Evaluation of the Performance of the Composite Bamboo/Epoxy Laminated Material for Wind Turbine Blades Technology

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Global energy sources such as coal and oil are limited, and the burning of such fossil resources creates pollution problems. Wind energy offers one of several promising clean alternatives to carbon-based fuels. However, the composite materials currently available for producing wind turbine blades cannot accommodate the scale-up of wind energy due to their high price and disposal challenges (e.g., carbon fiber/epoxy laminated, fiber-reinforced plastics) or environmental costs (e.g., wood/epoxy laminate materials derived from large-diameter natural forest wood). The purpose of this study was to explore the advantages of the composite bamboo/epoxy laminated material as a more cost-effective, sustainable alternative. Applying the classical theory of composite laminated plates, this study tested a prediction model of the composite bamboo/epoxy laminated material's elastic modulus values. The model accurately predicted the end product's elastic modulus values according to the single bamboo board's elastic modulus values and its manner of assembly, without destroying the material's basic structure and integrity. The composite bamboo/epoxy laminated material was judged to be less expensive than carbon fiber/epoxy laminated, fiber-reinforced plastics and to have advantageous mechanical properties relative to conventional wood/epoxy laminate materials.

Keywords: Moso bamboo; Wind turbine blades composite materials; Elastic modulus; Prediction model; Wood/epoxy laminate materials; Mechanical properties

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INTRODUCTION

As the energy-return-on-energy-investment of carbon-based fuels continues to decrease and citizens across the globe become more concerned about the environmental consequences of burning fossil fuels, wind power is receiving greater global attention as a clean, alternative energy source. As is well-known, wind energy is produced through the use of wind turbines, in which the turbine blades play a very important role. By far, blades composed of fiber-reinforced plastics (FRPs) have been the most widely used in electricity-manufacturing wind turbines (Pickering 2006; Huang *et al.* 2011; Yang *et al.* 2012). However, the FRPs used in the production of blades have two major drawbacks that impede the wider adoption of wind turbines as a whole: they are costly and difficult to recycle (Burton *et al.* 2001; Jiang *et al.* 2006; Darshil 2013).

Clearly, identifying a more affordable, recyclable material that at least equals the effectiveness of FRP is critical. Turbine blades work by rotation, which demands uniformity and low variability in the properties of the materials used. More importantly, the strength and stiffness of the materials must be high, with a low density (Huang *et al.* 2009). The fatigue properties of materials must be superior as well. It is also important that the materials used be widely available at a low cost. Furthermore, they must be easily disposable/recyclable when out of service.

Unfortunately, the only alternative to using FRP in turbine blade production to date has been wood/epoxy laminated composites, which are made from large-diameter natural forest wood, such as Douglas fir and *Swietenia*. However, these are not widely available and pose other environmental concerns (Lieblein *et al.* 1982), thus rendering them unsuitable for the scale-up in clean energy production that our planet requires.

A potentially highly lucrative, more sustainable resource that has not been fully explored for the production of wind turbine blades is moso bamboo (*Phyllostachys pubescens* Mazei ex H. de Lebaie), which accounts for about 70% of the world's total bamboo forest (Sun *et al.* 2011). It has been developing rapidly in China since the 1990s as an important, environmentally sensitive forest resource alternative to wood, because of its fast growing rate, high strength and stiffness, easy workability, and local availability (Zhang 1995; Jiang 2002). Compared with engineering materials such as glass fiber-reinforced plastic, the physical and mechanical properties of moso bamboo show great variability. Outer bamboo is a high-quality material that is simultaneously strong and flexible (Huang *et al.* 2011). The cost of the composite bamboo/epoxy laminate material that can be made by outer bamboo is substantially lower than that of FRP.

Equally important, the development and survival of the bamboo industry, which can contribute in the future to greater environmental sustainability, depends not only on an increase in quantity produced; it also depends on the development of new products and global product applications to increase its added value. Thus, research and development related to the potentially superior material properties of bamboo/epoxy laminate (BEL) for wind turbine blades may not only promote greater use of wind energy but also strengthen the more renewable, sustainable moso bamboo industry (Zhang *et al.* 2013).

The purpose of this study was therefore to identify, test, and complete the optimization design of the composite bamboo/epoxy laminated material (BEL) for use in blades (BEL blades). The composite BEL is composed of bamboo boards of similar class, glued under high pressure using an epoxy adhesive. According to the classical theory of composite laminated plates, the composite materials with excellent physical and mechanical properties must include the joining of different boards with the best mechanical properties. Typically, the quality of such a composite is measured through the elastic modulus parameter, the values for which can only be obtained through destructive tests. The intended outcome of this study was to develop and validate a predictive model to accurately calculate the end product's elastic modulus value based on a single bamboo board's elastic modulus value and its manner of assembly, without destroying the basic structure and integrity of the material. Therefore, the predictive method can decrease the test frequency and increase the accuracy by BEL material's predictive model. It can save money and time required for testing, while providing the standard method for any composite material.

