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Article *in* Construction and Building Materials · May 2019

DOI: 10.1016/j.conbuildmat.2019.05.004

Zheng Wang
Nanjing Forestry University

Construction and Building Materials 216 (2019) 542–551

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Dynamic and static testing methods for shear modulus of oriented strand board

Zheng Wang [a,b,*], Wenbo Xie [b], Yao Lu [b], Haitao Li [c], Zhiheng Wang [d], Zhong Li [a]

[a] National and Local Joint Engineering Research Center for Biomaterials Packaging Biomass Materials, Nanjing, Jiangsu 210037, China
[b] College of Materials Science and Engineering, Nanjing Forestry University, Nanjing, Jiangsu 210037, China
[c] College of Civil Engineering, Nanjing Forestry University, Nanjing, Jiangsu 210037, China
[d] Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA 90089, United States

HIGHLIGHTS

- A new dynamic and a new static method for testing shear modulus of OSB are proposed, respectively.
- Relationship of mode shape coefficient with length-width and width-thickness ratios is given.
- The static square-plate torsional test for shear modulus of orthotropic materials is described.
- The scheme of pasting the strain gauges in the direction of ±45° is proposed.
- The new dynamic method of testing OSB shear modulus is verified by static square-plate torsion.
- The result indicates the orthotropy of OSB and it is not simply a unidirectional composite.

ARTICLE INFO

Article history:
Received 31 October 2018
Received in revised form 28 April 2019
Accepted 1 May 2019

Keywords:
Oriented strand board
Shear modulus
Mode shape coefficient
Dynamic test
Static square-plate torsional test

ABSTRACT

In this work, a new dynamic and a new static method for testing shear modulus of oriented strand board (OSB) are proposed, respectively. ANSYS software was used to calculate the mode shape coefficient of the OSB free plate and cantilever plate specimens, and the relationship of the mode shape coefficient depending on the length-to-width and the width-to-thickness ratios of the plate specimen was given. According to the stress and strain analysis of static torsion of the square plate, the principle of static square-plate torsional test for testing the shear modulus of orthotropic materials was described and the scheme of pasting the strain gauges in the direction of ±45° was proposed to ensure the accuracy of testing static shear modulus of OSB. The correctness of the new method for dynamically testing OSB shear modulus was verified by static square-plate torsional test. The longitudinal elastic modulus E_x, transverse elastic modulus E_y, elastic modulus in the 45° direction $E_{45°}$, shear modulus in the plane G_{xy} and shear modulus in the 45° direction $G_{45°}$ were measured dynamically. The measured results of $E_x/E_y = 2.88$ and $G_{45°} < G_{xy}$ for OSB indicate that the orthotropy of OSB cannot be simply dealt with as a unidirectional composite.

1. Introduction

In the building materials industry, Oriented strand board (OSB) is a new, environmentally friendly wood-based composite. Logs with small diameters of 8–10 cm as raw material, are processed and thin slices of wood are shaved by a special slicing machine. After drying, sorting, and mixing, oriented pavement is achieved with a special device. The slices form an oriented structure board after hot pressing. The elastic modulus and static bending strength of the OSB in the horizontal (longitudinal) direction are usually 2–3 times higher than those in the vertical (transverse) direction and the relation can be adjusted depending on the purposes [1]. Since the emergence of the material in Canada in 1964, OSB has been one of the most rapidly developed new environmentally friendly wood-based composites globally. OSB has many good physical and mechanical properties such as good dimensional stability, good uniformness and high bending strength. In addition, it has beneficial environmental features including good thermal insulation performance and low energy consumption. Therefore, OSB has competitive environmental and physical properties with those high-grade core boards.

* Corresponding author at: National and Local Joint Engineering Research Center for Biomaterials Packaging Biomass Materials, Nanjing, Jiangsu 210037, China.
E-mail address: wangzheng63258@163.com (Z. Wang).

https://doi.org/10.1016/j.conbuildmat.2019.05.004
0950-0618/

OSB has been widely used in building, construction, furniture, transportation, and packaging industries. Especially in the field of civil engineering, as a structural or non-structural panel, OSB is gradually accepted on the construction market and widely used in building walls, floors, roofs and other components [2]. Also, OSB is commonly used as shear wall material of buildings and many researches have been conducted on the anti-seismic and lateral resistance performance of OSB. For instance, in 2004, Thomas found that planar shear stiffness modulus can be used for structural classification of OSB. However, it is difficult to obtain the data of planar shear stiffness modulus of OSB. This was attributed to the complexity and expensiveness of current methods for testing planar shear performance. Thomas obtained the planar shear modulus of 18-mm thick OSB board by bending test and planar shear test according to the European code EN 789 [3]. In 2009, Yoshihara conducted dynamic and static square-plate torsional and beam bending tests on the five-layer plywood made of Lauan in different dimensions. The shear modulus of this typical plywood material was obtained. In addition to experiments, finite element computation was conducted to verify the test method [4]. In addition, OSB is also used in building floor and base materials. Researchers have made lots of studies on its bending and shear resistance. In 2002, Thomas conducted parametric study of the shear and bending performance under the maximum deflection of the OSB floor decking model by the finite element method, and analyzed the effects of decking continuity, orthotropy, shear stiffness and Poisson's ratios on the deflection. The results show a good agreement between the deflections obtained from analytical solutions and the finite element method [5]. In 2011, Costel studied the physical and mechanical properties of OSB made of aspen/birch mixture and ponderosa pine, and developed a special OSB panel that has high bending MOE in the direction parallel to the grain. This special OSB panel can substitute plywood as a substrate for engineered wood flooring. The results show that the OSB panel made of aspen/birch mixture and ponderosa pine has high elastic modulus and can be used as customized OSB panel for specific applications [6].

