Prediction of Elastic Modulus and Mid-span Deflection of Bamboo-wood Composite Laminates

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To better guide the manufacturing of bamboo-wood composite laminates, classical theory, first-order shear theory, and finite element method were used to predict the elastic modulus and deflection of bamboo-wood composite laminates. The influence of the adhesive layer on the elastic modulus and deflection of composite materials was considered. The effect of transverse shear on the mechanical properties of materials became smaller and smaller with an increasing span-to-height ratio. The effects of the adhesive layer on the elastic modulus and deflection were ± 0.5% and -0.1% to 0.3%, respectively. The transverse elastic modulus and mid-span deflection predicted by the three methods were quite different from the experimental results. When the span-to-height ratio was equal to 20, the prediction error of longitudinal elastic modulus by the three methods was less than 6%, which can be used to predict the elastic modulus of composite materials. The results provide a novel method to predict the properties of bamboo-wood composite laminates.

Keywords: Bamboo-wood composite laminates; Classical theory; First-order shear theory; Finite element

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INTRODUCTION

A bamboo-wood composite laminates is a compound panel comprising glued bamboo and wood together in the same or different structural units (Guo *et al*. 2016). It combines the excellent properties of bamboo and wood, which make it widely used as structural materials in the field of engineering structures, such as container floors, car floors, and building templates. In addition, modified bamboo-wood composites serve as functional materials for electric heating and corrosion protection.

Due to the decrease in forest resources, the contradiction between the supply and demand of wood is increasingly prominent (Ettelaei *et al*. 2019). In addition, timber prices have fluctuated frequently and have maintained an upward trend in recent years. According to data from Random Lengths, a timber industry research organization, the price of timber in the United States reached $1,495 per thousand board feet in May 2021, a 318% increase compared to April 2020. Therefore, it is necessary to find a material that can replace wood to alleviate the problem. Bamboo, like wood, is a natural polymer similar to those of hardwood (Rao *et al*. 2018; Banik 2020). Moreover, bamboo is the fastest-growing and highest-yielding renewable natural material available to humans (Guo *et al*. 2016). Bamboo culms can be cut and used after three to five years, depending on the species (Lee *et al*. 2012; Liliefna *et al*. 2020). These make it a great potential alternative to wood (Verma *et al*. 2014; Banik 2018). By gluing wood and bamboo together to composite materials, the excellent characteristics of bamboo and wood were combined to obtain the double benefit of ensuring the quality of the products and reducing the production cost.

