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Reformed bamboo/glass fabric/aluminium composite as an ecomaterial

S. H. LI*, J. R. DE WIJN, K. DE GROOT
Biomaterials Research Group, University of Leiden, Professor Bronkhorstlaan 10, 3723 MB Bilthoven, The Netherlands
Q. Y. ZENG, B. L. ZHOU
Institute of Applied Ecology, and Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110015, People's Republic of China
E-mail: Li@RULLF2.LeidenUniv.NL

A super-hybrid (natural composite/fibre-reinforced composite/metal hybridization) ecomaterial, reformed bamboo/glass fabric/aluminium (RB/GF/Al) was developed. The addition of a sparse glass fabric/epoxy resin layer between reformed bamboo and aluminium proved to be effective in increasing the compressive, tensile strength of the composite material. In particular, the interfacial shear strength between the reformed bamboo and aluminium was improved, and was the transverse tensile strength. These were the major shortcomings of normal bamboo and reformed bamboo/aluminium composites. The good recyclability of reformed bamboo and aluminium make RB/GF/Al an environmentally friendly material. Extensive use of such an ecomaterial instead of wood would save natural forest resources. © *1998 Chapman & Hall*

1. Introduction

We are facing serious environmental problems, such as a global climate change and acid rain, due to air, water and soil pollution. These problems seem to originate from strains existing in a type of society with a large materials and energy consumption. Although man-made materials have supported the society by bringing advantages and conveniences to human life, they also impose a wide variety of burdens on the environment through each and every step of production, processing, circulation, consumption, use, recycling and disposal. Therefore, current environmental concerns are not altruistic but imperative as a result of the realization that the waste produced by a world population whose numbers and appetite for goods are growing at an unprecedented rate, could eventually destroy life on earth. Based on such background, the concept of environmentally conscious materials (ecomaterials) is being rapidly accepted by countries all over the world [1].

The most important feature of composite materials is that they can be designed and tailored to meet different requirements. However, in the past period of composite-materials development, only mechanical and functional performance were taken into account in the design and processing. In recent years, the realization of environmental crisis has dramatically changed the priorities for research and development of composite materials. Now it is time for us to think not only of better performance, but also of how materials and related technologies can become less hazardous to the environment.

The greenhouse effect caused by the increasing CO_2 concentration in the atmosphere is predicted to produce drastic changes in the global climate. Forests, especially tropical rain forests, are the most important ecosystems for CO_2 fixation and therefore forests should be well managed. To save the forest, it is not appropriate to use wood as a structural material. For this reason, bamboo and its composites have attracted much attention during recent years [2, 3]. Apart from being one of the fastest growing plants, so that harvest time can be short, bamboo has such attractive features as high specific strength and modulus, low density and, as a natural material, its degradability. To make full use of bamboo, a new technique was developed by the present authors leading to so-called reformed bamboo and reformed bamboo/aluminium (RB/Al) laminates [4]. Significant improvement was found in the mechanical properties of RB/Al compared with those of normal bamboo and other bamboo-reinforced composite materials available. However, the transverse tensile strength (i.e. perpendicular to the fibre direction) and interfacial shear strength between

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*Author to whom all correspondence should be addressed. Also affiliated with the Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110015, People's Republic of China.

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aluminium and reformed bamboo, remained a shortcoming.

To overcome this disadvantage, in the present work, a new ecomaterial, reformed bamboo/glass fabric/aluminium (RB/GF/Al) was developed. Various mechanical properties, including tensile, compressive, flexural strength and shear strength, were measured and compared with those of normal bamboo, reformed bamboo and reformed bamboo/aluminium composite. Furthermore, the hygroscopic properties of this new material were also evaluated. Finally, the recycling ability of this material was studied and discussed.

2. Manufacture of reformed bamboo/glass fabric/aluminium (RB/GF/Al)

The bamboo used in the present work was *Phyllostachys pubescens*, purchased in the People's Republic of China. Reformed bamboo (RB) was prepared using the technique reported elsewhere [4]. 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. The bamboo strips were then heated in a container at 120 °C to adjust the moisture content to a certain value. The strips were then compressed with a compressor until a required compressive ratio was obtained. Finally, under a certain pressure, strips were pressurized for 3 h for the purpose of fixture. During the process, the moisture content of the bamboo is very important. The detailed conditions were reported previously [4].