The shear and elastic modulus are two important elastic constants that are used to determine and mechanical properties of wood composites, such as OSB. In practical applications, the dynamic test method is more and more used to measure the shear and elastic modulus and has drawn increasing attention [7]. In the past decades, vibration method has been successfully used to evaluate the physical and mechanical properties of wood and wood composites [8–10]. For small cantilever specimens, vibration test method is a preferred technique to obtain vibration characteristics [11]. In 2001, Hu applied a stress method to measure the shear modulus of OSB and plywood by studying the reflection time [12]. In the same year, Hu also measured the shear modulus of plywood by the Timoshenko-Gones-Hearmon (TGH) method which considers the influence of the rotation effect of the shear force and beam section on the beam bending frequency [13]. In 2007, Zhou studied the effect of the shear force and rotational inertia on the natural frequency of free beams. The first-order and second-order natural frequencies contain the two elastic constants: elastic modulus E and shear modulus G. The iterative method was used to obtain the shear modulus G [14]. In the same year, Zhou used a torsional vibration equation of rectangular cantilever bar and tested the first-order torsional frequency of the cantilever bar to calculate the shear modulus of wood composite boards [15]. Wang and Cheng proposed a new method to dynamically test the shear modulus of wood and isotropic materials using torsional plate theory. The new method is based on the equation relating shear modulus and the first-order torsional frequency derived from the first-order torsional mode shape of free plates. By using this method, the first-order torsional frequency of the free plate is identified from the spectrum and then is substituted into the equation relating shear modulus and the first-order torsional frequency. Thus, shear modulus of metal and wood materials can be calculated. The correctness of this method has been verified by simulating calculations and dynamic and static tests of wood shear modulus. But in ANSYS programming, the input elastic constants are tangential so that the mode shape coefficient on the tangential section of the free plate are obtained and the shear modulus measured is along the grain on the tangential section G_{LT} [16,17]. Wang comprehensively studied the free-plate torsional mode shape method and obtained the mode shape coefficients on the tangential, radial and transverse sections of free plate specimens, which radically determined the test of shear modulus along the grain on the tangential section, along the grain on the radial section and across the grain on the transverse section [18].

In view of these, a new method for dynamic and static test of shear modulus of OSB plates is provided in this work. Mode shape coefficients of OSB free and cantilever plates are calculated by ANSYS program and the equation of mode shape coefficients depending on the length-to-width and width-to-thickness ratios is given. The correctness of this method is verified by simulating calculations, dynamic test and static square-plate torsional test. Among them, the OSB specimens used for dynamic measurement of shear modulus were cut from an entire OSB plate in three directions. The OSB specimens used for static square-plate torsional test of shear modulus were cut along the longitudinal or transverse directions of the plate. The equation provided in this work applies to calculating shear modulus of orthogonal anisotropic materials by static square-plate torsional test, which is a modification and expansion of the conventional equations. The shear modulus measured by static and dynamic tests are consistent with each other quite well.

It is worth mentioning that one of the differences between the static square-plate torsional test method proposed in this work and the method for testing shear modulus of wood-based structural plates specified in the code D3044 of ASTM is the test parameter. The former method is to test the strain at the center point along ±45° directions on the two surfaces of the tested square plate, while the latter method is to test the relative deflection between the points on the two diagonals of the square plate and the plate center [19].

2. Experiment

2.1. Dynamic tests of the elastic and shear modulus of the OSB

2.1.1. Specimens

The 0°, 90° and 45° OSB specimens were made by cutting the whole plate with dimension of 2400 mm × 1220 mm × 10.5 mm along the longitudinal direction (length direction of the plate, or 0° direction), transverse direction (width direction of the plate, or 90° direction), and 45° from the longitudinal direction (named 45° direction), respectively, as shown in Fig. 1.

There were ten 0° OSB longitudinal specimens cut along the longitudinal direction of the whole plate (see Fig. 1) with dimension of 600 mm × 120 mm × 10.5 mm, ten 90° OSB transverse specimens cut along the transverse direction of the whole plate (see Fig. 1) with dimension of 600 mm × 120 mm × 10.5 mm, and five 45° OSB specimens cut along the 45° direction with the longitudinal direction of the whole plate (see Fig. 1) with dimension of 420 mm × 82 mm × 10.5 mm. The average moisture content and density were 9.5% and 650 kg/m^3. The whole plate was composed of three layers in horizontal, vertical and horizontal direction alternately. The strands were 60 mm long, 5 mm wide and 0.45 mm thick.

