Flexural Vibration Test Method for Determining the Dynamic Elastic Modulus of Full-Size Strawboards for Use in Transportation Framed Cases

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This paper proposes an improvement in the test method for determining the flexural dynamic modulus of elasticity of strawboard with two triangular prisms as supports, for quality control and classification. Free-plate modal and free-plate transient excitation methods were used to test the elastic modulus of 1/4-plate and whole-plate strawboards. The dynamic test results were verified with the four-point bending method and tensile method. The results show that the elastic moduli of strawboards is approximately 2 GPa. The dynamic test method proposed is efficient, simple, repeatable, and accurate. This method is more suitable for factory applications than existing dynamic testing methods. The framed cases produced by the strawboard all meet the performance requirements in GB/T 7284 (2016).

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INTRODUCTION

China is largely an agricultural country and the first commercial straw-producing country in the world (Bi *et al*. 2018; Peng *et al*. 2018; Fang *et al*. 2021). According to the United Nations Agri-Food Organization (FAO) statistics, the total global straw production is 5,081 million tons, while the total annual production of straw in China reaches 940 million tons, accounting for 18.5% of the total world production (Zhang *et al*. 2015; Li *et al*. 2020; Jiang *et al*. 2021; Zhu *et al*. 2021). If 1% of its production can be used, the country can produce 6 to 12 million m^3 of wood-based panels, replacing 18 to 36 million m^3 of logs. Due to the lack of critical technological innovation and cost-cutting methods in the extensive usage of straw resources, its development has been deferred for a long time.

Strawboard has good sound and heat insulation properties, low density, high strength, and is non-toxic and non-hazardous. According to GB/T 27796 (2011), strawboard quality inspection and evaluation work in China mainly has adopted manual visual inspection and static sampling test methods (Ponzo *et al*. 2021; Jiang *et al*. 2022; Zhang *et al*. 2022). Azizi *et al*. (2011) conducted a static bending test on strawboards made from straw and scrap veneer chips. An increase in the content of waste veneer chips significantly reduced the modulus of rupture (MOR) of the boards but increased the modulus of elasticity (MOE). Wu *et al*. (2015) tested the MOR and the MOE of corn strawboards using the three-point bending method and found that the average range of the MOE of corn strawboards was 1.4 to 1.8 GPa. The static sampling method mainly uses the sampling and testing method, which cannot reflect the specific gaps in the same batch of products, and it cannot meet the requirements of many industries for grading the quality of strawboards (Mo *et al*. 2003; Boquillon *et al*. 2004; Tabarsa *et al*. 2011).

The application and promotion of non-destructive testing technology reflect the level of industrial development of a country (Wang *et al*. 2015, 2019a; Liu *et al*. 2022). Many studies have used probabilistic methods to evaluate the mechanical properties of materials (Wang *et al*. 2021, 2022, 2023). In recent years, many achievements have been made in testing the elastic constants of wood and wood composites using the dynamic vibration method (Dauletbek *et al*. 2021; Zhong *et al*. 2021; Zhou *et al*. 2021). Wang *et al*. (2018) used the cantilever plate transient excitation method to simultaneously determine the elastic modulus, shear modulus, and Poisson's ratio of wood and medium-density fiberboard (MDF) by improving the strain gauge attachment method. Giaccu *et al*. (2019) tested the elastic modulus and rolling shear modulus of a 3-layer cross-laminated timber (CLT) based on the cantilever plate transient excitation method. However, there has been a lack of research on non-destructive testing (NDT) methods in the field of strawboard. The mechanical property tests used in most studies are based on the test methods in EN 310 (1993), and the NDT method was not investigated.

This paper analyzed the dynamic testing of the elastic modulus E of strawboards using NDT methods such as the transient excitation method and to make a comprehensive assessment of its variability. According to the current market requirements for the classification of strawboard performance, research on the key technology of dynamic NDT on the strawboard assembly lines was carried out. A new type of strawboard inspection and its classification system was established to achieve its industrialization goal. Simultaneously, the design and production of framed case products and their corresponding mechanical properties were tested to verify the correctness and reliability of strawboard grading based on the grading results.