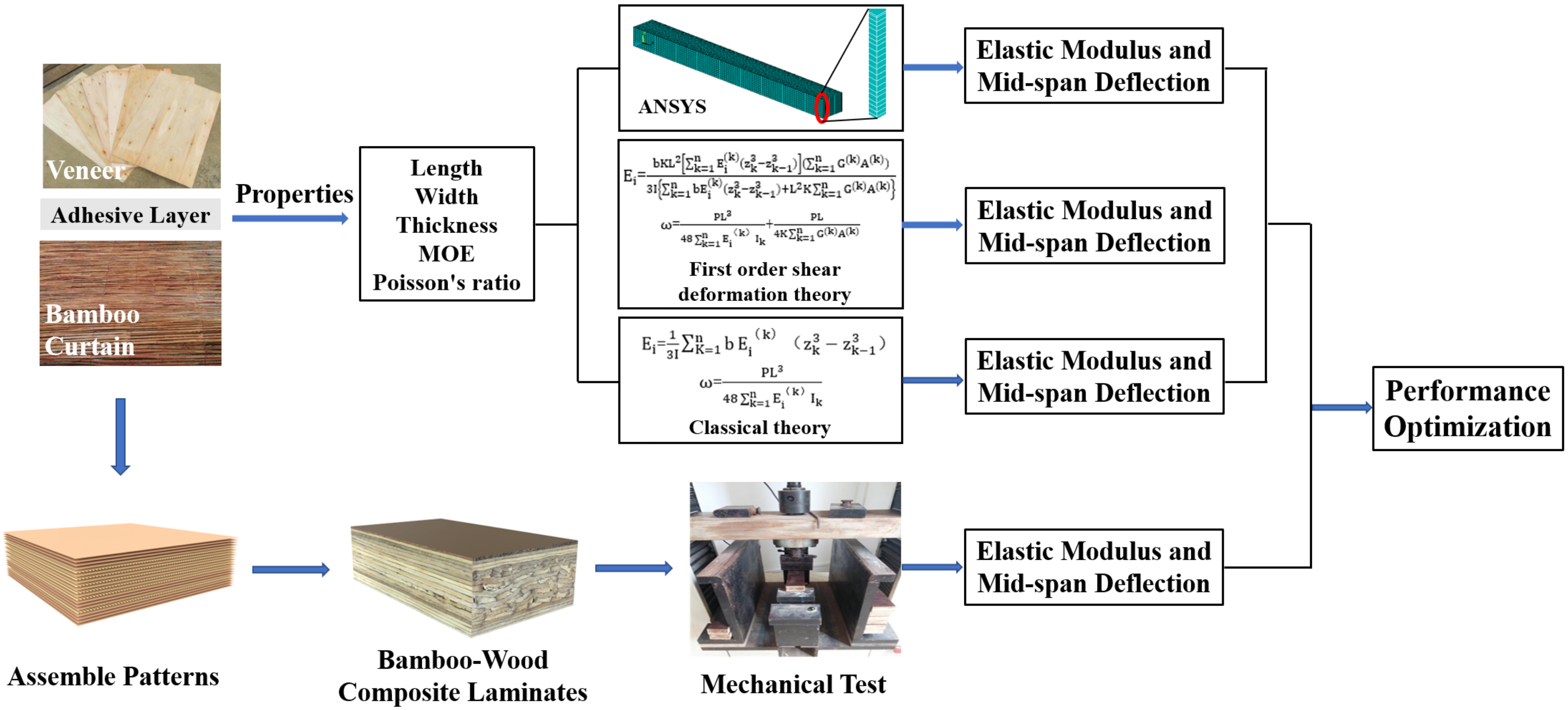

Fig. 1. Schematic chart of experiments

As an engineering material, the mechanical properties of bamboo-wood composite laminates are one of the important indexes for industrial requirements. The elastic modulus, which is an essential parameter of the macroscopic mechanical properties and reflects materials' ability to resist elastic deformation, reflects the properties of materials (Hu *et al*. 2005; Kazemi *et al*. 2005). The deformation of the material during bending is also an indicator of the mechanical properties of the material.

At present, the mechanical properties of bamboo-wood composite laminates are mainly obtained by measuring the samples in a destructive manner, which has caused certain resource waste (Ashaari *et al*. 2016; Chung and Wang 2019; Wei *et al*. 2019). In this paper, the relationship between the properties of component materials and the macromechanical properties of composites is established based on the theory of material mechanics, and the macroscopic mechanical properties were obtained. Xue and Hu (2012) calculated the elastic modulus of laminated veneer lumber using a mix of composite material mechanics, and the results were close to the measured values. Wei *et al*. (2019) proposed a theoretical model to derive the modulus of elasticity for laminated veneer lumber based on the laminated plate theory, and the validity of the model was proved by experiments.

Numerical simulation has been used to study composite materials by finite element method, which include the bending resistance of oriented particle board reinforced with bamboo and the behavior of oriented strand board beams (Bai *et al*. 1999; Zhu *et al*. 2005). Classical theory can theoretically predict the stiffness and strength of LVL and plywood, and the first-order shear deformation theory is used to calculate the deflection of the plate twist specimen, especially for thick, orthotropic laminated composites and sandwich plates (Perry 1948; Wei *et al.* 2019; Guillén-Rujano *et al.* 2017).

In this paper, based on an understanding the mechanical properties of component materials, the elastic modulus and deformation of bamboo-wood composite laminates were analyzed using the formulas derived from mechanical theory and numerical simulation by finite element analysis. The results were compared with those by experiments to obtain the relation between the assembly mode of component materials and the properties of composite materials. The schematic of experiments is shown in Fig. 1. This approach helps to reduce traditional trial efforts with theoretical analysis and numerical simulation in the trial production stage of actual production, saving considerable manpower and material resources.

EXPERIMENTAL

Theoretical Model

A laminated board, which is a symmetric orthogonal laminated board in a structure, is mainly affected by transverse loads perpendicular to the direction of the board surface. Due to the small Poisson factor, the Poisson effect can be ignored when studying the mechanical model. A section of the laminated beam is intercepted along a specific main direction defined for this research. Therefore, it is assumed that the axis is consistent with the neutral plane of the beam shown in Fig. 2.