The frequencies of the specimens in the free state and when they were clamped at one end were measured. For specimens with

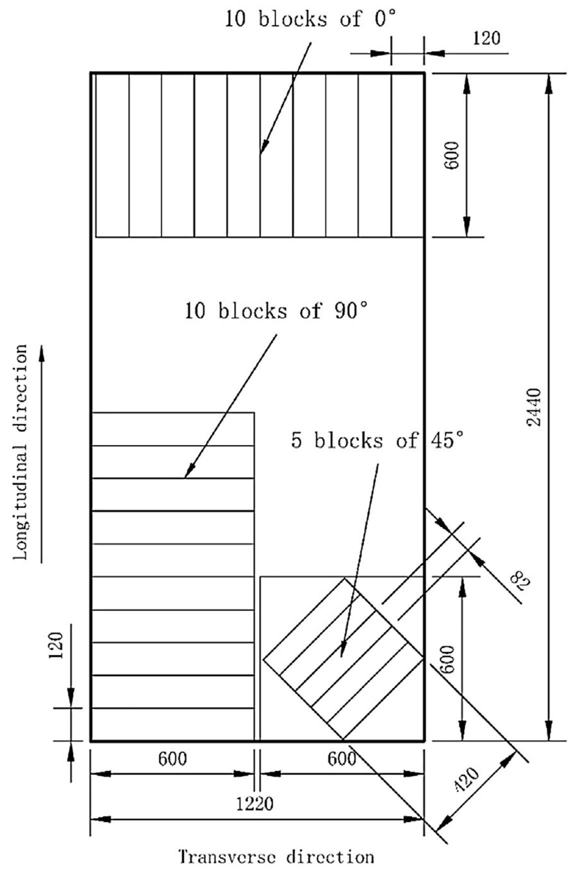

Fig. 1. Blanking map of OSB specimens.

dimension of 600 mm × 120 mm × 10.5 mm, the clamping length was 60 mm, while for 45° OSB specimens with dimension of 420 mm × 82 mm × 10.5 mm, the clamping length was 50 mm.

2.1.2. Block diagram

Figs. 2 and 3 show the block diagrams of the tests. For the free plate, the accelerometer was installed at 0.35 *l* from the free end on the long side of the plate. For the cantilever plate, the accelerometer was installed at 0.2 *l*–0.3 *l* from the free end on the long side of the plate. The corner point of the specimen was hammered to excite free vibration of the plate. Then the vibration signal was received by the accelerometer and was converted into electric signal output. Next, the electric signal was amplified and filtered by the signal conditioning instrument (made by Nanjing Analyzer Software Engineering Co., Ltd., Nanjing, China) and entered the signal collection box where the analog signal was transformed into the digital signal. Finally, the signal was processed by the signal and system analysis software named SsCras (made by Nanjing Analyzer Software Engineering Co., Ltd., Nanjing, China) and the frequency spectrum of specimens was displayed on the computer screen [20]. From the frequency spectrum, the first-order bending [21] and first-order torsional frequencies of the specimen could be read [22].

2.2. Static square-plate torsional test of OSB

2.2.1. Specimens

The OSB square plate specimens were cut from the same whole board that was used to make specimens in dynamic test. There were seven specimens and the nominal dimension was 128 mm × 128 mm × 10 mm. The average air-dry density of the specimens was 650 kg/m^3 and the average moisture content was 9.4%.

2.2.2. Test equipment

The loading device of static square-plate torsional test is shown in Fig. 4. It was loaded by weight. The strain signal was received by the strain gauge and was amplified by the dynamic strain gauge, and the output was connected to the acquisition card. After A/D conversion, the measured mean value of the strain was displayed by software.

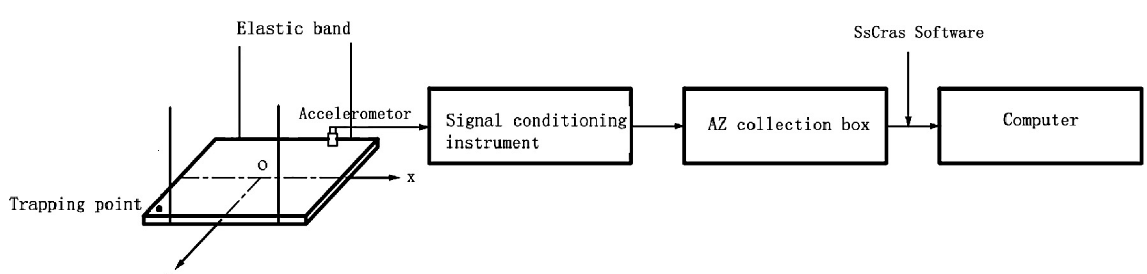

Fig. 2. Block diagram of the free plate test.