EXPERIMENTAL

Materials

The materials used were 33 straw particle boards (referred to as strawboard) from the four different production groups of 2440 mm ×1220 mm ×18 mm size manufactured by Wanhua Ecological Co. The moisture contents were measured to be 9 to 12% during the tests. The sample contained 33 whole strawboard plates numbered 1 to 33, and the No. 33 specimen was cut into 4 quarter pieces in the longitudinal direction coded Q1 to Q4.

The 0° and 90° strawboards specimens were made by cutting the Q4 along the longitudinal direction (or 0° direction), transverse direction (or 90° direction), respectively. There are six 0° specimens coded C. There are six 90° specimens with dimensions of 420 mm x 18 mm x 18mm, coded D.

Dynamic Testing of Elastic Modulus

Free plate modal test

Based on the dynamic signal vibration test method, the specimen was divided into a 10 x 6 grid according to the plate node diagram. According to the grid node diagram, the test specimen was divided into 10 x 6 grids. The grid nodes were knocked in sequence to produce transverse free vibration in the specimen. After the signal amplification and filtering by the signal conditioning instrument, and then the spectrum identification and orthogonal test by the structural modal analysis software MaCras, the modal parameters and vibration pattern of the strawboard specimen were finally obtained. The block diagram of the testing system is shown in Fig. 1(a).

Free plate transient excitation test (Hanging)

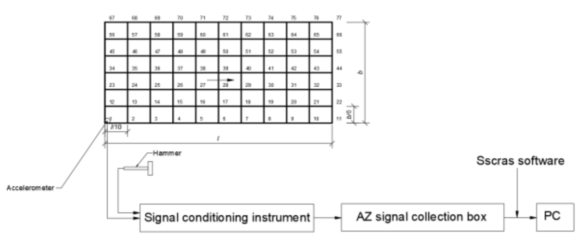
When a rubber cord is used to suspend the plate specimen to realize the free state, the transverse vibration is generated by striking the corner point of the plate with a knocking hammer. The vibration is received by the accelerometer and the first mode bending frequency of the freeboard is obtained from the spectrum identification of the time-frequency domain analysis software SsCras. The block diagram of the test system is shown in Fig. 1(b). According to the beam transverse bending vibration theory (Wang *et al*. 2019b), the relationship between the elastic modulus E and the first mode bending frequency f_b is Eq. 1,

$$E = 0.9462 \cdot \frac{\rho \cdot f_b^2 \cdot l^4}{h^2} \tag{1}$$

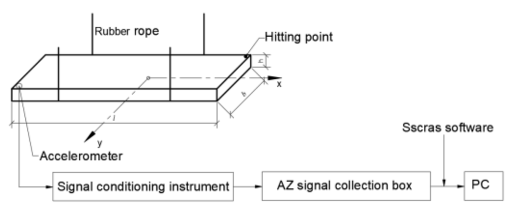
where ρ is density (kg/m^3), l is the length of the free plate (m), f_b first-order bending frequency of the free plate (Hz), h is the thickness of the plate (m).

Free plate transient excitation test (Triangular prisms support)

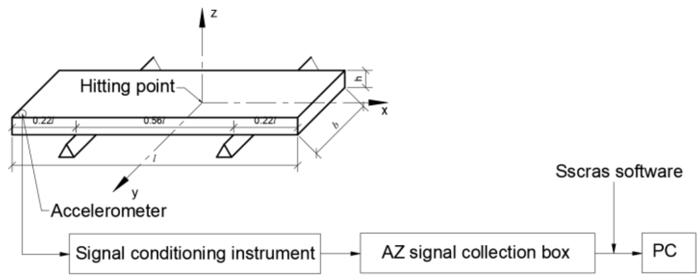
In the present work, the existing modal testing methods were improved by instituting a modal testing method that uses triangular prisms support. The free mode test of the plate specimen determines the position of the nodal lines with the amplitude of 0 at the first-order bending frequency. These nodal lines' positions are the location of the triangular prism supports.



a. Modal test system block diagram



b. Free plate transient excitation method (Hanging) test block diagram



c. Free plate transient excitation method (Triangular prisms support) test block diagram

Fig. 1. Dynamic test block diagram

As in Fig. 1(c), the two wooden triangular prisms are placed according to this system. It can realize the free vibration state at the first bending frequency. The first-order bending frequency of the plate obtained by hitting still meets the boundary conditions required by Eq. 1.