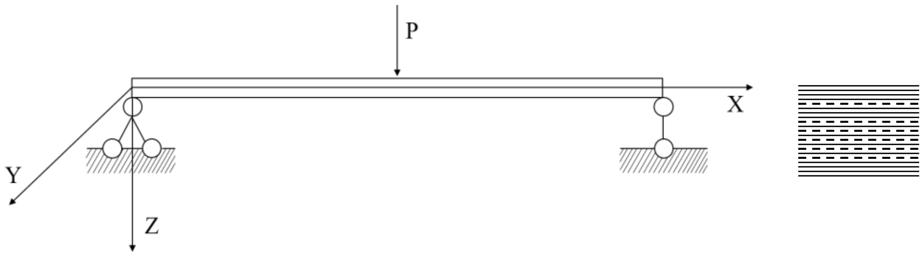

Fig. 2. Schematic diagram of laminated beam (-- bamboo curtain, —— wood veneer)

Classical Theory of Layers and Plates

(1) Straight line method assumption: The midplane normal direction is still normal to the midplane after deformation, and the thickness remains unchanged; that is, the effect of the transverse shear deformation and the effect of transverse normal stress ε_z are ignored. The cross-section of the beam is the cross-section perpendicular to the axis of the beam before deformation. After deformation, it is not only perpendicular to the axis, but is also a flat section.

(2) The stress component of the vertical neutral plane in the beam is far less than the in-plane stress value, excluding the effect of σ_z.

(3) Small deformation hypothesis.

The bending stiffness D_i of the laminated plate with n layers along the two principal axes can be expressed as follows,

$$D_i = \frac{1}{3}\sum_{K=1}^{n} E_i^{(k)} \left(z_k^3 - z_{k-1}^3\right) \qquad \text{(i= x, y)} \tag{1}$$

where $E_i^{(k)}$ is the bending elastic modulus of the material of the k-th layer of the material in the i-th principal direction of the plate (MPa). z_k and z_{k-1} are the height coordinates of the upper and lower surfaces of the k-th layer of the material (mm).

According to the equivalent beam theory, the elastic modulus E_i of the laminated plate with n layers along the two principal axes can be expressed as follows,

$$E_i = \frac{1}{3I}\sum_{K=1}^{n} b\, E_i^{(k)} \left(z_k^3 - z_{k-1}^3\right) \qquad \text{(i= x, y)} \tag{2}$$

where I is the moment of inertia of the cross-section axis of the laminated beam (mm^4), and b is the width of the laminated beam (mm).

At this point, the mid-span deflection of the laminated beam is calculated as,

$$\omega = \frac{PL^3}{48\sum_{k=1}^{n} E_i^{(k)} I_k} \tag{3}$$

where P is the load applied to the laminated beam (N), L is the length of the laminated beam (mm), $E_i^{(k)}$ is the same as in Eq. 1, and I_k is the moment of inertia of the cross-section axis of the k-th layer of the material.

First-order Shear Deformation Theory

Although the results of the classical theory (CS) are simple to derive and easy to analyze, classical theory does not consider the effect of the transverse shear effect, which will introduce significant error for short beams and a large shear effect. For bamboo-wood composite laminated beams, the material itself has strong anisotropy and a low interlaminar shear modulus. The influence of transverse shear on the bending deformation cannot be ignored. Here, the first-order shear deformation theory (FSDT) may be suitable.

The first-order shear deformation theory adopts the plane assumption, abandoning the assumption of the straight-line method, namely that the cross-section is still perpendicular to the axis after deformation comparing with the classical theory. According to the first-order shear deformation theory, after the cross-section of a beam is deformed, in addition to the angle change caused by the bending deformation, there is also a part of the angle change caused by the influence of the transverse shear force to reflect the average value and influence of shear deformation of cross section. However, this assumption does not conform to the actual situation. If the plane hypothesis is satisfied, the shear strain should be the same in the thickness direction; then, the generalized Hooke's law and the transverse shear modulus are finite values, and the transverse shear stress is also uniformly distributed along the thickness direction. This does not satisfy the boundary condition when the upper and lower surfaces of the beam are free from shear stress. To compensate for this contradiction, the method of modifying the shear stiffness is generally adopted; that is, the modified shear stiffness K is introduced, which is different for different comparison criteria. In this paper, the shear correction coefficient K^2= 5/6 calculated by Pietraszkiewicz *et al.* (Pietraszkiewicz 1979; Badur 1984; Chróścielewski *et al.* 2010). For a single layer board, K^2= 5/6.