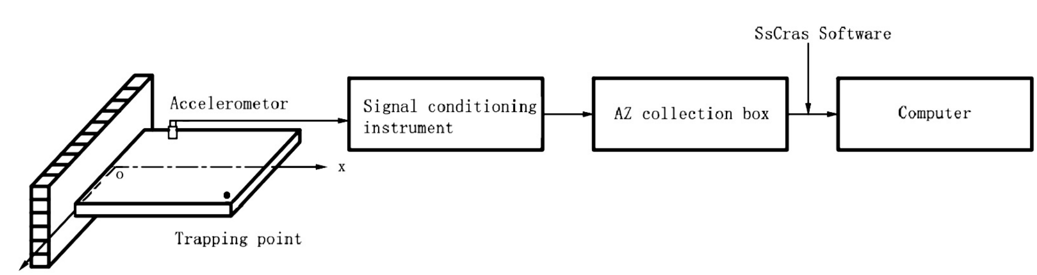

Fig. 3. Block diagram of the cantilever plate test.

Fig. 4. Loading device of square-plate torsional test.

2.2.3. Scheme of pasting strain gauges and the half-bridge measurement

A 45°and a −45° strain gages were pasted along the diagonals of the upper and lower surfaces on each square plate specimen. In the two-channel half-bridge measurement, the 45° and −45° strain gauges on the upper and lower surfaces had two independent channels. The correction factor was set to 2.08 (sensitivity coefficient of strain gauge is 2.08), and the weights used to load were as follows: 0.425 kg, 0.85 kg and 0.85 kg. First, the initial load was 4.165 N and adjusted balance, data was then collected and saved. Then, 8.33 N was added and data was collected and saved. Finally, another 8.33 N was added and data was collected and saved. Each specimen was tested three times and the mean value of the incremental strains was obtained from the last two tests.

3. Methods

3.1. Elastic modulus

The following describes the use of free and cantilever plate specimens to measure the elastic modulus of plates based on the relationship between the first-order bending frequency and elastic modulus from the beam theory [23].

3.1.1. Free plate (free-free ends)

According to the theory of beam transverse vibration, the relationship between the first-order bending frequency (f_b) and elastic modulus (E) of the free beam can be expressed as:

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

where E is the elastic modulus of the specimen (Pa); ρ is the air-dry density (kg/m^3); f_b is the first-order bending frequency of the specimen (Hz); l is the length of the specimen (m) and h is the thickness of the specimen (m).

The elastic modulus E of plate was derived from Eq. (1) by testing the first-order bending frequency of the free plate f_b.

3.1.2. Cantilever plate (fixed-free ends)

According to the theory of beam transverse vibration, the relationship between the first-order bending frequency f_b and elastic modulus E of the cantilever beam can be expressed as:

$$E = \frac{48\pi^2}{1.875^4}\frac{\rho f_b^2 l^4}{h^2} \tag{2}$$

where E is the elastic modulus of the specimen (Pa); ρ is the air-dry density (kg/m^3); f_b is the first-order bending frequency of the specimen (Hz); l is the extended length of the specimen (m) and h is the thickness of the specimen (m).

The elastic modulus E of plate was derived from Eq. (2) by testing the first-order bending frequency of the free plate f_b.

3.2. Shear modulus

The mode shape coefficient (γ) of OSB free plate and the mode shape coefficient (C_1 and C_2) of OSB cantilever plate were calculated by using the methods and principles of free-plate torsional mode shape and cantilever-plate torsional mode, respectively [16]. Through binary linear regression of the mode shape coefficients from different length-to-width and width-to-thickness ratios, the equations of longitudinal and transverse mode shape coefficients of OSB depending on length-to-width and width-to-thickness ratio of the plate were obtained were derived as Eqs. (3) and (4).

For the free plate [24], the shear modulus is expressed as:

$$G = \frac{\pi^2 \rho (l/2)^2 b^2 f_t^2}{\gamma \beta h^2} \tag{3}$$

where G is the shear modulus (Pa); ρ is the air-dry density (kg/m^3); l is the length of the free plate (m); b is the width of the free plate (m); f_t is the first-order torsional frequency of the free plate (Hz); γ is the mode shape coefficient of the free plate, related to the material and the length-to-width ratio of specimen; β is the shape factor of rectangular section $\beta = \frac{1}{16}\left(\frac{16}{3} - 3.36\frac{h}{b}\left(1 - \frac{h^4}{12b^4}\right)\right)$ which is related to the type of material and aspect ratio of the specimen, and h is the thickness of the free plate (m).

The mode shape coefficient of the free plates is expressed as:

For 0° OSB, longitudinally,

$$\gamma = 7.4539(1 - 0.1187b/l + 0.6013b^2/l^2 - 0.3824b^3/l^3)$$

(r = 0.99998, l/b between 2 and 8)

For 90° OSB, transversely,

$$\gamma = 7.4119(1 - 0.0184/l + 0.0565b^2/l^2 + 0.1023b^3/l^3)$$

(r = 0.99999, l/b between 2 and 8)

The shear modulus of the cantilever plate is expressed as:

$$G = \frac{\pi^2 \rho l^2 b^2 f_t^2}{C_1 \beta h^2} - C_2 E \tag{4}$$

where G is the shear modulus (Pa); ρ is the air-dry density (kg/m^3); l is the extended length of the cantilever plate (m); b is the width of the cantilever plate (m); f_t is the first-order torsional frequency of the cantilever plate (Hz); $\beta = \frac{1}{16}\left(\frac{16}{3} - 3.36\frac{h}{b}\left(1 - \frac{h^4}{12b^4}\right)\right)$; h is the thickness of the cantilever plate (m) and C_1 and C_2 are the mode shape coefficients of the cantilever plate, related to the type of material and the length-to-width and width-to-thickness ratios of specimen.