EXPERIMENTAL

Materials

Mature moso bamboo was collected from Franklinton, LA, USA. The bamboo specimens had lengths of approximately 15 m, and the radial diameters were greater than 10 cm. Bamboo pieces with dimensions of 2000 mm (length) × 20 mm (width) × 5 mm (thickness) were processed by a four-sided planer, as the outer bamboo remained (only with less green faces planed off). The bamboo pieces were put into a carbonization tank at 120 ℃ and 1 atm pressure for 120 min. The carbonized bamboo pieces were dried until the moisture content was under 8%.

The 618 epoxy was purchased from Yueyang Baling Petrochemical Company, Hunan, China. Its epoxide equivalent is 184 to 210 g/Eq. The SK epoxy was purchased from Sheng Ming Botong Technology Co. Ltd, Beijing, China. Its epoxide equivalent is 100 g/Eq. The phenolic resin was purchased from Taylor company, USA. Its solid content is 55 to 60%. Commercially available products including acetone were purchased from VWR, USA.

After the Young's modulus of the finished kiln-dried bamboo samples was determined using a DY-D99 dynamic multifunctional measuring instrument (Fig. 1), the measuring instrument was manufactured by Huibo Science and Engineering Instrument Research Institute, Nanjing, China. The bamboo samples were divided into two grades (first- and second-class) based on their Young's modulus values. The Young's modulus values of the first-class bamboo samples were 12,000 MPa and above, while those of the second-class fell between 10,000 and 12,000 MPa. Bamboo samples with values less than 10,000 MPa were discarded. The first-class bamboo samples were about 40%, the second-class bamboo samples were 40%, and the discarded bamboo samples with Young's modulus values less than 10,000 MPa were about 20%.

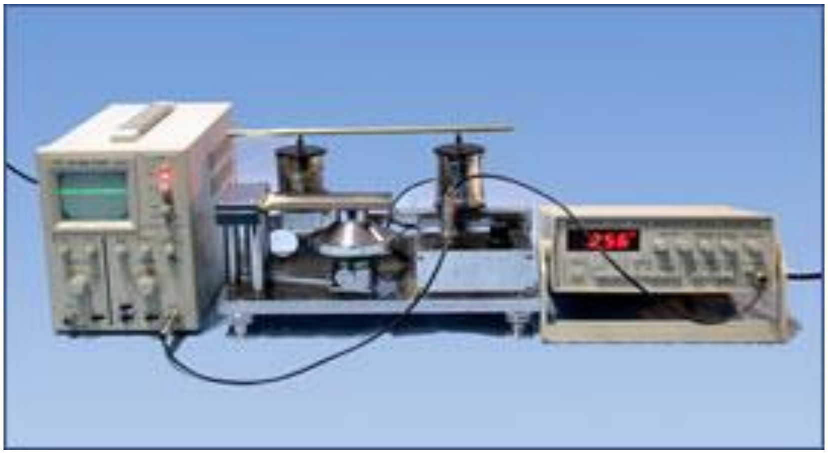

Fig. 1. DY-D99 dynamic multifunctional measuring instrument for determining Young's modulus

To laminate the bamboo, bamboo pieces from the same class were glued under high pressure using the bamboo flooring adhesives manufactured by Taylor company, USA. The glue-spread amount of bamboo pieces was controlled to be 120 g/m^2. The final bamboo board's thickness was 3 mm (Fig. 2). All single-layer bamboo board was checked using 2800 veneer testing instrument manufactured by Metriguard Inc, USA. The single-layer grading bamboo boards were divided into two grades based on their elastic modulus values: 12,000 MPa and above for first-class single-layer grading bamboo board, and 10,000 to 12,000 MPa for the second-class.

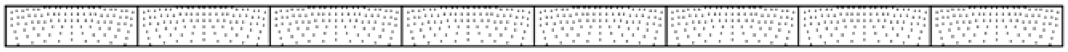

Fig. 2. The final single-layer bamboo board

Methods

The elastic modulus's prediction model of the end composite BEL material based on laminated plate theory

The structure of the composite bamboo/epoxy laminated material, modeled according to the classical theory of the composite laminated plates, is shown in Fig. 3.

