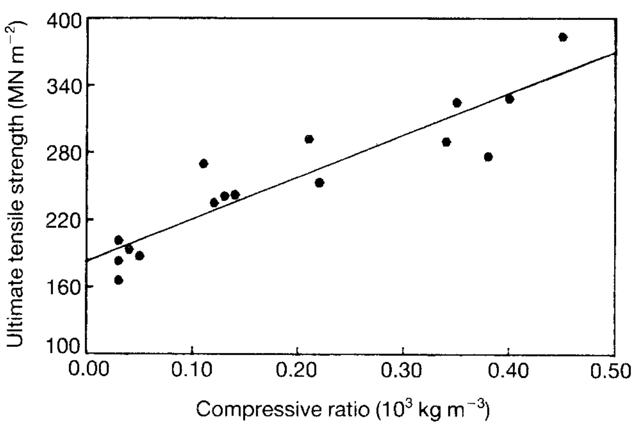

Figure 9 The tensile strength curve of reformed bamboo versus compressive ratio.

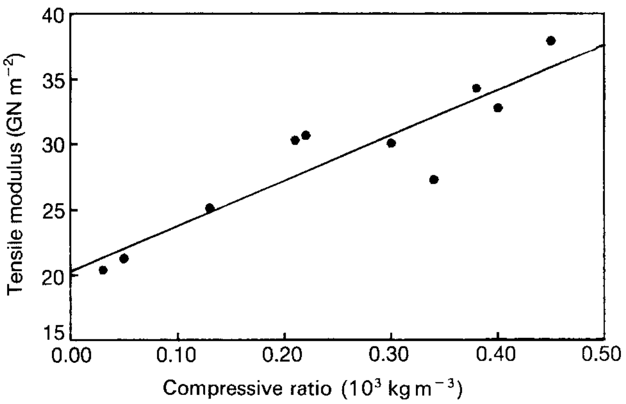

Figure 10 The tensile modulus curve of reformed bamboo versus compressive ratio.

TABLE II Specific properties of normal and reformed bamboo

	Reformed bamboo	Normal bamboo
Specific tensile strength (km)	31.84	31.88
Specific tensile modulus (Mm)	3.40	3.11
Specific flexural strength (km)	32.44	32.51
Specific flexural modulus (Mm)	2.72	2.03
Specific shear strength (km)	1.70	2.33

specimen must be increased to some extent, and thus so do the lengths of bast fibres. For a spirally coiled structure, like the cell wall of a plant, the increase in length must result in the decrease of the microfibril angle with the respect to the fibre axis, and this contributes to the increase of tensile property. The specific property, which is the ratio of the property to density, is of particular importance in composites. Table II gives a comparison of the specific properties of reformed and normal bamboo.

From Table II, it is clear that some major specific properties of both materials are very close, or even the same. This is easy to understand, because the effect of compression is to assemble the fibres more densely and the increase in the properties was accompanied by an increase in density.

3.4. Disadvantages of bamboo

Although reformed bamboo has many advantages over normal bamboo, it does not overcome the defects of other biomaterials. Because bamboo is a unidirectional fibre-reinforced composite, the mechanical properties in directions other than the fibre direction are less than those in the fibre direction, especially those across the fibre. For example, the tensile strength in the fibre direction is usually more than 50 times higher than that across the fibre, and the case in reformed bamboo is the same.

Another serious disadvantage of bamboo, also suffered by other biomaterials, is hygroscopicity. The shrinkage coefficient of a material represents its ability to absorb water in air and the shrinkage coefficient of reformed bamboo was found to be less than that of normal bamboo (cf. Table I); thus, the reformed bamboo is superior to the normal one in respect of retaining geometrical stability, in other words, under the same conditions, reformed bamboo absorbs less water from air than normal bamboo. After all, the moisture content of ligno-cellulosic bamboo will increase due to water in the air and will result in rot during service. The other parameter which describes hygroscopicity is the hygroscopic volume coefficient, H, which is defined as

$$H = W/V \tag{1}$$

where W is the moisture content in the specimen and V is the volume of the dry specimen. The hygroscopicities of normal bamboo and reformed bamboo composites were measured experimentally for 1 month. Specimens were placed in a container of 100% relative moisture and a temperature of $20^\circ \pm 2\,^\circ$C. The moisture contents of the specimens were measured regularly and the results are given in Fig. 11. Of the three start points in Fig. 11, those for reformed bamboo and reformed bamboo/aluminium are lower than that for normal bamboo; this is because the moisture content of reformed bamboo is lowered during the process of heating and compression. Up to 20 days, the hygroscopic volume coefficient (HVC) of reformed bamboo/aluminium remained the lowest. In the other two specimens, without aluminium sheets outside, the HVC of reformed bamboo increased more rapidly than that of normal bamboo; this is also because of the low moisture content in reformed bamboo after treatment. The situation after 20 days in Fig. 11 is seldom encountered in service, when the relative humidity of 100% in our experiment is taken into account.

4. Reformed bamboo/aluminium alloy

In order to overcome the disadvantages, improve the performance of reformed bamboo, and to replace some industrial aluminium alloy, in our work, reformed bamboo was applied to reinforce aluminium sheet, i.e. a new super-hybrid composite was designed according to different requirements.

