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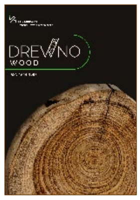

Dynamic Test and Analysis of Strength of Bamboo Curtain Plywood Based on Free Vibration Modal Method

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Bamboo curtain plywood is made of equal-thickness slotted bamboo slivers as its constituent units and is formed into boards with high pressure. In this paper, rectangular plates, beam specimens, and two sizes of square plates were tested to determine the elastic modulus and shear modulus of bamboo curtain plywood quickly, easily, and accurately. The free square board torsional vibration method was used to test the shear modulus of the square plates. The dynamic test results were also verified by means of the static four-point bending method. The main conclusions show that the dynamic elastic modulus, shear modulus and Poisson's ratio of this bamboo curtain plywood are 0.7 GPa, 1300 MPa and 0.12, respectively. The values of the elastic constants of these bamboo curtain plywood specimens measured by dynamic and static methods are consistent, and this dynamic test method has the advantages of fast, easy, good repeatability and high accuracy.

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Introduction

China is the main producer of bamboo in the world and has abundant bamboo resources. Nevertheless, unlike wood, at present bamboo is rarely used directly as building materials [Su et al. 2021]. Over the years, many scholars have carried out research on the technical feasibility of using bamboo to produce composite products with different structures [Ahmad and Kamke 2005; Quintero et al. 2022], including reconstituted bamboo and bamboo plywood. There are also cases of using bamboo products to reinforce existing buildings in the field of building protection [Chen et al. 2023; Li et al. 2023a].

A bamboo curtain is a kind of curtain made of woven flattened bamboo slivers. The flattened bamboo

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slivers are arranged in parallel and woven into a curtain. Bamboo curtain plywood is an artificial board used widely that is made of bamboo curtain and is formed into blanks with high pressure. Research has shown that bamboo fibers have good tensile and bending resistance [Zhao et al. 2023; Ahmad et al. 2023]. In the field of construction, it can be used as a filling material to improve material performance when combined with other materials. Bamboo plywood inherits this characteristic and has high hardness, good flexural resistance and good compression resistance, thus it has been used in many applications [Guan et al. 2018; Dauletbek et al. 2023; Li et al. 2023b]. It is also widely utilized in many kinds of containers, packing boxes, car and train car floors, household floors, indoor ceilings, door panels, furniture and other fields [Su et al. 2021; Dauletbek et al. 2021; Mimendi et al. 2022]. Bamboo has the characteristics of a short growth cycle and strong regeneration [Guo 2007a; Liu et al. 2022], which greatly reduces the raw material cost of bamboo plywood production [Chen 2003]. Therefore, using bamboo to make bamboo plywood to replace wood or non-recyclable materials not only saves resources, but also protects the environment, and has good economic and social benefits [Ghavami 2008]. However, at present, there are several national and international scholars and enterprises that study bamboo plywood mainly regarding traditional production technology [Guo 2007b; Gao et al. 2012; Li et al. 2020], ignoring the importance of quality inspection methods and the effective application of bamboo plywood.

The elastic modulus, shear modulus and Poisson's ratio are significant elastic constants to measure the mechanical properties of bamboo plywood [Dauletbek et al. 2021; Karampour et al. 2018]. According to the requirements of the current specification "Bamboo-mat Plywood" [GB/T 13123:2003] and "Wood-based panels – Characteristic values for structural design – Part 2: Plywood" [EN-12369-2:2004], the static failure test is generally used in the industry to ascertain the elastic constant and failure mechanism of bamboo plywood [Zhang et al. 2015; Zhou et al. 2016; Darzi et al.2020]. Wu et al. [Wu et al. 2012] determined the elastic modulus, shear modulus and Poisson's ratio of bamboo woven plywood by means of three-point bending and four-point bending failure test methods. Li [Li 2013] analyzed the mechanical properties of bamboo mat plywood and moso bamboo (Phyllostachys edulis (Carriere) J. Houzeau) sheet materials utilizing the three-point bending test, tensile shear test, along-grain tensile-compression test, and cross-grain tensile test methods.

In recent years, many results have been obtained using the dynamic vibration method to test the elastic constants of wood [Wang et al. 2015; Zhou et al. 2021] and solid wood composites [Wang et al. 2014; Dong et al. 2021]. At same time, much research has employed probabilistic methods to study the mechanical properties of materials [Peng et al. 2018; Wang and Ghanem 2021 and 2022]. Wang et al. [Wang et al. 2018] adopted the cantilever plate transient excitation method, and performed dynamic synchronous testing to ascertain the elastic modulus, shear modulus and Poisson's ratio of wood and medium density fiberboard (MDF) by improving the attachment method of strain gauges. Giaccu et al. [Giaccu et al. 2019] dynamically determined the elastic modulus and rolling shear modulus of 3-layer cross laminated timber (CLT) based on the cantilever plate transient excitation method, and by means of finite element analysis found that this method reflects the global elastic characteristics of CLT to some extent. It overcomes the influence of local defects of materials on the elastic modulus test; hence, this method is more suitable for practical application conditions. Predictably, the dynamic determination of elastic constants has been proved to be a commonly used and successful method, and its measurement results are consistent with those of traditional static methods. In contrast, static methods can cause damage to the material, and their operation is cumbersome, relying on high-cost equipment and highly-skilled personnel. Therefore, it is very important to introduce a fast, simple, accurate and reliable dynamic vibration method to determine the elastic constants of bamboo plywood.