The mode shape coefficients of the cantilever plate C_1 and C_2 are:

Longitudinally (for 0° OSB):

$$C_1 = 7.5243 + 2.4978b/l - 2.1835h/b$$

(r = 0.9909, n between 1.25 and 5)

$C_2 = 0.0109 + 0.0771b/l - 0.0978h/b$
(r = 0.9855, n = between 1.25 and 5)

Transversely (for 0° OSB):

$C_1 = 7.4229 + 1.4981b/l - 1.0591h/b$
(r = 0.9933, n between 1.25 and 5)

$C_2 = 0.0059 + 0.1345b/l - 0.1289h/b$

(r = 0.9913, n between 1.25 and 5)

The applicability of Eq. (3) which gives the mode shape coefficient of the free plate γ and Eq. (4) which gives the mode shape coefficients of the cantilever plate C_1 and C_2 will be verified from three aspects: dynamic and static tests of OSB specimens and simulation of shear modulus, respectively.

3.3. Square-plate torsional test for OSB –static shear modulus test

3.3.1. Pure shear strain analysis

From the dynamic test results, the elastic modulus of the specimens made by cutting the OSB along the longitudinal direction was 2.88 times of that of the specimens made by cutting the OSB along the transverse direction. It indicates that OSB has the feature of anisotropy. According to the result from square-plate torsional test, it was found that by pasting the strain gauges along the two diagonals of the square plate, there is a large difference between the shear modulus calculated by the conventional equations using the measured strain in different directions. The difference can be up to 20% and the dispersity is also large.

The plane strain components at a point are ε_x, ε_y, and γ_{xy}. The linear strain in any direction α is expressed as [25]:

$$\varepsilon_\alpha = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2}\cos 2\alpha - \frac{\gamma_{xy}}{2}\sin 2\alpha \tag{5}$$

where α is the rotation angle between the coordinate system across this point x_1-y_1 and the original coordinate system x-y. It is defined that counterclockwise rotation has a positive α, otherwise the α is negative.

If $\alpha = \pm 45°$, then:

$$\begin{aligned} \varepsilon_{45°} &= \frac{\varepsilon_x+\varepsilon_y}{2} - \frac{\gamma_{xy}}{2} \\ \varepsilon_{-45°} &= \frac{\varepsilon_x+\varepsilon_y}{2} + \frac{\gamma_{xy}}{2} \end{aligned} \tag{6}$$

For isotropic materials, $\varepsilon_x = \varepsilon_y = 0$ in the pure shear stress state. Thus, it gives:

$$\varepsilon_{-45°} = -\varepsilon_{45°} = \frac{\gamma_{xy}}{2} \tag{7}$$

For anisotropic materials, in the pure shear stress state, it gives:

$$\varepsilon_{-45°} - \varepsilon_{45°} = \gamma_{xy} \tag{8}$$

3.3.2. Stress analysis of the square-plate torsion

The four corner points of the square plate were subjected to four pairs of forces (P) with equal value in opposite directions. The force value is P (Fig. 5). According to the static equivalent principle, the four forces were equivalent to uniformly distributed torques acting on the four sides of the square plate (Fig. 6). The torque is $M_{xy} = M_{yx} = P/2$, representing the torque per unit length with unit of N. Under such a torque, the shear stress (τ) on the upper and lower edge points of the plate sides is expressed as:

$$\tau = \frac{6M_{xy}}{h^2} = \frac{6M_{yx}}{h^2} = \frac{3P}{h^2} \tag{9}$$

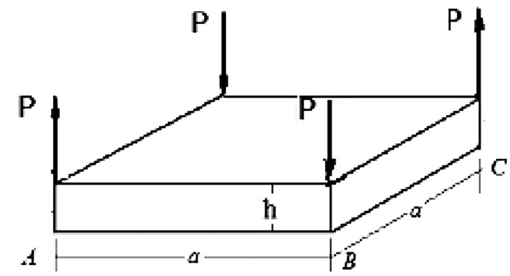

Fig. 5. Concentrated forces P acting at the four corner points of the square plate.

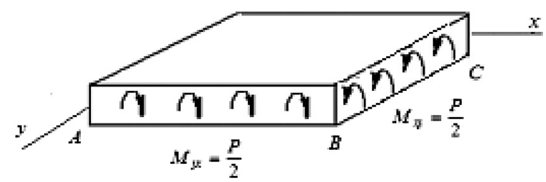

Fig. 6. Uniform torques (M_{xy} and M_{yx}) on the four sides of the square plate.