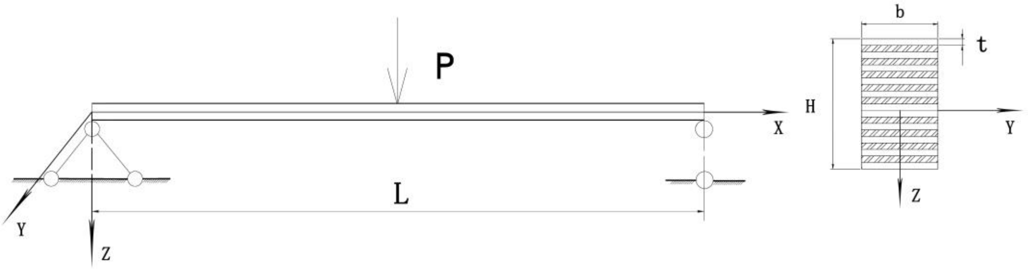

Fig. 3. Sketch of the model structure of laminated beam

The hypothesis of shifting is as follows,

$$\left.\begin{aligned} u &= \frac{\partial w}{\partial x}\cdot z \\ w &= w(x) \end{aligned}\right\} \tag{1}$$

where *u* is the shifting of the beam in the longitudinal direction and *w* is the deflection of the beam. The *n*-layer of the laminated beam is shown in Fig. 3. The stress of any of these layers (*i*-layer) can be expressed as:

$$\sigma_x^{(i)} = E^{(i)}\cdot\varepsilon_x = E^{(i)}\cdot\frac{d^2w}{dx^2}\cdot z \tag{2}$$

Therefore, the whole beam's deformation capability is,

$$\begin{aligned} U = {} & \int_0^l\int_{-\frac{b}{2}}^{\frac{b}{2}}\int_0^{z_1}\frac{1}{2}E_i^{(1)}(\frac{d^2w}{dx^2})^2\cdot z^2dxdydz + \int_0^l\int_{-\frac{b}{2}}^{\frac{b}{2}}\int_{z_1}^{z_2}\frac{1}{2}E_2^{(2)}(\frac{d^2w}{dx^2})^2\cdot z^2dxdydz \\ & + \int_0^l\int_{-\frac{b}{2}}^{\frac{b}{2}}\int_{z_2}^{z_3}\frac{1}{2}E_1^{(3)}(\frac{d^2w}{dx^2})^2\cdot z^2dxdydz + \cdots + \int_0^l\int_{-\frac{b}{2}}^{\frac{b}{2}}\int_{z_{k-3}}^{z_{k-2}}\frac{1}{2}E_1^{(k-2)}(\frac{d^2w}{dx^2})^2\cdot z^2dxdydz \\ & + \int_0^l\int_{-\frac{b}{2}}^{\frac{b}{2}}\int_{z_{k-2}}^{z_{k-1}}\frac{1}{2}E_2^{(k-1)}(\frac{d^2w}{dx^2})^2\cdot z^2dxdydz + \int_0^l\int_{-\frac{b}{2}}^{\frac{b}{2}}\int_{z_{k-1}}^{z_k}\frac{1}{2}E_1^{(k)}(\frac{d^2w}{dx^2})^2\cdot z^2dxdydz \end{aligned}$$

$$=\frac{1}{2}\left[bE_i^{(1)}\frac{z_1^3-0}{3}+bE_i^{(2)}\frac{z_2^3-z_1^3}{3}+bE_i^{(3)}\frac{z_3^3-z_2^3}{3}+\cdots\right.$$

$$\left.+bE_i^{(k-2)}\frac{z_{k-2}^3-z_{k-3}^3}{3}+bE_i^{(k-1)}\frac{z_{k-1}^3-z_{k-2}^3}{3}+bE_i^{(k)}\frac{z_k^3-z_{k-1}^3}{3}\right]\cdot\int_0^L(\frac{d^2w}{dx^2})^2dx$$

$$=\frac{1}{2}\left[E_i^{(1)}I_1+E_i^{(2)}I_2+E_i^{(3)}I_3+\cdots E_i^{(k-2)}I_{k-2}+E_i^{(k-1)}I_{k-1}+E_i^{(k)}I_k\right]\cdot\int_0^L(\frac{d^2w}{dx^2})^2dx$$

$$=\frac{1}{2}\left(\sum_{k=1}^{n}E_i^{(k)}I_k\right)\int_0^L(\frac{d^2w}{dx^2})^2dx \quad (i=1,2) \qquad (3)$$

where $E_i^{(k)}$ is the *i*-main direction's bending elastic modulus of the *k*-layer of laminate bamboo material and z_k, z_{k-1} are the coordinates of the upper and lower surface heights of the *k*-layer laminate bamboo material, and I_k is the *k*-layer of laminate bamboo material's area moment of inertia, respectively.