The aluminium sheet used in this work was LY 12 (purchased from Shenyang Songling Company) with a thickness of 0.3 mm. Its tensile strength is 453 MPa. The sparse glass fabric cloth used was purchased from the Yaohua glass fibre shop in Shenyang, People's Republic of China. There are 300 fibres in one yarn and the diameter of a single fibre is 23 μm. The epoxy resin used was type 618 (E51), made in Shenyang Polytechnic College, People's Republic of China.

The surface of reformed bamboo was roughened by sandpaper, then the sparse glass fabric cloth was adhered to it at room temperature for 24 h with epoxy resin at a pressure of 2 MPa. The epoxy resin was used as an adhesive, so only a small amount of resin penetrated into the RB; however, the resin is the matrix of the composite layer of GF/resin. Reformed bamboo/glass fabric/aluminium (RB/GF/Al) was manufactured following a similar method to that described previously [4]. The difference is that glass fabric was added between aluminium sheets and reformed bamboo. The relative volume fractions of GF and aluminium in the final composite material are 8.1% and 10.8%, respectively.

3. Mechanical properties of RB/GF/Al

Various static mechanical properties of RB/GF/Al were tested, the geometric parameters of the specimen and the testing methods were the same as reported previously [4, 5]. For each property, at least 10 specimens were tested, and the results are summarized in Table I and shown in Figs 1–10.

Fig. 1 shows the correlation between the ultimate tensile strength and the density of normal or reformed bamboo. A good linear correlation exists for normal bamboo, but for reformed bamboo, there is no such linear relation. Usually the linear correlation between tensile strength and density makes it possible to predict the tensile strength of bamboo by measuring its density

Fig. 2 shows a comparison of the average ultimate tensile strength of various materials used in the present experiment. Different from the case reported previously [4], where low-strength aluminium was reinforced by reformed bamboo, high-strength aluminium was selected to improve the transverse strength of the composite. In Fig. 2, RB/GF/Al exhibits the highest tensile strength of all the materials tested. The tensile strength of RB/GF/Al can be designed by adjusting the volume fraction of reformed bamboo or aluminium. In the present test, reformed bamboo comprises about 80% (vol/vol) of the composites

The correlation between the compressive strength of normal bamboo (NB), reformed bamboo (RB) and reformed bamboo/glass fabric (RB/GF) and their densities is shown in Fig. 3. Similar linear trends can

TABLE I Comparison of the mechanical properties of normal bamboo (NB) reformed bamboo (RB), glass fabric (GF), reformed bamboo/glass fabric (RB/GF), aluminium (Al) and reformed bamboo/glass fabric/aluminium (RB/GF/Al). S.D. given in parentheses

	NB	RB	GF	RB/GF	Al	RB/GF/Al
Ultimate tensile	144.1	187.2	93.0	172	453.8	200.3
strength (MPa)	(31.0)	(61.5)	(3.0)	(47.4)	(48.7)	43.2
Compressive	61.2	87.5		85.9		99.7
strength (MPa)	(14.2	(11.1)		(15.2)		(20.8)
Flexural strength	128.1 (NB1)	183.0 (RB1)		186.4		225.2
(MPa)	(35.5)	(17.0)		(14.8)		(43.3)
	111.1 (NB2)	138.1 (RB2)				
	(21.5)	(27.0)				
Longitudinal shear	11.6	17.1		21.4		35.0
strength (MPa)	(4.5)	(4.0)		(7.0)		(6.9)
Transversal tensile	3.0	4.7		5.7		6.4
strength (MPa)	(1.0)	(0.6)		(0.6)		(2.2)
Interfacial shear				7.3		9.8
strength (MPa)				(1.6)		(2.2)