3.3.3. Relationship between the shear modulus and linear strain

According to Hooke's law, $\tau_{xy} = G\gamma_{xy}$. As such, let $\tau_{xy} = \tau$ (Fig. 7) so that:

$$\tau = \frac{3P}{h^2} \tag{10}$$

About γ_{xy}, for isotropic materials:

$$\gamma_{xy} = 2\varepsilon_{-45°} = -2\varepsilon_{45°} \tag{11}$$

For anisotropic materials:

$$\gamma_{xy} = \varepsilon_{-45°} - \varepsilon_{45°} \tag{12}$$

Thus, it is derived that for isotropic materials:

$$G = \frac{3P}{2|\varepsilon_{45°}|h^2} = \frac{3P}{2|\varepsilon_{-45°}|h^2} \tag{13}$$

For anisotropic materials:

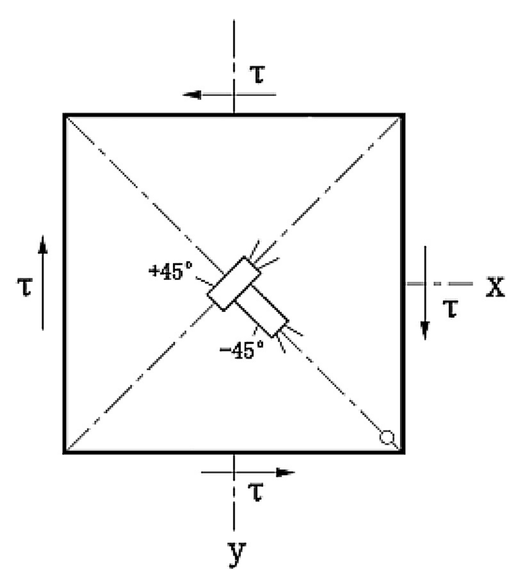

Fig. 7. Schematic diagram of the pure shear stress state.

$$G = \frac{3P}{|\varepsilon_{-45^\circ} - \varepsilon_{45^\circ}|h^2} \tag{14}$$

In Fig. 7, x and y directions are the longitudinal and lateral directions of the whole plate, respectively.

4. Results and analysis

4.1. Results

4.1.1. Measurement of E and G for OSB by free-plate torsional mode shape method

Table 1 shows the measured elastic and shear modulus of OSB by the free-plate torsional mode shape method.

4.1.2. Measurement of E and G for OSB by cantilever-plate torsional mode method

Table 2 shows the measured elastic and shear modulus of OSB by the cantilever-plate torsional mode method.

4.1.3. Shear modulus of OSB measured by the static square-plate torsional test

The measurement results of static shear modulus of OSB are shown in Table 3.

4.2. Analysis

4.2.1. The longitudinal and transverse elastic modulus of the OSB plates

The ratio of the longitudinal and transverse elastic modulus of the OSB plates measured by using free and cantilever plates is 2.88. It indicates the orthotropy of OSB plates.

4.2.2. Scheme of pasting strain gauges in +45° and −45° directions

According to the results from stress, strain analysis and test results, it all shows that when measuring shear modulus of OSB by static square-plate torsional test, it is necessary to paste the strain gauges along ±45° directions. Table 3 shows that average strain increment (coefficient of variation) of $\Delta\varepsilon_{-45^\circ}$, $\Delta\varepsilon_{45^\circ}$ and $\Delta\varepsilon_{-45^\circ}$, $-\Delta\varepsilon_{45^\circ}$ are 91.9 $\mu\varepsilon$ (19.0%), −77.2 $\mu\varepsilon$ (18.2%) and 169.1 $\mu\varepsilon$ (13.4%), respectively. From this set of data, it is clearly seen that the test data is highly dispersive if strain gauges are only pasted along +45° or only along −45° directions, while the dispersion of the data is reduced, and as a result, the test accuracy of the shear modulus is improved if strain gauges are pasted along both +45° and −45° directions. Besides, the difference between shear modulus measured by only pasting strain gauge in +45° and that by only in −45° direction reaches 19%, thus, strain gauges should be pasted in both +45° and −45° directions. The later scheme of pasting strain gauges is exactly the one that is necessary to measure shear modulus of orthotropic materials.

4.2.3. Measurement of shear modulus of OSB by the free-plate torsional mode shape and cantilever-plate torsional mode methods

The results of shear modulus measured for 0° and 90° specimens by dynamic test are almost equal, which means in-plane shear modulus of OSB can be measured with either 0° or 90° specimens.

The shear modulus of 45° OSB is less than the in-plane shear modulus. This is different from the maximum value of shear modulus in 45° of unidirectional fiber-layered composites.

The correctness of measuring in-plane shear modulus of OSB by the free-plate torsional mode shape and cantilever-plate torsional mode methods was validated by the static square-plate torsional test. The shear modulus of 0° OSB and 90° OSB specimens measured by the free-plate torsional mode shape method were 1.32 GPa and 1.31 GPa, respectively (Table 1), while the shear modulus measured

Table 1
Elastic modulus E_x, E_y, E_{45° and shear modulus G_{xy}, G_{45° of OSB measured by the free-plate torsional mode shape method.