Static Verification Test of Elastic Modulus

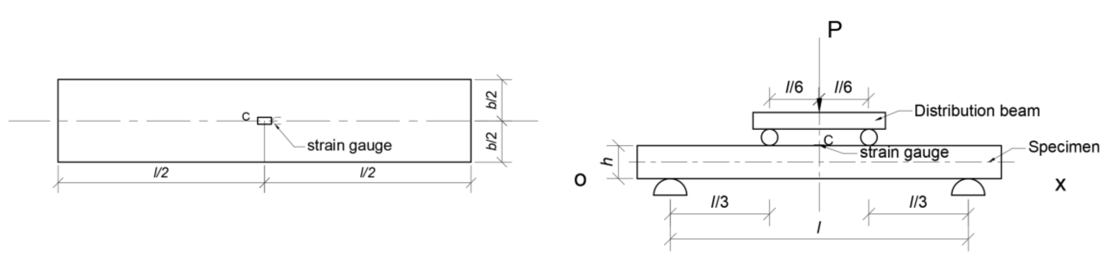
A symmetrical four-point bending test and axial tension method were used to verify the elastic modulus.

Symmetrical four-point bending test

Strain gauges were attached to the mid-span of the two symmetrical planes of the strawboard beam specimen to be tested, as shown in Fig. 2(a). The test setup for testing the elastic modulus is shown in Fig. 2(b). Weights were placed on the distribution beam for loading. The middle 1/3 section of the span is subjected to pure bending; the bottom of the beam is under tension, and the top is under compression when loaded. The static longitudinal elastic modulus of the beam specimen is obtained by Eq. 2,

$$E = \frac{\Delta P \cdot l}{b \cdot h^2 \cdot (\Delta \varepsilon_0)} \tag{2}$$

where l is the span (m), b is the beam width (m), h is the beam height (m), ΔP is the load increment (N) and $\Delta\varepsilon_0$ is the strain increment in (10^{-6} m/m).



a. Strain gauge pasted at the center point of the side of the beam surface

b. Loading schematic diagram of symmetrical four-point bending test

Fig. 2. Four-point bending test diagram

Axial tension test

A universal testing machine was used for tensile testing of the specimens. Strain gauges were used for measuring the longitudinal axial strain on specimens of. The ultimate load was determined by pre-testing to ensure that the applied loads are all within the elastic range of the strawboard beam. The modulus of elasticity was calculated using Eq. 3,

$$E = \frac{\Delta F}{b \cdot h \cdot (\Delta \varepsilon_0)} \quad (3)$$

where b is the beam width (m), h is the beam height (m), ΔF is the load increment (N) and $\Delta \varepsilon_0$ is the strain increment in (10^{-6}m/m).

Framed Case Test

The framed cases were designed according to the specification GB/T 7284 (2016). According to the elastic moduli of the whole boards, 28 whole boards (14 superior and 14 inferior ones) were selected to make 4 wood framed cases. A total of 14 whole boards with superior elastic moduli were used to make framed cases coded A. 14 whole boards with inferior elastic modulus were used to make framed cases coded B. Stacking test methods using a static load, bevel impact test methods, and forklift test were performed as shown in Fig. 3. Experiments were performed based on GB/T 4857.4 (2008), GB/T 4857.11 (2005), and GB/T 4996 (2014).

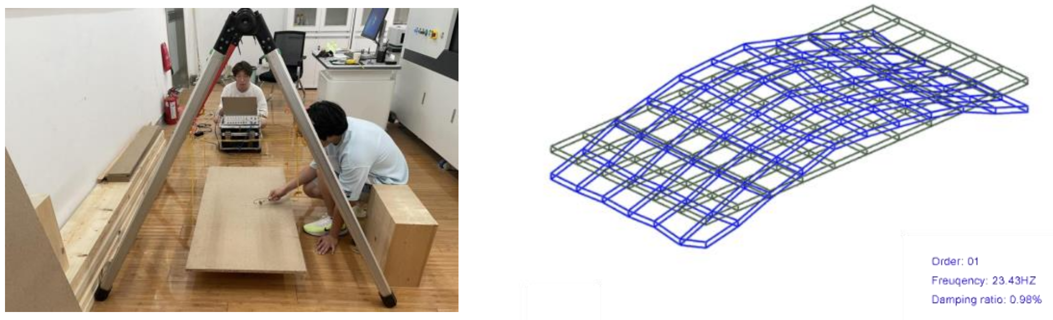
a. Stacking test methods using a static load **b.** Bevel impact test methods **c.** Fork lift test

Fig. 3. Framed case test

RESULTS AND DISCUSSION

1/4 Board Elastic Modulus Test

Free plate vibration tests were conducted on one 1/4 strawboard (Q-1), as shown in Fig. 4(a). The first-order bending mode is shown in Fig. 4(b). The first mode bending frequency of the plate was found to be 23.43 Hz.