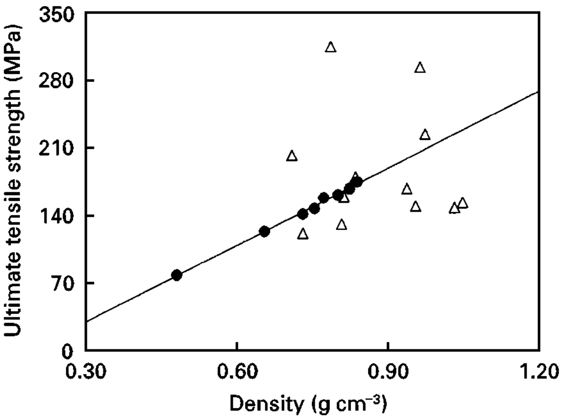

Figure 1 Correlation between the ultimate tensile strength and density of (●) normal bamboo and (△) reformed bamboo.

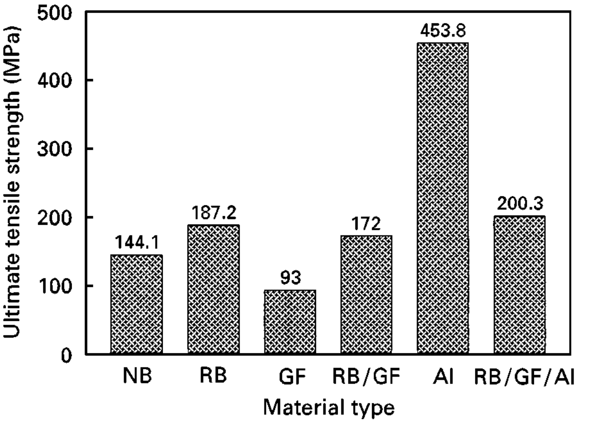

Figure 2 Comparison of the ultimate tensile strength of the various materials used.

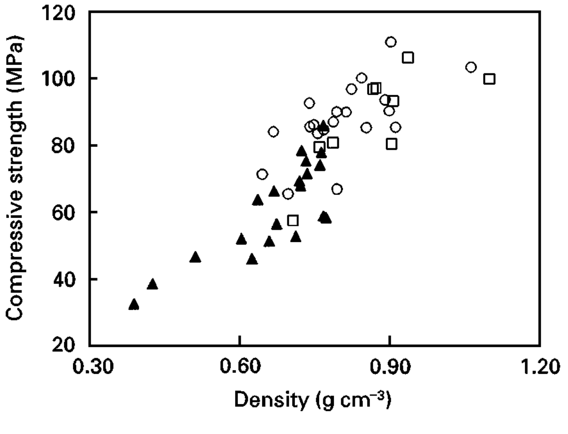

Figure 3 Correlation between the compressive strength and density of (▲) normal bamboo, (○) reformed bamboo and (□) reformed bamboo/glass fabric.

be found for the materials tested. Average densities and compressive strengths of NB, RB, RB/GF and RB/GF/Al are compared in Fig. 4. Although for RB/GF/Al the highest values of compressive strength and density were found, its average compressive strength is not much different from that of the other three kinds of materials.

Fig. 5 shows the flexural strength of normal bamboo, reformed bamboo, reformed bamboo/glass fabric and RB/GF/Al composite. Because bamboo has a gradient structure, the flexural strength is dependent on the sample orientation, and thus on which surface of the sample was subjected to tensile stress.

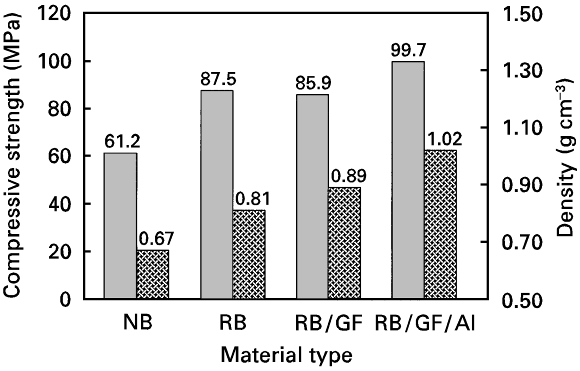

Figure 4 Comparison of the compressive strength of the various materials used: NB, normal bamboo; RB, reformed bamboo; GF, glass fabric; RB/GF, reformed bamboo/glass fabric composites; RB/GF/Al, reformed bamboo/glass fabric/aluminium.