$$I_k=b\frac{z_k^3-z_{k-1}^3}{3}=b\frac{h_k^3-h_{k-1}^3}{24} \qquad (4)$$

The potential energy of the integral beam is:

$$\prod=\frac{1}{2}\left(\sum_{k=1}^{n}E_i^{(k)}I_k\right)\int_0^L(\frac{d^2w}{dx^2})^2dx-P\cdot w(x)\Big|_{x=\frac{l}{2}} \qquad (5)$$

According to the minimum potential energy principle, $\delta\prod=0$.

$$\delta\prod=0=-\left[2\left(\sum_{k=1}^{n}E_i^{(k)}I_k\right)\frac{d^3w}{dx^3}+P\right]\cdot\delta w(x)\Big|_{\frac{L}{2}}+2\left(\sum_{k=1}^{n}E_i^{(k)}I_k\right)\frac{d^2w}{dx^2}\delta\left(\frac{dw}{dx}\right)\Bigg|_0^{\frac{L}{2}}$$

$$+2\left(\sum_{k=1}^{n}E_i^{(k)}I_k\right)\frac{d^3w}{dx^3}\delta w\Big|_{x=0}+2\left(\sum_{k=1}^{n}E_i^{(k)}I_k\right)\int_0^{\frac{L}{2}}\left(\frac{d^4w}{dx^4}\right)\delta w\cdot dx \qquad (6)$$

Because of the displacement function, *w*(*x*) satisfies the boundary conditions and deformation conditions, and the corresponding variations *δw* and *δ*(*dw*/*dx*) are arbitrary. Because the minimum potential energy δΠ equals 0, it is required that every particular of the Eq. 6 must be all be equal to zero. The differential equations governing the beam's bending deformation under the action of transverse forces are as follows:

$$\frac{d^4w}{dx^4}=0 \qquad (7)$$

A simply supported beam's boundary conditions are as follows:

$$\text{When } x=0,\quad w=0 \quad \frac{d^2w}{dx^2}=0 \qquad (8)$$

$$\text{When } x=\frac{L}{2},\quad 2\left(\sum_{k=1}^{n}E_i^{(k)}I_k\right)\frac{d^3w}{dx^3}+P=0 \quad \frac{dw}{dx}=0 \qquad (9)$$

Solving Eq. 7:

$$W(x)=c_1x^3+c_2x^2+c_3x+c_4 \qquad (10)$$

Using the boundary conditions, the constants of integration can be determined as follows:

$$c_1=-\frac{P}{12\sum_{k=1}^{n}E_i^{(k)}I_k}, \quad c_2=0, \quad c_3=\frac{PL^2}{16\sum_{k=1}^{n}E_i^{(k)}I_k}, \ c_4=0 \qquad (11)$$

When the integration constant is substituted into the formula for shifting, the beam's shifting function is as follows:

$$u_{(x,z)}=\frac{P}{16\sum_{k=1}^{n}E_i^{(k)}I_k}\left(L^2-4x^2\right)\cdot z \qquad (12)$$

$$w(x)=\frac{P\cdot x}{48\sum_{k=1}^{n}E_i^{(k)}I_k}\left(3L^2-4x^2\right) \qquad (13)$$

Because the laminated beams is supported at both ends and there is a concentrated force P at the middle, its structure sketch is shown in Fig. 3. In this way, according to the classical theory of the composite laminated plates, the influence of Poisson's effect can be ignored. The flexural stiffness of n-layers of laminated plates can be determined as follows:

$$D_i=\frac{1}{3}\sum_{k=1}^{n} E_i^{(k)}(z_k^3-z_{k-1}^3) \qquad i=1,2 \qquad (14)$$

where $E_i^{(k)}$ is the k-layer of laminate board's the tensile-compressive elastic modulus (i-main direction), and z_k and z_{k-1} are the coordinates of the upper and lower surface heights of the *k*-layer laminate bamboo material, respectively.

Using Eq. (13), the midpoint's deflection can be determined as follows:

$$w\left(\frac{L}{2}\right)=\frac{P\cdot L^3}{48\sum_{k=1}^{n}E_i^{(k)}I_k} \qquad (15)$$

According to the mechanics of materials, the across-beam deflection is:

$$w=\frac{PL^3}{48EI} \qquad (16)$$

From the equivalent beam theory, the elastic modulus of the laminated beam can thus be obtained:

$$E=\frac{\sum_{k=1}^{n}E_i^{(k)}I_k}{I} \qquad (17)$$

Substituting Eq. (4) into Eq. 17 results in the following expression:

$$\sum_{k=1}^{n} E_i^{(k)} I_k = \frac{b\sum_{i=1}^{n} E_i^{(k)}\left(z_{i-1}^3 - z_i^3\right)}{3} \tag{18}$$