4.1. Manufacturing technique

Epoxy resin (E44) was used as adhesive. Aluminium alloy sheet, 0.5 mm thick, is corrosion-resistant alumi-

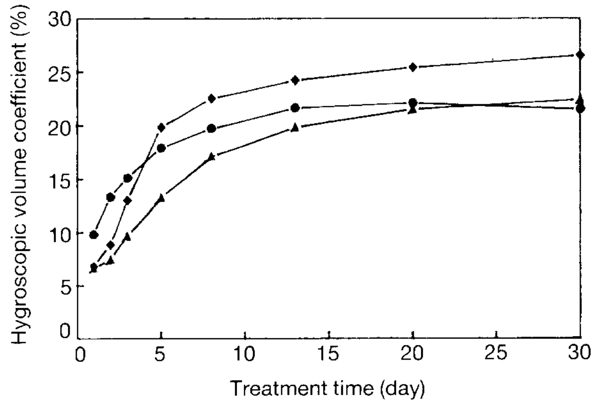

Figure 11 Hygroscopic curves of (●) normal bamboo, (◆) reformed bamboo and (▲) reformed bamboo/aluminium.

TABLE III Comparison of the properties of reformed bamboo/aluminium and aluminium used

	Reformed bamboo/Al	Al	BFRP [6]	BMC [6]
Tensile strength ($MN\,m^{-2}$)	369.8	140	175.3	110.5
Cleavage strength ($MN\,m^{-2}$)	3.4	–	–	–
Impact toughness ($kJ\,m^{-2}$)	80.9	–	45.6	34.0
Flexural strength ($MN\,m^{-2}$)	247.2	–	151.8	93.6
Flexural modulus ($GN\,m^{-2}$)	25.4	–	–	–
Compressive strength ($MN\,m^{-2}$)	107.1	–	–	–
Density ($10^3\,kg\,m^{-3}$)	1.2	2.7	0.975	0.908
Price (Yuan kg^{-1})	13.0	18	–	–
Tensile strength/(density price)	23.7	2.9	–	–
Specific tensile strength (km)	31.5	5.3	18.3	12.4
Specific flexural strength (km)	2.2	–	–	–

Note: 1 US\$ = 8.7 RMB Yuan.

nium with a tensile strength of 140 $MN\,m^{-2}$. In order to improve the adhesive ability, the surface of the aluminium sheet should be pretreated by a chemical or mechanical method: in our experiment, a mechanical method was used. The surface of the aluminium sheets were roughened by sand blasting. The reformed bamboo was adhered together as a plate with epoxy resin, and was then covered with aluminium alloy sheets on both sides. In the present work, the layers of reformed bamboo were placed along one direction; in practice, the fibre direction of each layer of reformed bamboo can be designed and adjusted to a certain value, according to different requirements.

4.2. Properties of reformed bamboo/aluminium

Some major mechanical properties of reformed bamboo were tested on a Shimadzu-DCS testing machine at room temperature. The results are listed in Table III. For comparison, the data of BFRP and BMC from [6] are also listed. From Table III, it can be noticed that the tensile strength of reformed bamboo/aluminium is more than twice that of aluminium, BFRP or BMC. Here, the crux of this phenomenon lies in the compressive ratio of reformed bamboo. In our experiment, this ratio can range from 0%–50%, corresponding to the compressive ratio, various mechanical properties of reformed bamboo are widely dispersed. The data for reformed bamboo in Table I are averaged values of all compressive ratio, but in the process of making reformed bamboo/aluminium specimens, only those with higher compressive ratio were chosen, thus relatively higher mechanical properties were undoubtedly obtained.

Bamboo is a renewable natural source and abundantly available. It is cheaper than wood and aluminium alloy. So reformed bamboo is cheap enough to be a prospective potential substitute for some industrial aluminium alloy. The thin aluminium sheet will protect the epoxy resin from ultraviolet rays and the reformed bamboo from corrosion, while the reformed bamboo can strengthen the aluminium and reduce the total weight of the material. Besides its mechanical properties, the overwhelming advantage of the new material is its low cost compared with industrial aluminium alloy; in our experiment, the cost is only two-thirds that of aluminium.

While the performance, density and price are considered simultaneously, the ratio of a materials performance to its price and density is a comprehensive criterion. We found that the ratio of tensile strength to density and price was increased by 717.2%.

5. Conclusion

Natural bamboo is a thick-walled circular cylinder with many nodes and diaphragms, and is difficult to use directly as a structural material. The compressive technique is an effective and convenient method to change the geometrical shape of bamboo into usable plate form. This is superior to the traditional method of using bamboo fibre strips or mats, because the new technique avoids the complexity of first making strips and thus saves raw material.

The fibre volume fraction and static mechanical properties of reformed bamboo are all increased remarkably compared with normal bamboo, and the overwhelming advantage of reformed bamboo is its low cost compared with other materials, such as BFRP, and its simple manufacturing technique.

Reformed bamboo is a prospective potential substitute for industrial aluminium alloy in some applications, especially for civil use, owing to its high performance and low price. On the one hand, aluminium alloy sheets outside the composite can protect the reformed bamboo from absorbing water in air and from rotting; on the other hand, the reformed bamboo can reinforce the aluminium alloy.

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