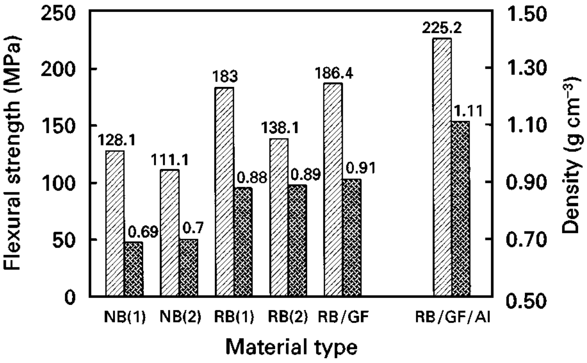

Figure 5 Comparison of the flexural strength of the various materials used. NB(1), normal bamboo with its rind side subjected to tension during the bending process. NB(2), normal bamboo with its pith-ring side subjected to tension during the bending process. RB(1), reformed bamboo with its rind side subjected to tension during the bending process. RB(2), reformed bamboo with its pith-ring side subjected to tension during the bending process. RB/GF, reformed bamboo/glass fabric; RB/GF/Al, reformed bamboo/glass fabric/aluminium.

Fig. 6 shows the results of the longitudinal shear strength test. The sampling and the geometric parameters of the specimen are shown in Fig. 7. For normal bamboo and reformed bamboo, the sample and test are the same as reported previously [4]; for RB/GF and RB/GF/Al the outside glass fabric layer or aluminium were cut together with the reformed bamboo layer. The experimental results reveal that these layers increase the longitudinal shear strength of the material.

The beneficial effect of adding a glass fabric layer between reformed bamboo and aluminium is proved by the interfacial adhesion and by the transverse tensile properties. Because bamboo is a unidirectional fibre-reinforced composite, the mechanical properties, other than in the fibre direction, are lower than those in the fibre direction, especially those across the fibre direction. For example the tensile strength along the

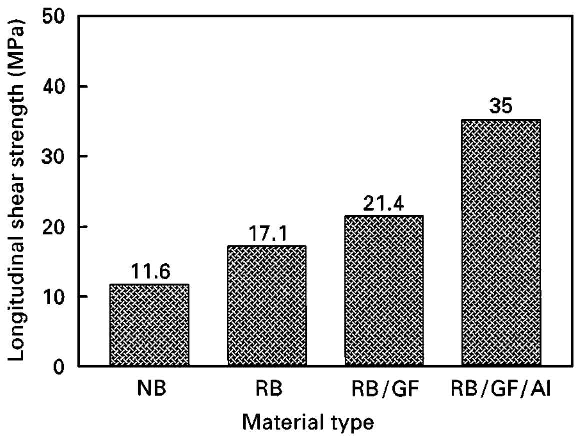

Figure 6 Comparison of the longitudinal shear strength of NB, RB, RB/GF and RB/GF/Al.

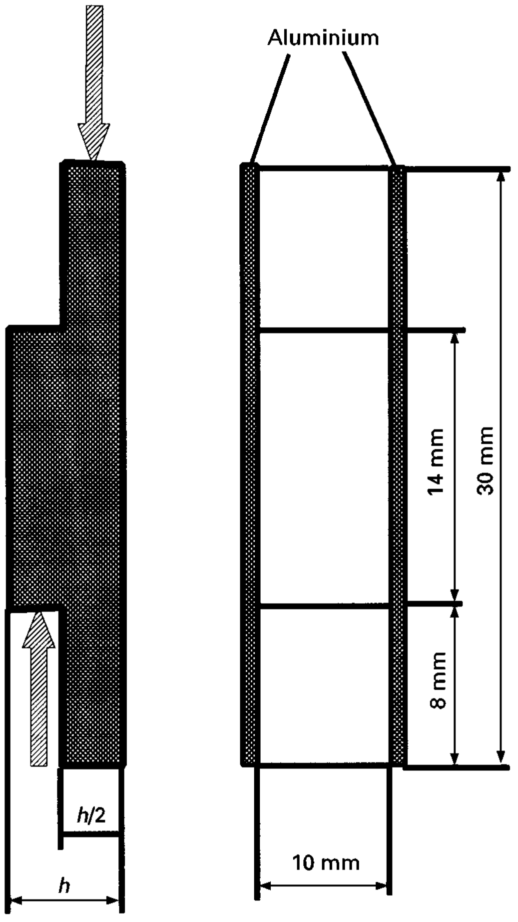

Figure 7 The sampling and the geometric parameters of the samples for longitudinal shear strength.