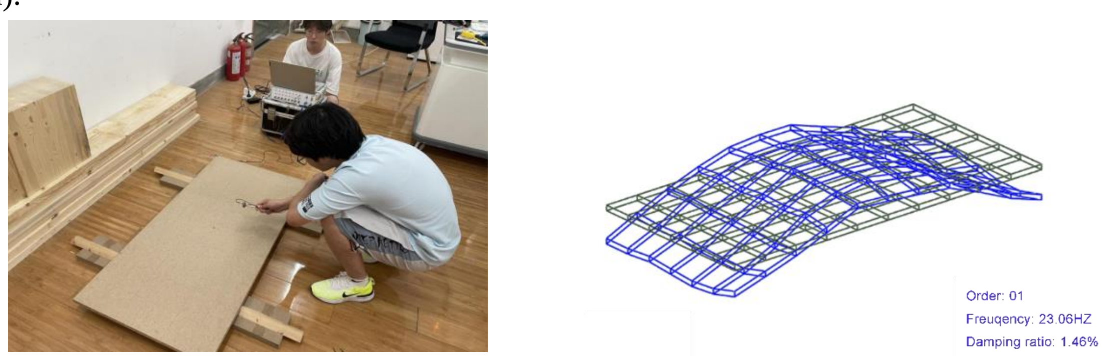
a. 1/4 board y-direction elastic modulus test **b.** First-order bending mode

Fig. 4. Free plate modal tests of 1/4 board

Based on the modal tests on the plate, the location of the first-order bending vibration nodal lines were determined, as the positions where the imaginary amplitudes are 0 between the two nodes with opposite displacements. As the plate is divided into 10 equal parts along the length direction, the distance between adjacent nodes along the length direction is 0.10*l*. For example, node 3 is 0.2*l* from the origin (node 1), and the Z-directional displacement value of node 3 is -0.0*1*. Node 4 is 0.3l from the origin, and the Z-directional displacement value is 0.04. Therefore, the point with the displacement value of 0 is located at 0.20*l*+0.10l×[|-0.01|/(|-0.01|+0.04)]=0.22*l* from the origin.

From Table 1, the locations of the two nodal lines can be determined at 0.227l and 0.779l from the width edge where the origin is located. Considering the test accuracy and the simplicity of the actual operation, the triangular prisms should be placed in symmetry with the middle line of the plate. Therefore, the locations of the above two nodes can be located at a distance of 0.224*l* ([0.227+(1-0.779)]/2=0.224*l*) from the two plate edges. This coincides with the location of the nodal line for the first-order bending oscillation of the plate in the free state by theoretical calculation.

Two triangular prisms were placed below this 1/4 board (Q-1) to realize support at 0.224·*l* from each end for modal testing. The laboratory test arrangement is shown in Fig. 5(a).

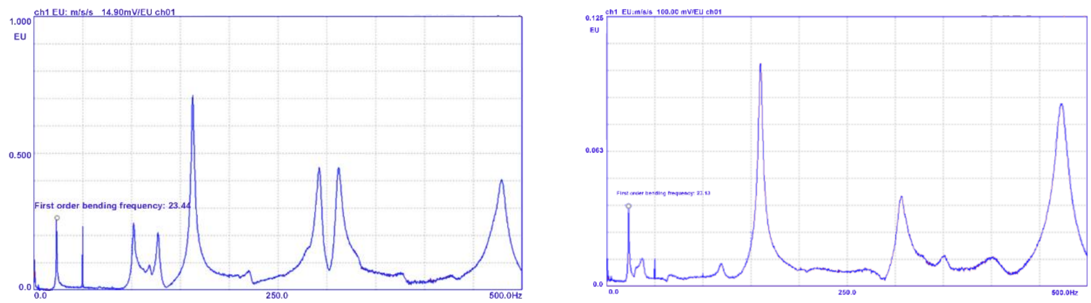


a. 1/4 board elastic modulus test **b.** First order bending mode

Fig. 5. Free plate modal tests of 1/4 board (triangular prisms support)

The measured first-order bending mode is shown in Fig.5(b). The first-order bending frequency of the plate was 23.1 Hz. This was only 1.6% smaller than the 23.43 Hz measured in the hung or practically floating elastic support condition, which shows that the measured first-order bending frequency of the plate was sufficiently accurate also for the triangular prisms supports condition.