If one puts $\sum_{k=1}^{n} E_i^{(k)} I_k$ (Eq. 18 into Eq. 17), then according to the classical theory of the composite laminated plates, the predictive formula of the available elastic modulus of the beam can be obtained as follows:

$$E = \frac{b\sum_{i=1}^{n} E_i^{(k)}\left(z_{i-1}^3 - z_i^3\right)}{3I} \tag{19}$$

According to the principle of equivalent beams, the available elastic modulus of the laminate bamboo board (the *i*-main direction) can be expressed as,

$$E_i = \frac{1}{3I}\sum_{k=1}^{n} bE_i^{(k)}(z_k^3 - z_{k-1}^3) \qquad （i = 1,2） \tag{20}$$

where *I* is the cross sectional's axis moment of inertia and *b* is the cross sectional width.

The composite BEL material's machining

The ingredient ratio of impregnated epoxy resin mixture was 618 epoxy 30%, SK epoxy 30%, and phenolic resin 40%. The solid content of the three-types mixture resin was tested according to GB/T 14074-2006. The final solid content was fixed at 40%, using sufficient acetone to reduce the mixed resin's solids content to the target value. The single-layer bamboo board was placed into the dipping tank under 0.8 MPa for 60 min. After being treated, the single-layer bamboo board was dried in a drying box where the temperature was 60 ^{o}C until the adhesive on the bamboo board's surface was not sticky. The elastic modulus of each piece of single-layer bamboo board was checked using 2800 veneer testing instrument and labeled number. Then the single-layer bamboo board was assembled according to the reservation scheme (Fig. 4) to calculate the elastic modulus of the composite bamboo/epoxy laminated material using the elastic modulus prediction equation (Eq. 20).

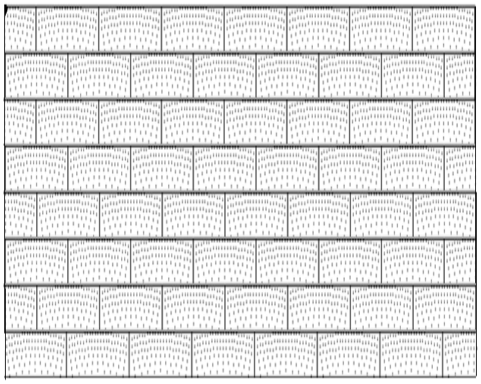

Fig. 4. The assembly sketches of the composite BEL material

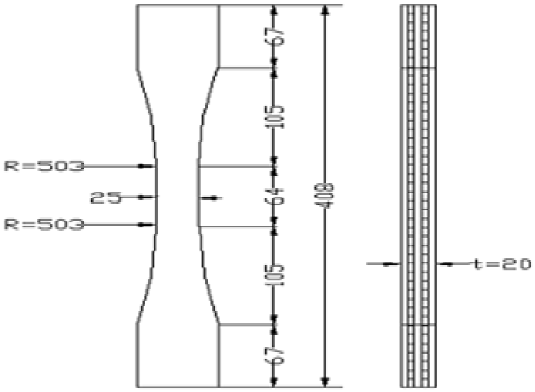

Fig. 5. The size of the tensile strength sample of composite BEL material based on ASTM3500C

The plates on and under the composite bamboo/epoxy laminated material were painted with 1000 centipoises silicone oil stripping to avoid damaging the hot plates. All of the assembled single-layer bamboo boards were glued by hot press, during which the hot press's temperature was 120 °C, with 3 MPa pressure for 100 min.

Method of testing the composite BEL material made from single-layer bamboo board

The composite bamboo/epoxy laminated material made from the same class single-layer bamboo board was sawn to the size of 500 mm × 200 mm × 20 mm, after being placed outside for more than 24 h. The size of the experimental sample was processed according to D3500-90 (ASTM Standard Test Methods for Structural Panels in Tension (Fig. 5). All of the text condition of BEL material's elastic modulus sample were met before the beginning of the experiment. Measured values of BEL material's elastic modulus were checked using the universal mechanical testing machine (INSTRON 5582) manufactured by INSTRON CORPORATION, USA. A comparison of the measured *vs.* predicted elastic modulus values is shown in Figs. 6 and 7. The characteristics of different types of the composite bamboo/epoxy laminated material and regular material for wind blades are shown in Tables 1 and 2.

RESULTS AND DISCUSSION

Comparison of Predicted and Actual Elastic Modulus Values of the Composite BEL Material

The predicted elastic modulus values of the composite BEL material were highly accurate for both first- and second-class single-layer bamboo board, with correlation coefficients between measured and predicted values of R^2 = 0.9399 for first-class and R^2 = 0.9241 for second-class, respectively.