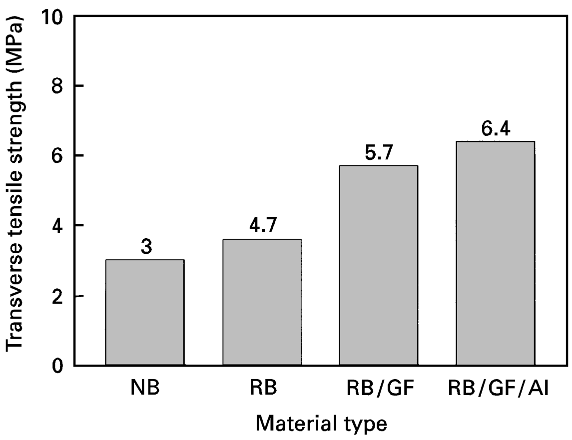

Figure 8 Comparison of the transverse tensile strength of NB, RB, RB/GF and RB/GF/Al.

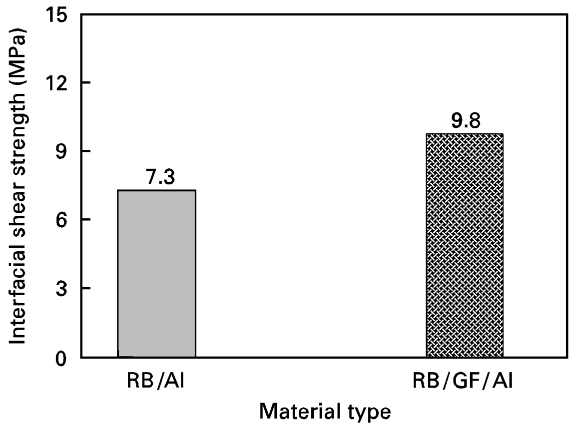

Figure 9 Interfacial shear strength of RB/Al and RB/GF/Al.

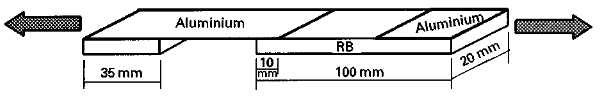

Figure 10 The shape and size of the sample for the interfacial shear test.

fibre direction is usually about 50 times higher than that across the fibre direction, the situation for reformed bamboo being similar. From Fig. 8 it becomes clear that both glass fabric and glass fabric/aluminium layer can increase the transverse tensile strength. Among the four kinds of materials tested, RB/GF/Al shows the highest value. Fig. 9 shows a comparison of the interfacial shear strengths of RB/Al and RB/GF/Al, the effect of adding the aluminium layer appearing significant. It is well known that interfacial properties are of critical importance for composite materials, especially for metal–polymer super-hybrid composites. Bamboo is a porous material of which the outer or inner surfaces are composed of fatty substances. Addition of a transition layer of glass fabric/epoxy resin layer will certainly increase the amount of epoxy resin in the interface; a sparse glass fabric can hold more resin than a dense fabric, and this also contributes to the increase in the interfacial shear strength. The geometric size of the sample for interfacial shear strength is shown in Fig. 10.

For comparison, the important specific properties of RF/GF/Al are listed in Table II together with those of other common materials.