The frequencies measured by the free plate transient excitation method should be compared with the modal test to verify the accuracy of the rigid triangular prisms support. The first-order bending frequency measured by the free plate transient excitation method for the 1/4 board (Q-1) in the hung condition was 23.4 Hz, as shown in Fig. 6(a), which agrees with the value measured by the modal test. The first-order bending frequency measured in the triangular prisms support condition was 23.1 Hz, as shown in Fig. 6(b), which was 1.3% smaller than the value measured in the modal test and is also in good agreement.



a. Free plate transient excitation method (Hanging)

b. Free plate transient excitation method (Triangular prisms support)

Fig. 6. First order bending mode of 1/4 strip board

The first-order bending vibration mode and supports are symmetrical about the plate centerline when knocking the central point in triangular prisms condition. In this case, the first-order bending frequency is more stable, and there will be no second-order bending and first-order torsion, which is convenient to highlight the first-order bending mode for identification.

Considering that the board may slightly shift relative to the supports when put into the assembly line, three 1/4 boards were taken for the test. Several sets of control tests were carried out in the trigonal support condition. The first-order bending mode frequency under each support placement configuration, the elastic modulus *E* was calculated according to Eq. 1.

For three 1/4 boards, the differences between the test results under the above five positions of triangular prisms' support conditions and hung conditions were not more than 8%. The difference between the elastic modulus tested for the 1/4 board specimens (numbered B and C), placed symmetrically or within 0.02l of the left and right lateral strip, and the elastic modulus determined in the hung condition was even less than 3%. For the 1/4 board, a slight movement of the plate relative to the symmetrically placed location of the triangular prisms can be seen during the test. This had no significant effect on the test and was allowed within the experimental error range. The investigation lays the foundation for the subsequent study of the influence of the placing method on the whole plate.

Verification Test of Elastic Modulus of Beam Specimens

To verify the accuracy of the elastic modulus determined on the whole strawboards and 1/4 boards, the whole 1/4 board (Q-4) was sawed and cut into beam specimens. Static bending tests were performed on the straw beam specimens. The four-point bending and axial tensile tests were used to determine the elastic moduli E of the beam specimens. At the same time, the elastic moduli of the beam specimens measured by the dynamic test method is given in Table 1.

Dynamic verification test

The c and d coded beam specimens were tested for their first mode free bending frequencies using the free transient excitation method, and their moduli of elasticity *E* were calculated according to the Eq. (1).

In the hung condition, the average elastic modulus E_x along the length of the whole board was 2230 MPa, and the average value of elastic modulus E_y along the width of the whole board was 2680 MPa, which was 20% greater than E_x, indicating that the material was anisotropic. The specimens were taken from different positions of the 1/4 board (Q-4), and both the coefficient of variation (CoV) of E_x and E_y were less than 3%. This indicates that the material of the strawboard was homogeneous, which also confirms the accuracy of the test.

Static verification test

The abovementioned 12 beam specimens were subjected to the symmetric four-point bending test and the axial tension test. In the symmetric four-point bending test, the span of the specimen was taken as l = 300 mm, and strain gauges along the length of the specimen were pasted at the span of the upper and lower surfaces of the beam.

The average value of elastic modulus E_x along the length of the whole board was 2580 MPa, and the average value of elastic modulus E_y along the width of the whole board was 3130 MPa, measured by the symmetric four-point bending test. The average value of elastic modulus E_x along the length of the whole board was 2010 MPa, and the average value of elastic modulus E_y along the width of the whole board was 2470 MPa, as measured by the axial tension test. The CoV of E_x and E_y were less than 6%, which confirms the reliability of the test.