Specimen Number	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m^3)	β	γ	First-order bending frequency (Hz)	First-order torsional frequency (Hz)	E (GPa)	G (GPa)
OSB0°-1	600	119.40	10.66	641	0.3146	7.4329	95.63	206.56	6.33	1.30
OSB0°-2	598	119.34	10.72	628	0.3145	7.4332	100.31	210.31	6.65	1.30
OSB0°-3	599	119.10	10.66	637	0.3145	7.4328	101.56	211.25	7.04	1.34
OSB0°-4	600	119.46	10.65	654	0.3146	7.4329	105.31	208.75	7.85	1.36
OSB0°-5	599	119.84	10.76	648	0.3145	7.4335	95.31	202.5	6.19	1.25
OSB0°-6	597	119.96	10.73	638	0.3145	7.4340	103.1	201.6	7.08	1.22
OSB0°-7	598	119.90	10.73	665	0.3145	7.4337	95.31	211.3	6.35	1.40
OSB0°-8	600	119.76	10.61	649	0.3147	7.4332	96.88	209.4	6.64	1.38
OSB0°-9	599	119.65	10.75	637	0.3145	7.4333	100	201.9	6.72	1.22
OSB0°-10	600	120.10	10.65	664	0.3147	7.4335	102.5	212.8	7.56	1.45
Mean Value (GPa)									6.84	1.32
Coefficient of Variation									7.9%	5.9%
OSB90°-1	599	119.36	11.32	658	0.3134	7.4074	59.38	219.06	2.21	1.34
OSB90°-2	600	119.74	10.86	646	0.3143	7.4074	58.75	209.06	2.32	1.31
OSB90°-3	600	119.72	10.91	657	0.3142	7.4074	63.13	210.63	2.70	1.34
OSB90°-4	600	119.86	10.99	641	0.3141	7.4074	54.69	199.06	1.95	1.15
OSB90°-5	600	118.46	10.79	635	0.3142	7.4071	59.38	203.44	2.36	1.21
OSB90°-6	601	119.27	10.93	622	0.3141	7.4073	62.19	197.2	2.49	1.10
OSB90°-7	601	119.82	10.63	664	0.3147	7.4074	57.5	204.7	2.40	1.35
OSB90°-8	601	119.81	10.73	662	0.3145	7.4074	59.38	213.8	2.50	1.44
OSB90°-9	602	119.72	10.85	658	0.3143	7.4073	60.94	213.8	2.58	1.40
OSB90°-10	602	119.94	10.83	692	0.3144	7.4073	54.38	212.9	2.17	1.48
Mean Value (GPa)									2.37	1.31
Coefficient of Variation									9.2%	9.4%
OSB45°-1	426	81.00	10.89	634	0.3040	7.4281	150.6	430.6	3.78	1.28
OSB45°-2	426	80.90	10.89	650	0.3035	7.4280	136.3	408.1	3.17	1.18
OSB45°-3	425	80.75	10.76	616	0.3042	7.4280	131.3	405.6	2.83	1.12
OSB45°-4	426	80.86	10.85	622	0.3042	7.4279	130.6	408.1	2.81	1.14
OSB45°-5	425	80.80	10.71	608	0.3041	7.4281	129.4	398.8	2.74	1.08
Mean Value (GPa)									3.07	1.16
Coefficient of Variation									14.1%	6.7%

Table 2
Elastic modulus E_x, E_y, $E_{45°}$ and shear modulus G_{xy} of OSB measured by the cantilever-plate torsional mode method.