4. Hygroscopic properties

If the new material RB/GF/Al is to be used in a damp environment, the hygroscopic properties have to be

TABLE II A comparison of the mechanical properties of natural bamboo with some other materials

Material	Density ($g\,cm^{-3}$)	Tensile strength (MPa)	Specific tensile (strength) ($N\,mg^{-1}$)	Tensile modulus (GPa)	Specific tensile modulus ($kN\,mg^{-1}$)	Compress. strength (MPa)	Specific compress. strength ($N\,mg^{-1}$)
Wood	0.46	104	226	10	22	37	80
Concrete	2.5	4	2	48	19	69	28
Glass	2.5	50	20	69	28	50	20
Aluminium	2.7	247	88	69	25	–	–
Cast iron	7.8	138	18	207	26	120	15
Steel (0.06%C)	7.9	459	58	203	26	800	101
ABS	1.1	50	45	3	3	50	45
PVC	1.5	59	39	2.4	1.7	55	37
Polyester	1.8	276	153	18	10	270	150
Epoxy	1.8	1100	611	45	25	400	222
CFRP	1.5	1040	693	180	120	1040	693
Normal bamboo	0.66	206	312	20	31	79	120
RB/GF/Al	1.02	200.3	196	–	–	99.7	98

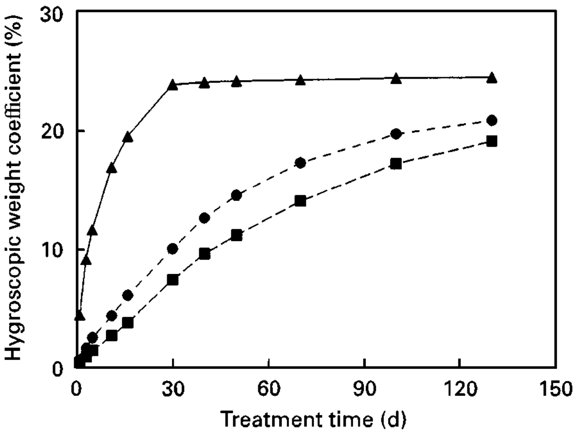

Figure 11 The hygroscopic weight coefficients of (▲) RB, (●) RB/Al and (■) RB/GF/Al.

taken into consideration because the uptake of moisture by bamboo will consequently result in rot during service. Usually the hygroscopic weight coefficient is used to evaluate the hygroscopic behaviour of a material. This coefficient is defined as: $H = W_1/W_0$, W_1 is the increase of specimen weight, W_0 is the weight of the dry specimen. The specimens were placed in a container at 100% relative humidity at a temperature of 20.2 °C and the weight of the specimens was measured regularly. The changing trends of the hygroscopic weight coefficient of each kind of sample are shown in Fig. 11. The new composite, with the addition of glass fabric, shows the slowest rate of water uptake and thus RB/GF/Al may be expected to have an improved water resistance.

As an additional layer of glass fabric improves the interfacial shear strength, defects in the interface were apparently reduced. This will also impede water in air from penetrating into the bamboo, thereby improving durability and weatherability.

5. Recyclability

As an ecomaterial, recyclability is a very important feature. For this new RB/GF/Al material, this problem had been considered in the design process. First, more than 80% of the material is reformed bamboo, which is inherently a biological material and is degradable or combustible. Aluminium sheet can be re-used directly if it can be separated from GF and reformed bamboo. Organic solvents are available for epoxy resin (ethylene dichloride, dioxane, etc. [6]) and glass fabric/epoxy resin which can be recycled according to a method reported by Kitamura *et al.* [7].

6. Conclusion

RB/GF/Al is an environmentally friendly material, more than 80% of its content being reformed bamboo, which is biologically regenerated. Reformed bamboo can be directly degraded; glass fabric and aluminium are also recyclable. Extensive uses of this material will save wood resources and thus protect forests.

The addition of a sparse glass fabric/resin layer between RB and aluminium can increase the interfacial shear strength by 34%, as well as the transverse strength by 78% with respect to RB.

The comprehensive mechanical properties are increased to different extents compared with those of NB, RB, RB/GF; for instance, ultimate tensile strength, compressive strength, flexural strength, longitudinal and transverse tensile strength.

The most important improvement of RB/GF/Al for the practical application is in the aspect of its hygroscopic property: the new composite shows a slower rate of water uptake compared with RB and RB/Al.

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