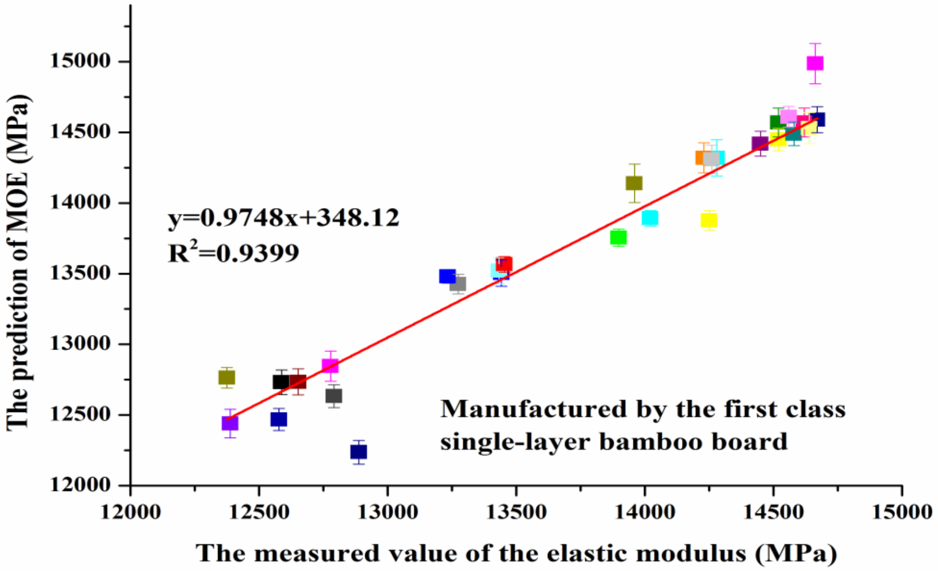

Fig. 6. Comparison of the measured and predicted elastic modulus values of the composite bamboo/epoxy laminated material made of first-class single-layer bamboo board

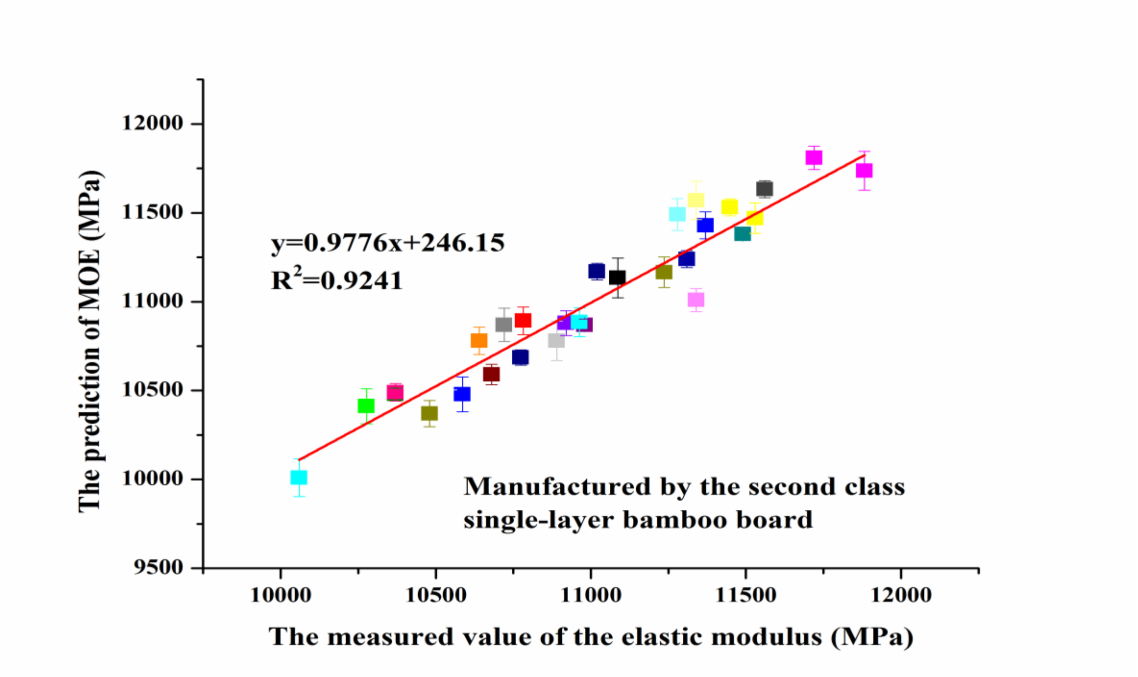

Fig. 7. Comparison of the measured and predicted elastic modulus values of the composite bamboo/epoxy laminated material made of second-class single-layer bamboo board

Comparison of Composite BEL Material to Regular Material for Wind Blades

All parameters of the regular material for wind blades are shown in Table 1 (*e.g.*, density, max tensile strength, max compression strength, unit compressive strength (UCS), modulus of elasticity (MOE), and specific stiffness) (Tony 2007).