In addition, the elastic modulus E_i of the n-layer laminate along the two principal axes can be derived, which can be expressed as follows,

$$E_\mathrm{i} = \frac{bKL^2\left[\sum_{\mathrm{k}=1}^{\mathrm{n}} E_\mathrm{i}^{(\mathrm{k})}(z_\mathrm{k}^3-z_{\mathrm{k}-1}^3)\right](\sum_{\mathrm{k}=1}^{\mathrm{n}} G^{(\mathrm{k})}A^{(\mathrm{k})})}{3\mathrm{I}\left\{4\sum_{\mathrm{k}=1}^{\mathrm{n}} bE_\mathrm{i}^{(\mathrm{k})}(z_\mathrm{k}^3-z_{\mathrm{k}-1}^3)+L^2K\sum_{\mathrm{k}=1}^{\mathrm{n}} G^{(\mathrm{k})}A^{(\mathrm{k})}\right\}} \tag{4}$$

where K is the modified shear stiffness coefficient, $G^{(\mathrm{k})}$ is the shear elastic modulus of the k-th layer of the plate (MPa), $A^{(\mathrm{k})}$ is the cross-sectional area of the k-th layer of the plate (mm^2), and $E_\mathrm{i}^{(\mathrm{k})}$, z_k, and $z_{\mathrm{k}-1}$ are the same as in Eq. 1, and b and I are the same as in Eq. 2, and L is the same as in Eq. 3.

At this point, the mid-span deflection of the laminated beam is calculated as follows,

$$\omega = \frac{PL^3}{48\sum_{\mathrm{k}=1}^{\mathrm{n}} E_\mathrm{i}^{(\mathrm{k})}\mathrm{I}_\mathrm{k}} + \frac{PL}{4\mathrm{K}\sum_{\mathrm{k}=1}^{\mathrm{n}} G^{(\mathrm{k})}A^{(\mathrm{k})}} \tag{5}$$

where P, L, and I_k are the same as in Eq. 3, $E_\mathrm{i}^{(\mathrm{k})}$ is the same as in Eq. 1, and $G^{(\mathrm{k})}$ and $A^{(\mathrm{k})}$ are the same as in Eq. 4.

Finite Element Method Analysis

The finite element method (FEM) is a computational approach used in approximating complex real-world engineering problems within certain boundary conditions (Muhammad *et al*. 2020). The basic idea of it is to discretize the object into a finite number of unit combinations that are connected to each other in a certain way to simulate or approximate the original object. Thus, it simplifies a continuous infinite degree of freedom problem. But it entails dividing the structure into tiny components referred to as elements for static and dynamic analysis under various design constraints (Muhammad and Shanono 2019).

In this study, the SHELL99 element, which is based on the general-purpose finite element analysis software ANSYS, was employed to consider the influence of each layer anisotropy of the laminated beam and the transverse shear effect. Meanwhile, the SHELL99 element is a representative plate and shell element and is a commonly used fournode element, where each node has six degrees of freedom, namely, translational degrees of freedom in the X, Y, and Z directions and rotational degrees of freedom around the X, Y, and Z axes. It can be used for layered shell structures. Therefore, this paper constructs a laminated beam model by inputting the physical properties of each layer of the material. When the mechanical properties of bamboo-wood composite laminated plates are tested, the material undergoes elastic deformation. ANSYS software is used to simulate the stress process of elastic deformation. Then, Eq. 6 can be used to calculate the elastic modulus under this method; the largest deformation in the deformation graph of the ANSYS output result is the deflection under the load.

Component Materials and the Assembly Patterns

The bamboo-wood composite laminated beam shown in Fig. 2 was taken as the analysis object. The direction along the grain of the first layer veneer is considered as the direction of the length of the laminated beam (X direction), as the Y direction of the horizontal stripes on the board surface and as the Z direction perpendicular to the board surface (thickness direction). The bamboo-wood composite laminates were assembled based on patterns as shown in Table 1. Before assembling, adhesive was applied to the bamboo curtain and wood veneer, and then the assembling patterns were processed by cold pressing and hot pressing to prepare bamboo-wood composite laminates.