Materials and methods

In this study, elastic modulus E and shear modulus G of longitudinal and transverse bamboo curtain plywood specimens were measured by the free plate transient excitation method. The E and G of the square plate specimen were ascertained by the free plate modal method, and G was determined by the free square board torsional vibration method. Finally, the static four-point bending method test was used to verify the accuracy and reliability of the E and G of the bamboo curtain plywood specimens measured by the dynamic test, and the Poisson's ratio μ of the material was ascertained.

Bamboo curtain plywood, 1 piece, 2440 mm (l)×2440 mm (b)×12 mm (h), was manufactured by Fujian Xinhengda Compartment Backplane Co., Ltd. A bamboo curtain is a kind of curtain made of woven flattened bamboo slivers. The flattened bamboo slivers are arranged in parallel and woven into a curtain. The technological process is: raw material → slicing → bamboo curtain → drying → dipping → twice drying → assembling (as shown in Figure 1(a)) → hot pressing

→ trimming → packaging. The raw material is moso bamboo. The outermost layer (average thickness 1.5-1.8 mm) close to the bamboo bark is used to be sliced into 15 mm wide bamboo slivers. The bamboo slivers are arranged in parallel to form a single-layer board structure (bamboo curtain). The arrangement directions are perpendicular to each other. The thickness of the center layer of the board is 2.5 mm, the thickness of the remaining layers is 1.8 mm, the two sides are decorated with thin wood, and the thickness of the finished bamboo curtain plywood is 12 mm (±0.5 mm). The actual bamboo curtain plywood product is employed as construction panels. The pattern surface of bamboo curtain plywood is defined as the P surface and the wood grain surface as the N surface, as shown in Figure 1(b). The N-side has a thin wood surface, while the P-side has a thin wood and abrasion-resistant, patterned and impregnated paper surface.

a. Photo from production

b. Definition of P and N sides of bamboo curtain plywood

Fig. 1. Bamboo curtain plywood

In this study, the length direction of the bamboo sliver in the center layer of the bamboo curtain plywood is defined as the longitudinal direction (x-direction) and the direction perpendicular to this direction is defined as the transverse direction (y-direction) as shown in Fig. 2.

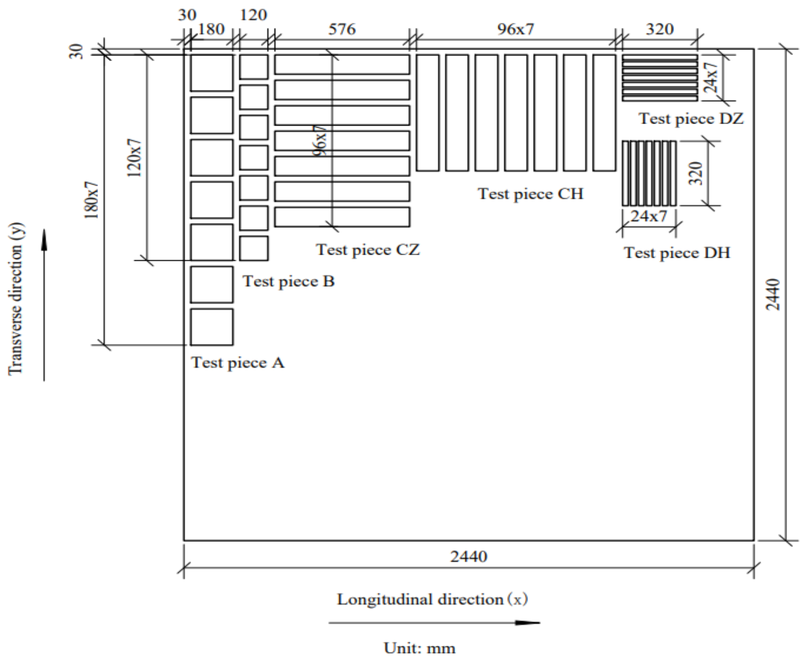


Fig. 2. Blanking diagram of bamboo curtain plywood specimen

1. Dynamic testing of elastic modulus and shear modulus

Free-plate modal test

In order to ensure the accuracy of the first-order bending and torsion frequencies of the parts determined by the free-plate transient excitation method, the free-plate modal test method was conducted. The specimen was divided into 2×6 meshes, and the number of measurement nodes is 21, as shown in Figure 3. Put the 1-channel accelerometer in position 3, hang the plate, build the geometric model and set the parameters. Hit the 2-channel force hammer on the plate, observe whether the waveform was normal with an oscilloscope, and then test and collect the data from Point 1. Finally, we moved the 2-channel hammer to hit the position of Point 2 to collect data and test the remaining 19 points as above. The mode shape was simulated after initial estimation of the parameter, curve fitting, measurement direction processing, constraint equation processing, and mode shape normalization. According to the characteristics of the mode shape animation, the required first-order bending and torsional frequencies can be analyzed.