One of the most important parameters of wind turbine blade materials is its specific stiffness, or the ratio of the material's elastic modulus to its density. It is widely known that the specific stiffness value determines the natural frequency of wind turbine blades (Tony 2007). According to Table 1, the specific stiffness value of the composite bamboo/epoxy laminated material, whether made of first- or second-class single-layer bamboo board, was slightly higher than that of a *Fagus sylvatica*/epoxy laminate.

A second critical parameter of wind turbine blade materials is unit compressive strength (UCS), or the ratio of the material's compressive strength to its density. Table 1 shows that the UCS value of the composite BEL material that was made of first- or second-class single-layer bamboo board was higher than that of *Swietenia managom*/ epoxy laminated or *Betula*/epoxy laminated materials.

Comparison between the composite bamboo/epoxy laminated material and the regular composite materials, the other parameters of wind turbine blade materials (*e.g.*, density, max tensile strength, max compression strength, modulus of elasticity (MOE)) were investigated. The results show that the density values of first- and second-class composite BEL material were slightly higher than that of wood/epoxy laminated material (e.*g*., *Swietenia managom*, *Betula*), and the density values were much lower than that of the regular glass fiber material (e.*g*., glass/polyester, glass/epoxy) and the carbon fiber/epoxy laminated materials. This means that the wind turbine blade can be installed more conveniently when using the proposed composite structure.

Table 1. Comparison between the Composite Bamboo/Epoxy Laminated Material and the Regular Composite Materials Used for Wind Turbine Blades

Material	Density (g/cm^3)	Max tensile strength (MPa)	Max compression strength (MPa)	UCS (g/cm^3)	MOE GPa	Specific stiffness (GPa)
Glass /polyester	1.85	860~900	720	389	38	20.5
Glass /epoxy	1.85	860~895	720	389	38	20.5
Carbon fiber /epoxy laminated	1.58	1830	1100	696	142	89.9
Swietenia managom /epoxy laminated	0.55	82	50	90.9	10	18.2
Betula /epoxy laminated	0.67	117	81	120.9	15	22.4
Fagus sylvatica /epoxy laminated	0.72	103	69	95.8	10	13.9
First-class BEL	0.82	185	136	165.9	13.8	16.8
Second-class BEL	0.82	172	116	141.5	11.6	14.1

Among currently available wind turbine blade materials, carbon fiber/epoxy composite laminated material has the strongest mechanical properties, but it is the most expensive (Tony 2007). As of publication, the market price of one ton of carbon fiber /epoxy composite material is $60,000, which is not substantially higher than other contemporary wind turbine blade materials such as glass /polyester or glass /epoxy. These costs have been partially prohibitive for wind energy's wider scale-up. By contrast, at the time of publication (and after careful calculation), the cost of one ton of the composite bamboo/ epoxy laminated material is estimated to be $3,000, or 5% of the most effective wind turbine blade option on the present market (Huang 2008). Beyond the staggering price advantage of the composite BEL material, the moso bamboo, of which it is made, is widely recognized as an environmentally positive forest resource alternative for wood because of its fast growth rate, easy workability, and local availability.

Comparison of the Composite Bamboo/Epoxy Laminated Material and Conventional Wood/ Epoxy Laminate Materials

In Britain, wind turbine blades have been traditionally manufactured from *Swietenia managom*, while Douglas fir is the mainstay of wind turbine blades in the USA. Given the decreasing availability of large-diameter natural forest wood, manufacturers have been turning to other European tree species for wind turbine blades, such as *Populus tomentosa*, Baltic pine, *Betula platyphylla*, and *Fagus sylvatica* (Tony 2007).

According to Table 2, functional indices of the composite BEL material such as tensile strength, compressive strength, elastic modulus, and shear strength are equal to or surpass those of conventional wood/epoxy laminate materials, with the exception of the comparatively slightly higher density value of conventional wood/epoxy laminate materials.