Table 1. Assemble Patterns

Layer	Material	Direction	Thickness (mm)
1	Poplar Veneer	Longitudinal	1.0
2	Eucalyptus Veneer	Transverse	1.7
3	Eucalyptus Veneer	Longitudinal	1.7
4	Eucalyptus Veneer	Longitudinal	1.7
5	Bamboo curtain	Longitudinal	2.2
6	Eucalyptus Veneer	Transverse	1.7
7	Bamboo curtain	Longitudinal	2.2
8	Eucalyptus Veneer	Longitudinal	2.2
9	Bamboo curtain	Longitudinal	2.2
10	Eucalyptus Veneer	Longitudinal	2.2
11	Bamboo curtain	Longitudinal	2.2
12	Eucalyptus Veneer	Longitudinal	2.2
13	Bamboo curtain	Longitudinal	2.2
14	Eucalyptus Veneer	Longitudinal	2.2
15	Eucalyptus Veneer	Transverse	1.7
16	Eucalyptus Veneer	Longitudinal	1.7
17	Bamboo curtain	Longitudinal	2.2
18	Eucalyptus Veneer	Longitudinal	1.7
19	Eucalyptus Veneer	Transverse	1.7
20	Eucalyptus Veneer	Longitudinal	1.7
21	Weedtree Veneer	Longitudinal	0.6

The mechanical properties of the raw materials (veneer and bamboo curtain) are shown in Table 2 (Cheng 1980; Bai *et al.* 1999; Li 2006).

Table 2. Properties of the Component Materials

Component Material	Longitudinal Elastic Modulus (MPa)	Transverse Elastic Modulus (MPa)	Shear Modulus (MPa)	Poisson's Ratio
Poplar Veneer	7724.5	461.7	384	0.282
Bamboo Curtain	10641	490	275	0.31
Eucalyptus Veneer	18900	945	500	0.3
Weedtree Veneer	20000	1000	550	0.3
Adhesive Layer	6900	6900	2650	0.3

Bending Test of the Bamboo-Wood Composite laminates

According to GB/T 17657-2013, the mechanical properties of specimens are tested by the three-point bending method. The thickness of the test piece is fixed, so the span is changed to carry out the test with different span-to-height ratio. The test is divided into three groups, each with six test pieces (650 mm×650 mm). During the testing, the loading speed is set to 10 mm/min, and elastic modulus was calculated with the following formula,

$$E = \frac{l^3}{4 \times b \times t^3} \times \frac{\Delta F}{\Delta a} \tag{6}$$

where E is the elastic modulus of the specimen (MPa), l is the distance between the two supports, b is the width of the specimen (mm), t is the thickness of the specimen (mm), ΔF is the increase of load on the straight line segment of the load-deflection curve (N), and Δa is the increment of deformation corresponding to ΔF (mm).

Performance Criteria

Absolute percentage error (APE) was used to evaluate the performance of the three methods in this paper. The equations of these performance criteria are given below,

$$\mathrm{APE} = \frac{|m - m_d|}{m} \times 100\% \tag{7}$$

where m is the measured values, m_d is the theoretical values.

RESULTS AND DISCUSSION

Mechanical Properties without the Adhesive Layer

Elastic modulus

The elastic modulus E of the laminated beam was calculated according to Eqs. 2, 4, and 6. The effect of span-to-height ratio of bamboo-wood composite laminates on the elastic modulus was considered. The results are shown in Table 3 (x and y represent the longitudinal and transverse directions, respectively). The absolute percentage error between predicted and measured elastic modulus is calculated according to Eq. 7. The results are shown in Fig. 3.

Table 3. Predicted and Measured Modulus of Elasticity

L/H	CS E_{1x}/MPa	CS E_{1y}/MPa	FSDT E_{2x}/MPa	FSDT E_{2y}/MPa	FEM E_{3x}/MPa	FEM E_{3y}/MPa	Meas-ured E_x/MPa	Measured E_y/MPa
10	11818.63	5576.98	9041.18	4870.88	11368.41	5289.32	10060	3932
15	11818.63	5576.98	10398.84	5239.41	11590.43	5453.56	11090	4420
20	11818.63	5576.98	10975.70	5381.93	11657.98	5509.03	11624	4703