1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21

Fig. 3. Mesh division diagram

Free plate transient excitation test: Dynamic measurement of elastic modulus and shear modulus by dynamic method

The elastic modulus value was obtained by the free-plate transient excitation method according to the transverse bending theory of Euler beams. The relationship between the first-order bending frequency of the free beam and elastic modulus E is shown in Eq. 1 [Timoshenko 1965].

$$E = 0.9462\rho \frac{l^4 f_{1b}^2}{h^2} \qquad (1)$$

Where ρ is the density (kg/m^3); l is the length of the free plate (m); f_{1b} first-order bending frequency of the free plate (Hz); h is the thickness of the free plate (m).

Using the free plate mode coefficient γ in the free plate torsional mode method, the free plate mode coefficient of bamboo curtain plywood is calculated, and shear modulus G is obtained.

The relationship between the first-order torsional frequency of the free plate and the shear modulus is shown in Eq. 2 [Wang et al. 2019a].

$$G = \frac{\pi^2 \rho (l/2)^2 b^2 f_{1t}^2}{\gamma \beta h^2} (l/b = 1\sim 8) \qquad (2)$$

Where ρ is the density (kg/m^3); l is the length of the free plate (m); b is the width of the free plate (m); f_{1t} is the first-order torsional frequency of the cantilever plate (Hz); γ is the mode shape coefficient of the free plate, which can be calculated by the width-to-length and thickness-to-width ratios of the free plate;

$$\beta \approx \frac{1}{16}\left[\frac{16}{3} - 3.36\frac{h}{b}\left(1 - \frac{h^4}{12b^4}\right)\right].$$

Free plate mode coefficient γ adopts Eqs. 3 and 4 (Wang et al. 2019a):

Endwise:

$$\gamma = 7.4539\left(1 - 0.1187\frac{b}{l} + 0.6013\frac{b^2}{l^2} - 0.3824\frac{b^3}{l^3}\right) \qquad (3)$$

Broadwise:

$$\gamma = 7.4119\left(1 - 0.0184\frac{b}{l} + 0.0565\frac{b^2}{l^2} + 0.1023\frac{b^3}{l^3}\right) \qquad (4)$$

The test principle is as follows: Suspend with cowhide tendons at a distance of 0.224L and 0.776L from one end of the bamboo curtain plywood specimen to realize the free constraint condition and fix the accelerometer at the corner of the board to connect the CRAS vibration and dynamic signal acquisition and analysis system and its SsCras signal analysis software. The free vibration of the plate was stimulated by hammering the corner points of the specimen so that the accelerometer would receive the vibration signal and convert it into an electrical signal for output. The AZ-802 signal conditioner amplified and filtered the electrical signal and then inputted it to the acquisition box. The analog signal was converted into a digital signal by AD conversion. The frequency spectrum of the specimen was then processed by the dynamic signal acquisition and analysis system software SsCras, from which the first-order bending and first-order torsion frequencies of the specimen can be read [Wang et al. 2019b; Wang et al. 2016]. Finally, substitute its frequency value into Eqs. 1 and 2 to calculate the E and G of bamboo curtain plywood, as shown in Figure 4.

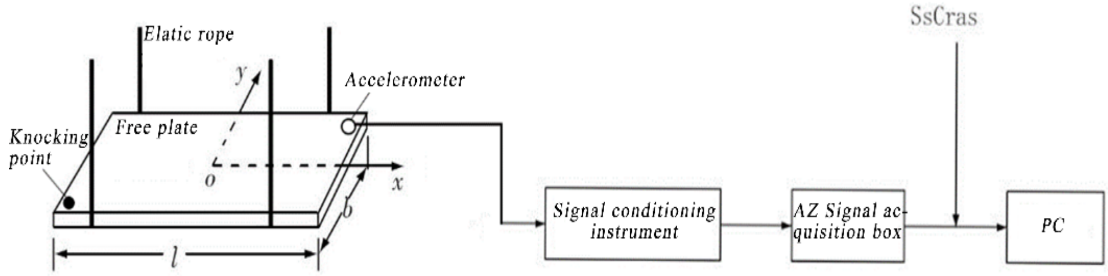


Fig. 4. Block diagram of free plate transient excitation test system

The test principle is that the square plate was suspended with two elastic ropes that cross each other. One elastic rope extended along the length direction of the square plate and was located in the middle position in the width direction of the square plate, and the other elastic rope extended along the width direction of the square plate and was located in the middle position in the length direction of the square plate. The accelerometer was installed on the upper surface of the square plate at a distance of 3/8 l from the corner point along the length direction, and the square plate was excited to vibrate freely by hammering the corner point on the upper surface of the square plate so that the accelerometer received the vibration signal and converted it into an electrical signal for output. After amplifying and filtering the electrical signal, it was converted by AD, and the first-order torsion frequency f_{1t} of the specimen was read from the frequency spectrum, and the shear modulus value could be obtained, as shown in Figure 5. The relationship between the first-order torsion frequency of the free beam and shear modulus G is as shown in Eq. 5 [Wang et al. 2019a].

$$G = \frac{\pi^2 \rho}{32.48\beta}\left(\frac{lb}{h} f_{1t}\right)^2 \qquad (5)$$

Where ρ is the density (kg/m^3); l is the length of the free square plate (m); b is the width of the free square plate (m); f_{1t} is the first-order torsional frequency of the free square plate (Hz); h is the thickness of the free square plate (m);

$$\beta \approx \frac{1}{16}\left[\frac{16}{3} - 3.36\frac{h}{b}\left(1 - \frac{h^4}{12b^4}\right)\right].$$