Table 2. Comparison of Composite Bamboo/Epoxy Laminated Material to Conventional Wood/ Epoxy Laminate Materials Used for Wind Turbine Blades

Material	Density (g/cm^3)	Tensile strength (MPa)	Compressive strength (MPa)	Elastic modulus (GPa)	Shear strength (MPa)
Swietenia managom	0.55	82	50	10	9.5
Douglas fir	0.58	100	61	15	12
Populus tomentosa	0.45	63	52	10	9
Baltic pine	0.55	105	40	16	9.3
Betula	0.67	117	81	15	16
Fagus sylvatica	0.72	103	69	10	16
First-class BEL	0.82	185	136	13.8	19.2
Second-class BEL	0.82	172	116	11.6	18

CONCLUSIONS

1. The predicted elastic modulus values of the composite bamboo/epoxy laminated material were highly accurate for both first- and second-class single-layer bamboo board, with coefficients of determination between measured and predicted values of $R^2 = 0.93999$ for first-class and $R^2 = 0.9241$ for second-class.
2. The composite bamboo/ epoxy laminated material has several advantages over carbon fiber /epoxy composite laminated material— the source material for wind turbine blades most currently in use—in that it is mechanically superior; easier to recycle; sourced from moso bamboo, a renewable, environmentally preferable resource; and 5% of the current market cost at time of publication.
3. The composite bamboo/ epoxy laminated material has several advantages over conventional wood/epoxy laminated materials—the conventional source material for wind turbine blades that is declining but still in use—in that it is functionally superior or equal except for a slightly higher density value; derived from a more renewable, vastly environmentally preferable resource than large-diameter forest wood; and lower than the current market cost at time of publication.
4. Given its radically lower cost, higher effectiveness, and environmental advantages, the composite bamboo/epoxy laminated material has enormous market potential to replace current wind turbine blade materials, rendering wind energy production more affordable and accessible.

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REFERENCES CITED

ASTM 3500-90 (2003). "Standard test methods for structural panels in tension," ASTM International, West Conshohocken, PA.

Burton, T., Sharpe, D., Jenkins, N., and Bossanyi, E. (2001). *Wind Energy Handbook*, John Wiley & Sons, New York.

Darshil, U. S. (2013). "Developing plant fibre composites for structural applications by optimise composite parameters: A critical review," *Journal of Materials Science* 48(18), 6083-6107. DOI:10. 1007/s 10853-013-7458-7

GB/T 14074-2006 (2006). "Testing methods for wood adhesives and their resins," General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ). Standardization Administration of the People's Republic of China.

Huang, X. D. (2008). "Evaluating and manufacture of grading bamboo/wood laminated of wind Turbine blades composite materials," Dissertation Chinese Academy of Forestry, Beijing, China.

Huang, X. D., Jiang, Z. H., and Chen, L. (2009). "Evaluation of strength grading *Cunninghamia lanceolata* as reinforcement of wind-turbine-blade composites," *China Wood Industry* 23(1), 24-27.

Huang, X. D., and Liu, Y. (2011). "Evaluation the performance of two kinds bamboo laminated of wind turbine blades composite," *Advanced Materials Research* 393-395, 737-741. DOI:10.4028/www.scientific.net/AMR.393-395.737

Jiang, Z. H. (2002). *World Bamboo and Rattan* (in Chinese), Liaoning Science & Technology Press, Shenyang, Liaoning.

Jiang, Z. H., Sun, Z. J., and Ren, H. Q. (2006). "Application of advanced bio-composites in wind blades," *Acta Materiae Compositae Sinica* 26(3), 127-129.

Lieblein, S., Gougeon, M., Thomas, G., and Zuteck, M. (1982). "Design and evaluation of low-cost laminated wood composite blades for intermediate size wind turbines," *Blade Design, Fabrication Concept and Cost Analysis*, DOE/NASA /0101-1, NASA CR-165463.

Pickering, S. J. (2006). "Recycling technologies for thermoset composite materials current status," *Composites Part A: Applied Science and Manufacturing* 37(8), 1206-1215. DOI: 10. 1016/j. composites a. 2005. 05. 030

Sun, F. L., Zhou, Y. Y., Bao, B. F., Chen, A. L., and Du, C. G. (2011). "Influence of solvent treatment on mould resistance of bamboo," *BioResources* 6(2), 2091-2100.

Yang, Y. X., Boom, R., Irion, B., Heerden, D. J. V., Kuiper, P., and Wit, H. (2012). "Recycling of composite materials," *Chemical Engineering and Processing: Process Intensification* 51, 53-68. DOI: 10. 1016/j. cep. 2011. 09. 007

Zhang, Q. S. (1995). *Industrial Utilization of Bamboo in China* (in Chinese), China Zhang, Y. M., Yu, Y. L., and Yu, W. J. (2013). "Effect of thermal treatment on the physical and mechanical properties of *Phyllostachys pubescens* bamboo," *Eur. J. Wood Prod.* 71(1), 61- 67. DOI:10.1007/s00107-012-0643-6

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