Comparative analysis of dynamic test and static test results

Results of the dynamic and static tests of the beam specimens are summarized in Table 1. For the E_x, the symmetrical four-point bending test result of the beam specimen was 13.5% larger than the dynamic result, and the tensile test result was 10.8% smaller than the dynamic result. For the E_y, the symmetrical four-point bending test result of the beam specimen was 14.4% larger than the dynamic result and the axial tensile test result was 8.16% smaller than the dynamic result. This phenomenon is because in the symmetrical four-point bending test, the loading induces compression in the upper surface and tension in the lower surface, so the test result can be assumed to represent the average value of the tensile and the compressive elastic moduli. However, the tensile test achieves pure unidirectional tension, and the test result represents the uniaxial static tensile modulus of elasticity. The uniaxial tensile E_x and E_y values, on the average, were smaller than the symmetric four-point bending test results by about 20%, which shows that for the strawboards tested, the compressive elastic modulus, on the average, was greater than the tensile elastic modulus. Additionally, the value of the dynamic elastic modulus was between the static uniaxial tensile modulus and bending elastic modulus of the static test from the statistics of each test result. It demonstrates that the dynamic test results of the elastic modulus were more representative.

Table 1. Dynamic and Static E-test Results of Beam Specimens

Test Method	Ex (mPa)	Ey (mPa)
Free plate transient excitation test (Hanging)	2229 (1.16%)	2676 (2.10%)
Symmetric four-point bending test	2578 (3.38%)	3128 (5.07%)
Axial tension test	2011 (3.92%)	2474 (5.00%)
* In parenthesis are the coefficients of variation of the test results		

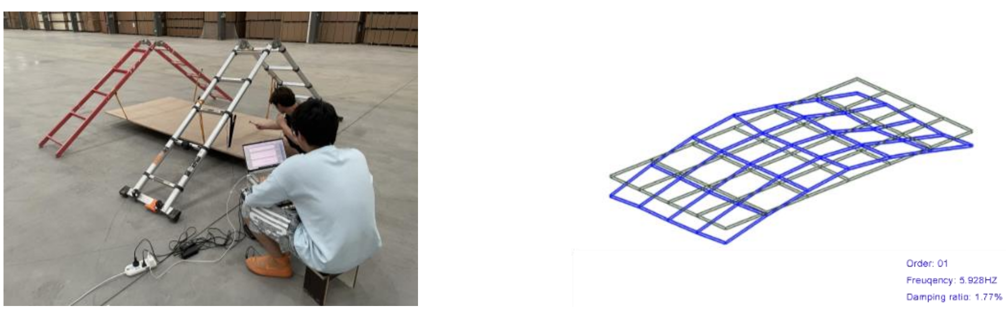
Regardless of the dynamic and static tests, the longitudinal elastic modulus E_x of the strawboard was about 18% smaller than the transverse elastic modulus value E_y, which shows that the strawboard was an anisotropic material. The test deviations of the longitudinal and transverse elastic modulus were similar for each test, which confirmed the reliability of each test.

The elastic modulus of the 1/4 board (Q) measured in section 3.1.2 was E_x, and the test result was 2373 MPa. This result matched the test results of the beam specimen. It reflects the fact that the size effect on the strawboards was small. The reliability and accuracy of the dynamic test results of the 1/4 board were confirmed, which laid the foundation for the subsequent dynamic test of the elastic modulus of the whole plate.

Full-scale Test

To achieve the goal of testing strawboard products on the assembly line, this study carried out the test work of the whole strawboard's elastic modulus in the factory field. Modal tests were conducted on one strawboard whole board (No. 6) in hung condition, and its test site is shown in Fig. 7(a).

Figure 7(b) shows the measured first-order bending vibration mode, whose first-order bending frequency was 5.93 Hz. The elastic moduli of 32 whole plates obtained from the free plate transient excitation tests in the hung condition was 2197 MPa (CoV: 10.4%). The elastic modulus of 32 whole plates obtained from the free plate transient excitation test in the triangular prisms support was 2019 MPa (CoV: 8.08%). Considering the possible slight movement of the board relative to the support in the actual assembly line, three whole boards were selected for the control experiment. The results are shown in Table 2.



a. Whole board elastic modulus test **b.** First bending mode shape

Fig. 7. Free plate modal tests of the whole board

Table 2. First-order Bending Frequencies and Elastic Modulus of the Whole Board Under Different Placement Conditions