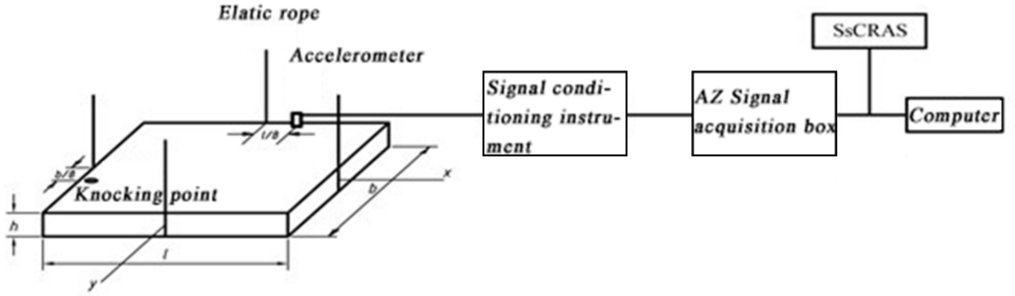


Fig. 5. Block diagram of free square board torsional vibration test system

Static verification tests for elastic modulus, shear modulus and Poisson's ratio

The symmetrical four-point bending beam (*l*/3-*l*/3-*l*/3 loading), the normal stress at each point on the upper and lower surfaces of the beam in the pure bending section is as shown in Eq. 6 [Wang et al. 2023].

$$E = \frac{\Delta P \cdot l}{bh^2 \Delta\varepsilon_x} \quad (6)$$

Where ΔP is the load increment (N); l is the length of the beam (m); b is the width of the beam (m); h is the thickness of the beam (m); $\Delta\varepsilon_x$ is the longitudinal strain increment (μmm).

The symmetrical four-point bending beam (l/3-l/3-l/3 loading), if the test values of the transverse strain and longitudinal strain at the center point of the upper and lower surfaces of the beam in the pure bending section are ε_y and ε_x, respectively, Poisson's ratio can be written as:

$$\mu = -\frac{\Delta\varepsilon_y}{\Delta\varepsilon_x} \quad (7)$$

Where $\Delta\varepsilon_x$ is the longitudinal strain increment (μmm); $\Delta\varepsilon_y$ is the transverse strain increment (μmm).

Attach 90° (longitudinal) and 0° (transverse) strain gauges to the center points of the upper and lower surfaces of the beam specimen. A symmetrical four-point bending load was applied to the beam, and the longitudinal and transverse strains at the center point were measured. A weight of 1.275 kg was placed on the auxiliary beam three times to apply a load to the four-point bending system, and the software was used to record the strain value of the specimen after each placement of the weight for the subsequent calculation.

The loading schematic diagram of the asymmetric four-point bending beam is shown in Figure 6. The asymmetric four-point bending beam method determines the shear modulus of a material based on Hooke's law for shear stress and the formula for calculating the maximum shear stress at a point on the neutral axis of a beam with a rectangular section. The shear modulus was derived by measuring the shear strain at a point on the neutral axis.

According to Hooke's law for shear stress, shear modulus G can be expressed as:

$$G = \frac{3\Delta P}{8bh\Delta\varepsilon} \quad (8)$$

Where ΔP is the load increment (N); b is the width of the beam (m); h is the thickness of the beam (m); $\Delta\varepsilon$ is the strain increment readings for full bridge measurements (μmm).

45° strain gauges were attached at the center points of the front and rear side surfaces of the beam specimen. The beam was subjected to an asymmetrical four-point bending load, and the shear strain at the center point was measured. +45° and -45° strain were gauged on the front and rear side surfaces of the beam occupying one channel of the strain gauge according to the full bridge method.

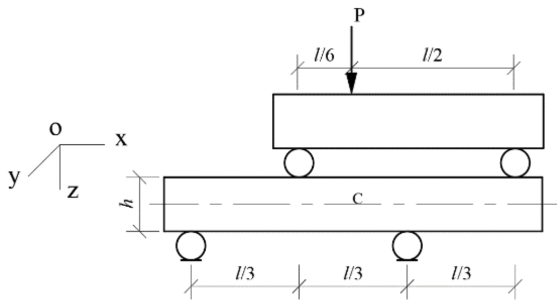


Fig. 6. Schematic diagram of test device for asymmetrically loaded four-point bending beams

Results and discussion

1. Results and analysis of free plate specimen

All of the specimen CZ and CH were selected for testing, and the first-order bending frequency and first-order torsion frequency of the bamboo curtain plywood specimen were preliminarily determined. It is clear that the first-order bending frequency of CH-1 in the free state is 106.5 Hz, and the first-order torsional frequency is 266.7 Hz, as shown in Figure 7.