As shown in Table 3, the longitudinal elastic modulus of the bamboo-wood composite laminates was much greater than the transverse elastic modulus. The elastic modulus predicted by classical theory is not influenced by the span-to-height ratio. The true elastic modulus of the material will not change, but as the span-to-height ratio increases, the elastic modulus predicted by the first-order shear theory and finite element method is increased, and approaches the value predicted by the classical theory. It also can be found that the increment of the elastic modulus decreased with the increase of span-to-height ratio. This shows that the effect of shear decreased with the increase of the span-to-height ratio. Under the same span-to-height ratio, the elastic modulus determined by the first-order shear deformation theory was less than that by the finite element method. In the calculation process, the farther away from the neutral axis, the greater the contribution of veneer or bamboo curtain (the direction must be the same as the laminate direction) to the elastic modulus. This result is similar to the experimental results obtained by Chen *et al.* (2016). The bamboo curtains are discontinuous. If the bamboo curtains are placed continuously, it will cause larger defects in the composite material. Therefore, the bamboo curtains were not put together. Rather, they were separated with wood veneers, which is also one of the reasons for the assembly patterns used in this article.

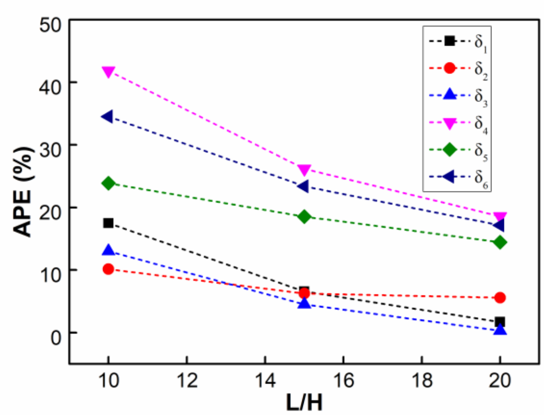

Fig. 3. The absolute percentage error between predicted and measured elastic modulus

As shown in Fig. 3, the δ_1, δ_2, and δ_3 represent the absolute percentage error between the longitudinal elastic modulus predicted by classical theory, first-order shear deformation theory and finite element method, and the measured longitudinal elastic modulus respectively. The δ_4, δ_5, and δ_6 represent the absolute percentage error between the transverse elastic modulus predicted by classical theory, first-order shear deformation theory and finite element method, and the measured longitudinal elastic modulus respectively. As shown in Fig. 3, the absolute percentage error decreases as the increase of the span-to-height ratio. The absolute percentage error in the longitudinal direction is smaller than those in the transverse direction. This is mainly due to the fact that the shear modulus of component materials has far less influence on the longitudinal elastic modulus of composite materials than its influence on the transverse elastic modulus of composite materials.

Mid-span deflection

The mid-span deflection ω of the laminated beam was calculated according to Eqs. 3, 5, and the ANSYS output result. The effect of span-to-height ratio of bamboo-wood composite laminates on the mid-span deflection was considered. The results are shown in Table 4. The absolute percentage error between predicted and measured mid-span deflection is calculated according to Eq. 7. The results are shown in Fig. 4.

Table 4. Predicted and Measured Mid-span Deflection

L/H	CS ω_1/mm	FSDT ω_2/mm	FEM ω_3/mm	Measured ω/mm
10	1.756	2.295	1.825	2.47
15	5.925	6.735	6.042	8.68
20	14.046	15.124	14.239	22.00

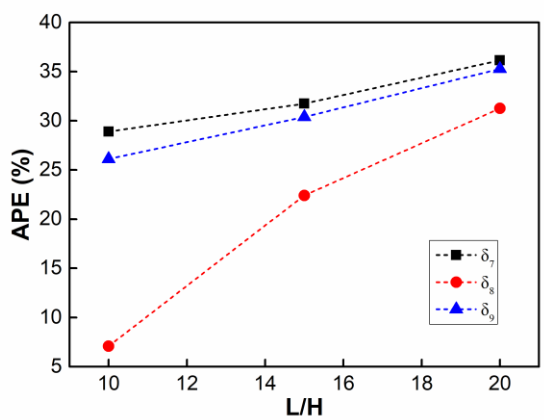

Fig. 4. The absolute percentage error between predicted and measured mid-span deflection

Table 4 shows that as the span-to-height ratio increased, the deflections calculated by the three methods increased geometrically. The mid-span deflection predicted by the three methods are relatively close. As shown in Fig. 4, the δ_7, δ_8, and δ_9 represent the absolute percentage error between the mid-span deflection predicted by classical theory, first-order shear deformation theory and finite element method, and the measured mid-span deflection respectively. As shown in Fig. 4, the absolute percentage error increases as the increase of the span-to-height ratio. Regardless of the span-to-height ratio, $\delta_8 < \delta_9 < \delta_7$, which shows that the finite element method was superior to first-order shear theory and classical theory in predicting mid-span deflection. The first-order shear theory was better than the classical theory because the first-order shear theory considers the influence of shear strain on bending.