Placement Conditions		Specimen Number					
		1		6		22	
		f_b (Hz)	*E* (mPa)	f_b (Hz)	*E* (mpa)	f_b (Hz)	*E* (mPa)
Hanging		5.938	2341	5.938	2381	5.625	208.9
Triangular prisms support	Symmetrical with the two supports	5.875	2292 (2.11%)	5.875	2331 (2.11%)	5.625	208.9 (0)
	Shift 0.01*l* to right	5.875	2292 (2.11%)	5.75	2233 (6.23%)	5.625	208.9 (0)
	Shift 0.01*l* to left	5.75	2195 (6.23%)	5.75	2233 (6.23%)	5.625	208.9 (0)
	Shift 0.02*l* to right	5.75	2195 (6.23%)	5.75	2233 (6.23%)	5.500	199.7 (4.40%)
	Shift 0.02*l* to left	5.75	2195 (6.23%)	5.625	2137 (10.26%) (6.23%))	5.500	199.7 (4.40%)

* The differences between the result of this condition and the hanging test result are shown in parentheses.

The differences between the test results under the above five kinds of triangular prisms support conditions and hung conditions were not more than 7%, except for the data of $0.02 \cdot l$ left shift of specimen plate No.6. It can be seen that for the whole board, a slight movement of the board relative to the symmetrically placed position of the triangular prisms during the test did not affect the test too much and could be allowed within the error range. The above study provides a reference for designing and fabricating the subsequent grading assembly line.

Full-scale Test Classification of Quality

The free plate transient excitation test was conducted on 32 whole boards at the factory, and the quality of the strawboard specimens was classified according to the test results. The results were arranged in order from largest to smallest and graded. $E \geq$ 2200 MPa was the first grade, 1900 MPa $\leq E <$ 2200 MPa was the second grade, and $E <$1900 MPa was the third grade. Of the 32 whole boards tested, there were 21 first-grade products, 7 second-grade products, and 4 third-grade products, as shown in Fig. 8.

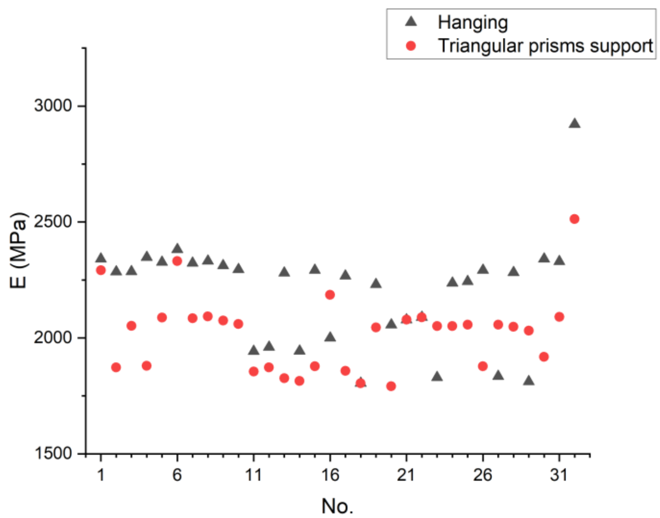
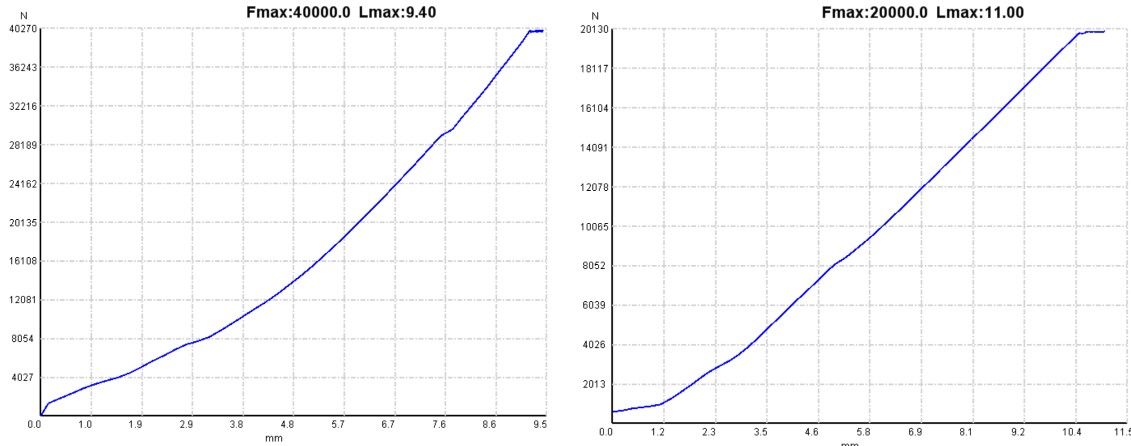