Figure 8 shows the frequency spectrum of the CH-1 free plate specimen. The first order bending frequency is 106.3 Hz, and the first-order torsional frequency is 265.0 Hz, which are basically consistent with the frequencies measured in the suspension mode. Table 1 shows the results of the free-plate modal test and the transient test, which are within 2% error, fully demonstrating the accuracy of the transient test.

a. First-order bending mode b. First-order torsional mode

Fig. 7. CH-1 first-order mode diagram

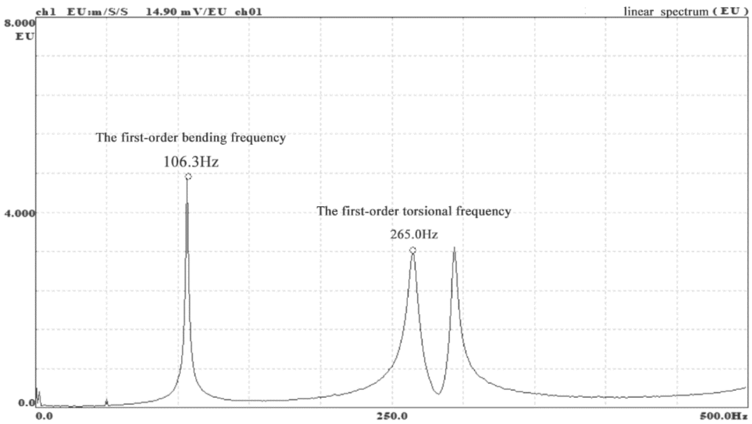


Fig. 8. CH-1 strain spectrum

Table 1. Free plate modal and transient test results

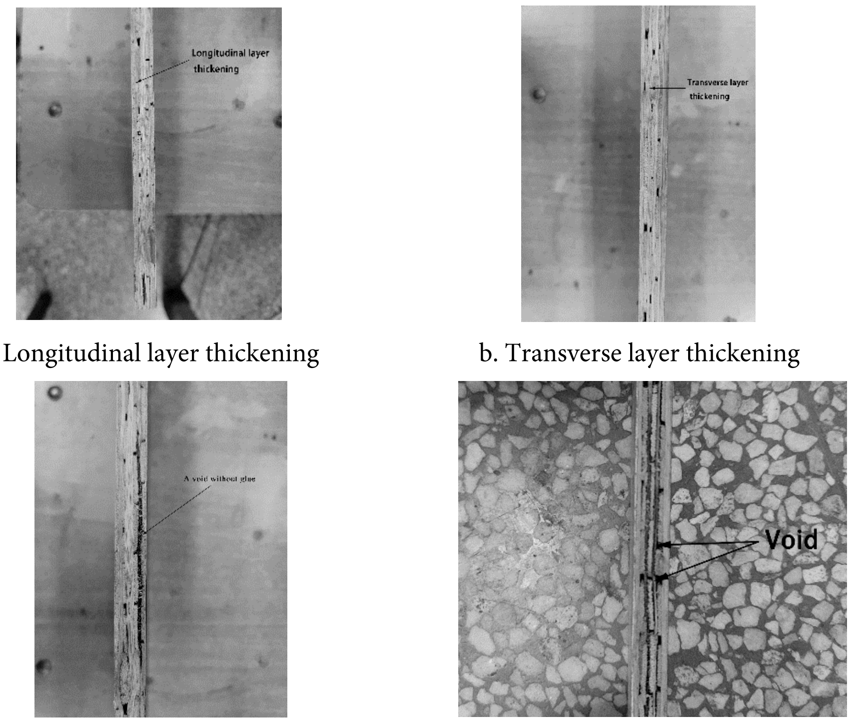
Specimen	*E*/MPa			*G*/MPa		
	Modal	Transient	Deviation	Modal	Transient	Deviation
CH	7866	7836	-0.3%	1402	1384	-1.3%
CZ	7010	7022	0.2%	1343	1320	-1.7%

The average elastic modulus E_y of the CH specimens measured by the transient test is 7836 MPa (COV: 9%), and shear modulus G_{yx} is 1384 MPa (COV: 4.31%). The measured average elastic modulus E_x of the CZ specimen is 7022 MPa (COV: 9.8%), and shear modulus G_{xy} is 1320 MPa (COV: 4.31%). According to the results, it is proved that the elastic modulus of this bamboo curtain plywood has a large variability, which is mainly due to technical (the processing precision is not high enough, hence the manual screening method and manual grouping Pi are used) and material reasons (the thickness of the bamboo wall decreases gradually from the root to the top, thus it is difficult to keep the thickness of the bamboo slivers consistent even after planing). The average elastic modulus of the transverse plates E_y is 10.3% larger than E_x of the longitudinal plates; the average shear modulus of the transverse plates is 4.6% larger than that of the longitudinal plates, while the average first-order bending frequency and average first-order torsional frequency are essentially similar.

The bamboo curtain plywood board structure is a 7-layer orthogonal structure, and a thin wood decorative layer is attached to the outer side. Before hot pressing, the central layer is 2.5 mm thick, while the remaining layers are 1.8 mm thick. Theoretically, the longitudinal layer has fewer glue seams in the length direction, thus the elastic modulus will be better than that of the transverse layer. For this kind of bamboo curtain plywood with a 7-layer orthogonal structure, the theoretical elastic modulus of the transverse board CH with 4 longitudinal layers is slightly larger than that of the longitudinal board with only 3 longitudinal layers. However, this structure determines that the thickness of the longitudinal layer of the transverse plate is 7.2 mm, and the thickness of the longitudinal layer of the longitudinal plate is 6.1 mm, and the result is the thickness before hot pressing. Since bamboo is a vascular bundle structure and the bamboo slivers have a certain radian, it will shrink to a certain extent after hot pressing. Due to the fact that the thickness of the bamboo wall decreases gradually from the root to the top, it is difficult to maintain the thickness of the bamboo slivers. This leads to some panels where the thickness of the vertical layer in some locations exceeds the design thickness. Alternatively, as the thickness of the horizontal layer exceeded the design thickness in some locations, that section squeezed the vertical layer, resulting in a thinner vertical layer thickness in that other section. This is shown in Figure 9(a) and Figure 9(b).In the test, this is directly reflected in the first-order bending frequency of the sheet; the thickness of the vertical layer significantly increases the elastic modulus, and the thickness of the horizontal layer reduces the elastic modulus.