Mechanical Properties with the Adhesive Layer

Adhesive layer influence

Many long slits are formed along the fiber direction in the process of weaving bamboo curtains and these are inevitable. The adhesive infiltrates the bamboo and forms three parts in the process of bamboo curtain dipping, drying, cold pressing, and hot pressing. The first part forms an adhesive layer with a certain strength and rigidity on the upper and lower surface of the bamboo by curing, which connects the adjacent bamboo curtains (boards) into a whole. The second part penetrated the bamboo fiber. In the third part, the liquid glue was filled into the slit of the bamboo curtain. This part of the liquid glue solidified into a crisp solidified body almost without pressure and hardly affects the performance of the plywood (Sun 2001).

The adhesive penetrates the veneer, enters the cell cavity, and may even enter the cell wall in the process of veneer coating, assembling, and hot pressing (Furuno *et al*. 2004; Konnerth *et al*. 2008; Huang *et al*. 2012). The portion of the veneer where glue penetrates was considered the glue line, and the results showed that the glue line's influence on the properties of the material can be neglected (Okuma 1976; Wei *et al*. 2015). The glue that has not penetrated the veneer is cured on the veneer's surface to form an adhesive layer.

The glue line's influence was ignored, and only the influence of adhesive layer on the properties of the composite was considered. The adhesive layer is assumed to be an isotropic wood veneer and with a thickness of 0.0025 mm (Bai *et al*. 1999).

Elastic modulus

The elastic modulus E of the laminated beam was calculated according to Eqs. 2, 4, and 6. The effect of span-to-height ratio of wood-bamboo composites on the elastic modulus was considered. The results are shown in Table 5. The absolute percentage error between predicted and measured mid-span deflection was calculated according to Eq. 7. The results are shown in Fig. 5.

Table 5. Predicted and Measured Modulus of Elasticity

L/H	CS E_{4x}/MPa	CS E_{4y}/MPa	FSDT E_{5x}/MPa	FSDT E_{5y}/MPa	FEM E_{6x}/MPa	FEM E_{6y}/MPa	Measured E_x/MPa	Measured E_y/MPa
10	11811.67	5578.88	9051.44	4876.50	11362.54	5271.52	10060	3932
15	11811.67	5578.88	10401.87	5243.23	11584.32	5455.97	11090	4420
20	11811.67	5578.88	10974.97	5384.97	11651.28	5511.01	11624	4703

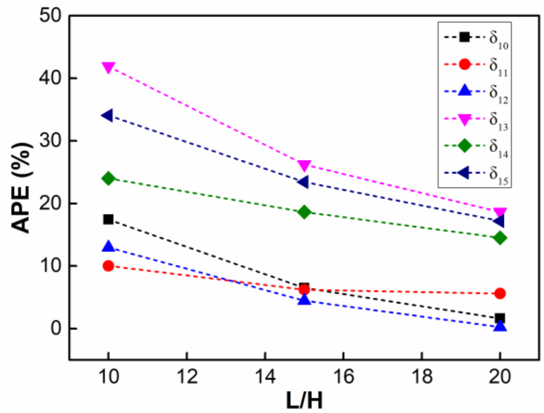

Fig. 5. The absolute percentage error between predicted and measured elastic modulus

As shown in Table 3 and 5, the adhesive layer does not affect the relationship between the elastic modulus and the span-to-height ratio. That is, the elastic modulus predicted by classical theory has nothing to do with the span-to-height ratio, and the elastic modulus predicted by the first-order shear theory and finite element method are increased with the increase in the span-to-height ratio. Compared with the elastic modulus without the adhesive layer, under the classical theory and first-order deformation theory, the transverse elastic modulus with the adhesive layer is greater than that without the adhesive layer, and others are uncertain. Under the classical theory, the longitudinal elastic modulus with the adhesive layer is smaller than that without the adhesive layer. This is inconsistent with our previous theoretical analysis. In the theoretical analysis, it was thought that the elastic modulus with the adhesive layer should be larger than that without the adhesive layer. Combining the formulas of Eqs. 2 and 4, and their derivation process, this is mainly due to the adhesive layer's influence on the stiffness of the laminated board being less than that on the moment of inertia of the section when the elastic modulus of the laminated board reaches a certain level. It is also possible that the elastic modulus of adhesive layer is lower than the longitudinal elastic modulus of wood veneer and higher than the transverse elastic modulus of wood veneer.