Fig. 8. Elastic modulus of strawboards

In this paper, a kind of straw particle board was used. Except for specimen No. 32, all of the boards had a thickness of 18.3 mm (±0.02 mm), but the thickness of No.32 board was 18.9 mm. its core layer (OSB) was thicker than the other specimens, and OSB elastic modulus was larger than the ordinary strawboard. According to the theory of plywood stacking, it can be seen that the increase in core layer thickness will result in the composite panel overall performance is closer to the elasticity modulus of the core layer. According to the theory of laminate stacking, it is known that the thickening of core layer will lead to the overall performance of composite panel closer to the elastic modulus of the core layer. Therefore, the modulus of elasticity of No. 32 board was higher.

Results and Analysis of Framed Case Test

According to the results of the whole board test, the 14 pieces whole sample strawboards with the best elastic moduli (No. 32, 7, 30......15, 26, 3) were selected to make framed case named A. The 14 pieces with the least elastic moduli (No. 25, 24, 19......23, 29, 18) were selected to make framed case named B. The thickness of each panel was guaranteed to be consistent in this process and was maintained at 18 mm (±0.02 mm) by surface treatment. Figure 9 shows the stacking test methods using a static load and the fork lift test of framed case A. The test results are shown in Table 3.



a. The stacking test methods using a static load

b. Fork lift test

Fig. 9. Displacement load curve of framed case test

In the stacking test, the maximum deformation of type A box was 11.7% smaller than that of type B case. The sizes of the cases were the same in the stacking test, the maximum deformation of the box and the value of the elastic moduli of the materials were inversely proportional. Thus, the test results showed that the elastic modulus value of the material used in the A-type box was greater than the B-type box, which is consistent with the elastic modulus of the material, that is, the accuracy of the classification.

In the bevel impact test, both the A-type and B-type cases were not clearly broken, and there was no functional damage to the components, which shows that the quality of the strawboard framed case designed and made in this study was in line with the actual use requirements.

Table 3. Comparison of Framed Box (case) Performance

Method	Framed box/case A	Framed box/case B
The stacking test methods using a static load	Maximum deformation: 8.30 mm. After the test, there is no apparent damage to the sample and no functional damage to the components.	Maximum deformation: 9.40 mm. After the test, there is no apparent breakage of the sample and no functional damage to the components.
Bevel impact test methods	After the test, there is no apparent damage to the sample and no functional damage to the components.	After the test, there is no apparent damage to the sample and no functional damage to the components.
Fork lift test	Load deflection: 11.00 mm Unloading deflection: 3.00 mm After the test, the pallet was not damaged.	Load deflection: 11.00 mm Unloading deflection: 3.10 mm After the test, the pallet was not damaged.

In the fork lift test, the deflection of the bottom bracket of type A and type B framed cases were equal under load. However, the deflection of the A-type case bottom bracket was 3.2% smaller after unloading than that of the B-type case bottom bracket. Therefore, the B-type case bottom bracket had a relatively large plastic deformation after loading.

It is evident that the strawboard A-type case made of superior products was better than the strawboard B-type case made of inferior products in the overall performance test, which verifies the correctness and reliability of the strawboard online inspection quality grading method proposed by this research.

CONCLUSIONS

1. The dynamic modulus of the whole board of strawboard was found to be (2.0 to 2.5) GPa. The strawboard plate beam specimen test showed that the straw plate had some anisotropic characteristics.
2. The free transient excitation method for determining the elastic modulus of the strawboard on the same plate was consistent with the static testing of the elastic modulus of the strawboard. It was shown that the free-hanging transient excitation method and the trigonal support transient excitation method can be used to test the elastic modulus of the strawboard.
3. The dynamic test method can be used to test the whole large-format board. It is efficient, simple, repeatable, and accurate. Compared with the static method, the dynamic test method is more suitable for testing the elastic modulus of the strawboard. The test results of the two dynamic test methods were basically the same, which demonstrated that the free transient excitation method of triangular prism support meets the test requirements.
4. Compared with free hanging, the modified method is more convenient, easier to implement, and more suitable for factory assembly line operation. It can be used for monitoring the statistical production control level.

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