There are some voids without glue in some plates, as shown in Figure 9(c), which directly affected the internal bonding strength of the plates and reduced the elastic modulus of the plates. This is because the raw material of the bamboo curtain plywood is mainly selected from the outermost bamboo middle layer close to the bamboo outer layer, and the poor craftsmanship results in some bamboo outer layer tissue remaining on the base bamboo slivers. The bamboo outer layer contains silica cells, and the silicon component affects the penetration of the adhesive, which eventually leads to glue failure in some places.

In addition, due to technological reasons, there are holes and voids visible to the naked eye on the plate, as shown in Figure 9(d). These voids directly lead to an increase in the porosity of the sheet and a decrease in the density, making the average density of the CZ specimens 6.2% lower than that of the CH specimens. It can be seen that the density of bamboo curtain plywood has a major influence on its elastic modulus and shear modulus.



a. Longitudinal layer thickening

b. Transverse layer thickening

c. Void without glue

d. Voids

Fig. 9. Material and process defects of bamboo curtain plywood

The above reasons in the three previous paragraphs lead to the result that the elastic modulus of the transverse plate CH specimen is 10.3% larger than the average elastic modulus of the longitudinal plate CZ specimen in the dynamic test of the bamboo curtain plywood.

Since the shear modulus is an elastic constant that reflects the in-plane properties of the material, the shear modulus measured in this test is the shear modulus of the xy plane, hence it has nothing to do with the length of the specimen. The results also confirm that the only factor affecting the shear modulus of the transverse and longitudinal plates is the density of the plates. The torsional shear modulus in the xy plane can reach more than 1300 MPa, and it has good torsion resistance. This proves its high resistance to lateral forces and is suitable for use as panels in building structures.

2. Results and analysis of free beam specimen

In order to verify whether the material has an undercut location effect and facilitates static verification, the longitudinal beam specimen DZ and the transverse beam specimen DH were cut out from other places in the original whole plate. The free transient excitation test was carried out on it, and the vibration spectrum was obtained. In addition, the first-order bending frequency was obtained by spectrum identification, and the elastic modulus was calculated.

The calculated average elastic moduli of the longitudinal beams E_x is 6565 MPa (COV: 6.4%) and the transverse beams E_y is 7707 MPa (COV: 7.1%). The elastic modulus of the transverse beam E_y is 15.2% larger than that of the longitudinal beam E_x, and the first-order bending frequency of the transverse beam is 11.6% larger than that of the longitudinal beam.

Because the size of the beam specimen is smaller than the size of the plate, it has fewer defects than the plate. According to Eq. 1, it can be seen that the first-order bending frequency is the most important factor affecting the elastic modulus. When the difference of the first-order bending frequency of the beam specimen is large, even if the density of the DH specimen is 4.8% smaller than that of the DZ specimen, the elastic modulus of the DH specimen is still better than that of the DZ specimen.

Table 2. Beam specimen density and elastic modulus comparison table

Specimen	ρ/kg*m^{-3}	E/MPa	Specimen	ρ/kg*m^{-3}	E/MPa
DH-1	776	8139	DZ-1	798	6195
DH-2	753	8416	DZ-2	868	7388
DH-3	768	7079	DZ-3	773	6082
DH-4	778	7802	DZ-4	773	6559
DH-5	732	6903	DZ-5	808	6465
DH-6	773	7673	DZ-6	807	6686
DH-7	760	7941	DZ-7	787	6578

It is known from Table 2 that the density of the beam specimen affects the value of the elastic modulus. The higher the density of the same beam specimen, the smaller the void, and the larger the elastic modulus.

3. Dynamic test results and analysis of shear modulus by free square board torsional vibration method

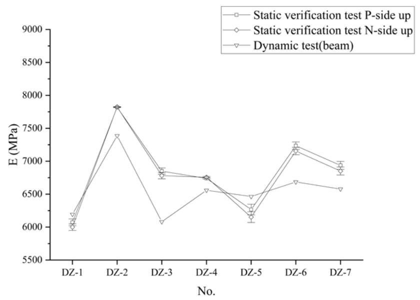
In order to study whether the bamboo curtain plywood is affected by the size effect, a square board with an aspect ratio of 1 and a rectangular board with an aspect ratio of 6 were used for comparison. Two kinds of square plates were used to test their shear modulus, and they were divided into two types of specimens, A and B, according to their size.

Calculate the shear modulus of each plate specimen according to Eq. 5. The average shear modulus of the A square plate with a length and width of 180 mm is 1424 MPa (COV: 4.5%), and the average shear modulus of the B square plate with a length and width of 120 mm is 1381 MPa (COV: 6.9%). The average elastic modulus (E_x) of the A square plate is 7155 MPa (COV: 4.5%) and E_y is 8235 MPa (COV: 7.0%). The elastic modulus of the B square plate specimen was not tested.