It can be concluded from Figs. 5 and 3 that the difference between δ_{10} and δ_1, δ_{11} and δ_2, δ_{12} and δ_3, δ_{13} and δ_4, δ_{14} and δ_5, and δ_{15} and δ_6 were within ±0.5%, which shows that the adhesive layer had little influence on the elastic modulus. Therefore, the adhesive layer can be ignored when predicting the elastic modulus. When L/H=20, the prediction error of longitudinal elastic modulus is less than 6%, and the prediction error of transverse elastic modulus is less than 19%, which shows that these three methods can be used to predict the elastic modulus of composites, and it is more suitable for predicting the longitudinal elastic modulus.

Mid-span deflection

The mid-span deflection ω of the laminated beam is calculated according to Eqs. 3, 5, and the ANSYS output result. The results are shown in Table 6. The absolute percentage error between predicted and measured mid-span deflection is calculated according to Eq. 7. The results are shown in Fig. 6.

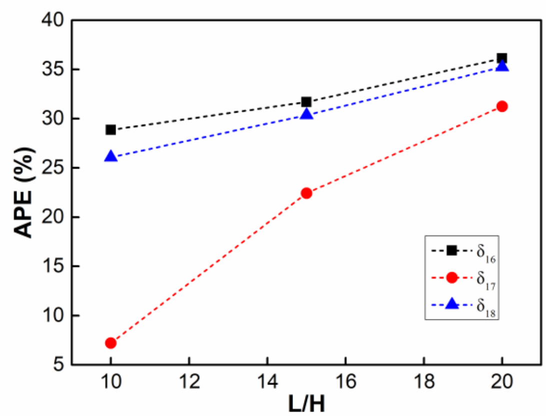

Fig. 6. The absolute percentage error between predicted and measured mid-span deflection

Table 6 shows that as the span-to-height ratio increased, the deflections calculated by the three methods increased geometrically. The mid-span deflection predicted by the three methods were relatively close. As shown in Fig. 6, the δ_{16}, δ_{17} and δ_{18} represent the absolute percentage error between the mid-span deflection predicted by classical theory, first-order shear deformation theory and finite element method, and the measured mid-span deflection respectively. As shown in Fig. 6, the absolute percentage error increases as the increase of the span-to-height ratio. As can be seen from Fig. 6 and 4, the differences between δ_{16} and δ_7, δ_{17} and δ_8, and δ_{18} and δ_9 all ranged from -0.1% to 0.3%, which shows that the adhesive layer had little influence on the mid-span deflection.

Table 6. Predicted and Measured Mid-span Deflection

L/H	CS ω_4/mm	FSDT ω_5/mm	FEM ω_6/mm	Measured ω/mm
10	1.757	2.292	1.826	2.47
15	5.929	6.733	6.045	8.68
20	14.054	15.125	14.247	22.00

CONCLUSIONS

1. The transverse shear effect affects the mechanical properties of the material. As the span-to-height ratio increases, the transverse shear effect becomes smaller and smaller.
2. The effect of the adhesive layer on the elastic modulus and deflection was ± 0.5% and -0.1% to 0.3%, and it was not necessary to consider the adhesive layer when predicting the elastic modulus and deflection. However, the adhesive layer is unavoidable in the process of perfecting the laminate model. In this respect, the adhesive layer is still worthy of continued research.
3. When L/H = 20, the prediction error of longitudinal elastic modulus is less than 6%, and the prediction error of transverse elastic modulus is less than 19%, which shows that these three methods can be used to predict the elastic modulus of composites, and it is more suitable for predicting the longitudinal elastic modulus.
4. On the basis of knowing the properties of component materials, it is feasible to predict

the properties of composite materials through theoretical calculations and numerical simulations, which can reduce the traditional trial production work and save a lot of manpower and material resources.

ACKNOWLEDGMENTS

The authors are grateful for the support of the National Natural Science Foundation of China (31660174), and the Guangxi Innovation-Driven Development Special Fund Project of China (AA17204087-16).

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Article submitted: June 28, 2021; Peer review completed: August 10, 2021; Revised version received and accepted: September 11, 2021; Published: October 4, 2021.
DOI: 10.15376/biores.16.4.7784-7798