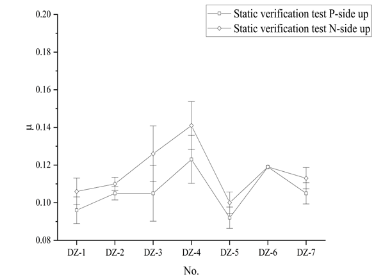
From the above results, it can be seen that the shear modulus of the 180 mm square plate A is 3.1% larger than that of the 120 mm square plate B. The results are basically consistent with the results of the free-hanging transient excitation test of the rectangular plate. There is a certain difference between the square plate elastic modulus and the results of the rectangular plate free suspension transient excitation test. The deviation is about 4%. The differences that exist are mainly a consequence of plate uniformity and dimensional differences.

4. Static Verification Test Results and Analysis of Elastic Modulus, Shear Modulus and Poisson's Ratio

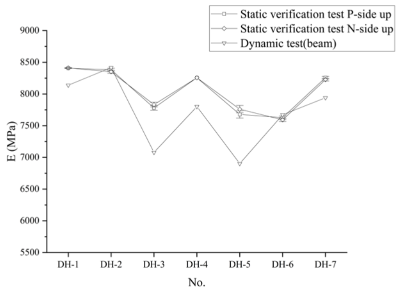
In order to verify the accuracy of the elastic modulus of the bamboo curtain plywood specimen in the dynamic test, the static symmetrical four-point bending method was used for the test. This paper mainly compares the dynamic and static elastic moduli of the DZ and DH beam specimens and tests the static Poisson's ratio of the beam specimens as the basis for judging whether the bamboo curtain plywood is anisotropic. Considering the poor uniformity of the bamboo curtain plywood itself, and the fact that bamboo as a natural material, the outer layer is close to the bamboo outer layer and the inner layer is close to the bamboo inner layer, there are certain structural differences in the cell tissues on both sides. During the test, two groups of tests were carried out, namely, P-side up and the N-side up groups of tests. The P-side and N-side are shown in Fig. 1. The specific results are shown in Figure 10.



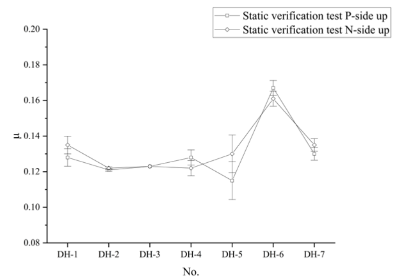
a. Elastic modulus of DZ specimen



b. Poisson's ratio of DZ test piece



c. Elastic modulus of DH specimen



d. Poisson's ratio of DH test piece

Fig. 10. Summary of static symmetric four-point bending test results

It can be seen from Figure 10 that the average longitudinal elastic modulus E_x of the beam specimen measured by the symmetrical four-point bending test is 6817 MPa, and the average transverse elastic modulus E_y is 8059 MPa. The elastic modulus of the longitudinal beam is 15.4% smaller than that of the beam, and the Poisson's ratio of the longitudinal beam is 15.1% smaller than that of the beam. During the test, flipping the upper and lower surfaces of the specimen has little effect on the test results. The coefficients of variation of the test values of E_x and E_y were all less than 5%, which confirm the reliability of the test.

In order to verify the accuracy of the dynamic test, a static asymmetric four-point bending test was carried out to verify the shear modulus.

Calculate the shear modulus of each plate specimen according to Eq. 8. It can be seen that the average value of *Gxy* measured by the asymmetric four-point bending test of the beam specimen is 1298 MPa, and the average value of *Gyx* is 1370 MPa, both of which are the shear modulus in the xy plane, and the test results differ by only 5.3%. The coefficients of variation of the test values of *Gxy* and *Gyx* were all less than 2.5%, which confirmed the reliability of the test.

The dynamic test and static test results of the composite beam specimens are presented in Table 3 and Table 4.

It can be seen from Table 4 that the dynamic elastic modulus of the longitudinal beam specimen is 3.7% smaller than the static elastic modulus, and the dynamic elastic modulus of the transverse beam specimen is 4.3% smaller than the static elastic modulus. The accuracy of the dynamic free-hanging transient excitation test can be confirmed. The test deviations of the longitudinal and transverse elastic modulus values of the beam specimens in each test are similar, which confirms the reliability of each test. The elastic modulus of the static longitudinal beam is 15.4% smaller than that of the transverse beam, which is very close to that of the dynamic beam, and is 15.2% smaller than that of the transverse beam. It can be seen that this bamboo curtain plywood is an anisotropic material.

The shear modulus of the free-hanging longitudinal slab is 6.7% and 1.3% smaller than that of the asymmetric longitudinal and transverse beams, respectively. The shear modulus of the free square plate A is 9.8 and 4.0% larger than that of the asymmetric four-point bending longitudinal beam and transverse beam, respectively. The shear modulus of the free square plate B is 6.5% and 0.8% larger than that of the asymmetric four-point bending longitudinal beam and the transverse beam, respectively. The longitudinal and transverse shear moduli are both shear moduli in the xy plane. The test results of the two are similar, and the deviations of the dynamic and static test results are within 10%, which confirms the reliability of the dynamic test results.

Table 3. Dynamic and static test results of beam specimens' *E*

Specimen direction	*E*/MPa			
	Free plate transient excitation		Free square plate A	Symmetrical four-point bending
	Plate	Beam		
Longitudinal	7022 (9.8%)	6565 (6.4%)	7155 (4.5%)	6817 (8.8%)
Transverse	7836 (9.0%)	7707 (7.1%)	8235 (7.0%)	8059 (4.1%)

Note: coefficient of variation of test results is in brackets

Table 4. Dynamic and static test results of plate and beam specimens' G

Specimen direction	G/MPa			
	Asymmetrical four-point bending	Free square plate A	Free square plate B	Free plate
Longitudinal	1298 (6.9%)	1424 (4.5%)	1381 (6.9%)	1384 (4.3%)
Transverse	1370 (6.3%)			1320 (4.8%)

Note: coefficient of variation of test results is in brackets

Table 5. Principal elastic constants of 7 tree species[Yin 1996] and LVL

Varieties	E_L /GPa	E_R /GPa	G_{XY} /GPa
Picea asperata Mast.	11.6	0.90	0.75
Pinus sylvestris L.	16.3	1.10	1.16
Fagus longipetiolata Seemen	13.7	2.24	1.61
Pseudotsuga sinensis Dode	16.4	1.30	1.18
Fraxinus excelsior L.	15.8	1.52	1.31
Swietenia mahagoni (L.) Jacq.	12.4	0.97	0.61
Ochroma lagopus Sw.	6.3	0.30	0.31
Laminated veneer lumber (LVL)	10.8	0.47	1.08

From Table 5, the principal modulus of elasticity E_L of all solid wood panels except *Ochroma lagopus* Sw. is larger than the principal modulus of elasticity E_y of the bamboo curtain plywood, which is mainly because the laminates of the bamboo curtain plywood in this paper adopt an orthogonal structure, where the length direction (principal direction) of the adjacent laminates is perpendicular to each other. The main reason for this phenomenon is that the structure of the bamboo curtain plywood is orthogonal, with the lengths of the adjacent plies perpendicular to each other, and the main direction of it is slightly weaker than that of the solid wood and an LVL with a smooth ply arrangement, but the E_x is much larger than that of the other panels in the table owing to the orthogonal structure. This is demonstrated by the fact that the bamboo curtain plywood has better resistance to lateral forces. Also, the shear modulus of bamboo curtain plywood is higher than most of the materials in the table, especially LVL, which is also a wood engineering material. The orthotropic structure of bamboo veneer and the bamboo fibers together contribute to this phenomenon. The orthogonal structure itself is considered to have good torsional properties. It is also widely accepted in academic circles that the mechanical properties of bamboo fibers are superior to those of wood fibers. As a result, a bamboo curtain bamboo vinyl sheet has strong bending and tensile resistance, along with excellent resistance to lateral forces and torsion.

Conclusions

The aim of this study was to attempt to apply the non-destructive testing of bamboo plywood in production activities to be used directly on the production line. By tapping on bamboo plywood to generate a vibration, the machine automatically collects key frequencies and calculates parameters such as the elastic modulus, the quality of the board can be quickly graded. By utilizing relevant equipment, products can be quickly classified, which can reduce the labor demand of factories, improve work efficiency, and promote technological upgrading in the bamboo and wood industry. The conclusions are as follows:

The elastic modulus and shear modulus of bamboo curtain plywood measured by the free-plate transient excitation method are consistent with the modal test results. The average values of the elastic modulus, shear modulus and Poisson's ratio of bamboo curtain plywood in the dynamic test are 0.7 GPa, 1300 MPa and 0.12, respectively, all of which meet the requirements in GB/T13123-2003 and EN-12369-2-2004.

The ratio of the transverse to longitudinal elastic modulus is 1:1.15. Because of its orthogonal structure, bamboo plywood has better lateral force properties and torsion resistance. This also leads to the fact that bamboo plywood can be used in more applications than common wooden materials.

The elastic constant error of the bamboo curtain plywood beam specimen measured by the dynamic and static methods is less than 7%, indicating that the bamboo curtain plywood dynamic test has the characteristics of high accuracy and good reliability. The method has fewer test limitations, does not require larger equipment or sites, and does not damage the material. It is even possible to directly test larger specimens or entire plates of material with the same equipment. This is not possible with static testing. Owing to its fast testing, accurate results and small requirements on material dimensions, the method is more suitable for application in practical production.

The bamboo curtain plywood tested in this experiment has a large size effect, and the main reason for this phenomenon is that the production process precision of the bamboo curtain plywood is not high, and the homogeneity of the raw materials is poor. For this phenomenon, the following suggestions are made. Improve the thickness planing accuracy of bamboo slivers and improve their width selection so as to reduce the bending degree of the bamboo slivers. It is recommended to reduce the spacing of the bamboo sheets and the size of the glue joints when forming the bamboo sheets.

The values of the elastic constants of the bamboo curtain plywood specimens measured by the dynamic and static methods are consistent, and this dynamic test method has the advantages of a fast and easy procedure, good repeatability and high accuracy.

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List of standards

GB/T13123-2003 Bamboo-mat plywood

EN-12369-2-2004 Wood-based panels – Characteristic values for structural design – Part 2: plywood