Specimen Number	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m^3)	β	C_1	C_2	First-order bending frequency (Hz)	First-order torsional frequency (Hz)	E (GPa)	$G_{\text{unmodified}}$ (GPa)	G (GPa)
OSB0°-1	540	119.40	10.66	641	0.3146	7.8867	0.0184	18.13	116.38	6.04	1.26	1.15
OSB0°-2	540	119.34	10.72	628	0.3145	7.8852	0.0184	16.75	117.63	4.99	1.25	1.16
OSB0°-3	540	119.10	10.66	637	0.3146	7.8848	0.0184	17.88	121.63	5.83	1.36	1.26
OSB0°-4	540	119.46	10.65	654	0.3146	7.8873	0.0184	19.25	124.25	6.96	1.47	1.34
OSB0°-5	540	119.84	10.76	648	0.3145	7.8876	0.0184	19.25	120.75	6.75	1.36	1.23
OSB0°-6	540	119.96	10.73	638	0.3145	7.8889	0.0185	18.75	117.5	6.34	1.28	1.16
OSB0°-7	540	119.90	10.73	665	0.3146	7.8885	0.0185	18.50	124.00	6.44	1.48	1.36
OSB0°-8	540	119.76	10.61	649	0.3147	7.8898	0.0185	18.75	124.9	6.60	1.49	1.37
OSB0°-9	540	119.65	10.75	637	0.3145	7.8867	0.0184	18.38	123.15	6.07	1.39	1.28
OSB0°-10	540	120.10	10.65	664	0.3147	7.8912	0.0186	19.13	124.88	6.99	1.53	1.40
Mean Value (GPa)										6.30		1.27
Coefficient of Variation										9.6%		7.5%
OSB90°-1	540	119.36	11.32	658	0.3134	7.6594	0.0229	10.63	119.06	1.89	1.24	1.20
OSB90°-2	540	119.74	10.86	646	0.3143	7.6651	0.0235	10.63	115	2.01	1.24	1.19
OSB90°-3	540	119.72	10.91	657	0.3142	7.6645	0.0235	11.25	114.69	2.28	1.25	1.19
OSB90°-4	540	119.86	10.99	641	0.3141	7.6643	0.0234	10.63	115	1.95	1.20	1.16
OSB90°-5	540	118.46	10.79	635	0.3142	7.6611	0.0231	11.56	115.3	2.37	1.21	1.16
OSB90°-6	540	119.27	10.93	622	0.3141	7.6627	0.0233	11.38	117.4	2.20	1.22	1.17
OSB90°-7	540	119.82	10.63	664	0.3147	7.6675	0.0238	11.63	120.80	2.59	1.47	1.41
OSB90°-8	540	119.81	10.73	662	0.3145	7.6665	0.0237	11.63	121.3	2.53	1.45	1.39
OSB90°-9	540	119.72	10.85	658	0.3143	7.6650	0.0235	11.50	121.80	2.41	1.42	1.36
OSB90°-10	540	119.94	10.83	692	0.3146	7.6660	0.0236	10.25	116.1	2.02	1.36	1.32
Mean Value (GPa)										2.18		1.21
Coefficient of Variation										11.4%		8.4%
OSB45°-1	370	81.00	10.89	634	0.3051	7.7863	0.0143	30.31	253.8	3.52	1.28	1.23
OSB45°-2	370	80.90	10.89	650	0.3051	7.7853	0.0143	27.81	236.3	3.04	1.14	1.09
OSB45°-3	370	80.75	10.76	616	0.3054	7.7872	0.0144	27.5	249.1	2.89	1.22	1.18
OSB45°-4	370	80.86	10.85	622	0.3052	7.7861	0.0143	26.88	250.3	2.74	1.23	1.19
OSB45°-5	370	80.80	10.71	608	0.3055	7.7889	0.0144	26.56	229.7	2.68	1.04	1.00
Mean Value (GPa)										2.97		1.14
Coefficient of Variation										11.3%		8.3%

Table 3
Measured static shear modulus of OSB (load increment $\Delta P = 8.33$ N).

Specimen Number	Thickness (mm)	$\Delta\varepsilon_{-45} \times 10^6$	$\Delta\varepsilon_{45} \times 10^6$	$\Delta\varepsilon_{-45} \times \Delta\varepsilon_{45} \times 10^6$	Measured shear modulus (GPa)
OSB-1	10.79	103.9	−67.7	171.6	1.25
OSB-2	10.87	70.9	−85.8	156.7	1.35
OSB-3	10.77	82.8	−61.0	143.8	1.50
OSB-4	10.71	89.2	−64.6	153.8	1.42
OSB-5	10.68	86.1	−100.1	186.2	1.18
OSB-6	10.49	124.7	−85.6	210.3	1.08
OSB-7	10.44	85.7	−75.6	161.3	1.42
Mean Value (GPa)					1.31
Coefficient of Variation					11.4%

by the static square-plate torsional method was 1.31 GPa (Table 3). The relative error between them is less than 0.8%. On the other hand, the relative errors of the shear modulus of the 0° OSB and 90° OSB specimens measured by the cantilever-plate torsional mode and the static square-plate torsional methods are 3.1% and 7.6%, respectively. The error increases because the fixed edge of the cantilever plate cannot be perfectly realized in the test, which results in a decrease in the measured frequency (Table 4).

The shear modulus measured by the cantilever-plate torsional mode method are $G_{0^\circ} = 1.27$ GPa, $G_{90^\circ} = 1.21$ GPa which are 96.9% and 92.4% of (or 3.1% and 7.6% less than) the shear modulus from the square-plate torsional test $G = 1.31$ GPa. The reason could be the fixed end not perfectly clamped, leading to lower first-order bending and torsional frequencies measured than their theoretical values. To some extent, the testing accuracy can be raised by improving clamping. However, the difficulty of realizing perfectly clamping reveals the advantage of the dynamic free-plate torsional mode shape method for testing shear modulus.

Shear modulus of 45° OSB is less than the in-plane shear modulus (see data in Tables 2 and 3), which is different from those

Table 4
Comparison of shear modulus of OSB plates measured by static and dynamic tests.

Shear modulus	Static square-plate torsional test method			Dynamic free-plate torsional mode shape method	
	Using 45° strain gauge	Using −45° strain gauge	Using 45° and −45° strain gauges	G_{0°	G_{90°
Mean value/GPa	1.46	1.22	1.31	1.32	1.31
Standard deviation/GPa	0.25	0.20	0.15	0.08	0.12
Coefficient of variation	17.0%	16.0%	11.4%	5.8%	9.4%

composite materials laying fibers unidirectionally of which the shear modulus reaches the maximum in the 45° direction.

4.2.4. Comparison with other methods to test shear modulus

The Japanese code A1127-2001 describes the resonance method for testing dynamic elastic modulus, stiffness and Poisson's ratio of concrete. In the code, the method for testing shear modulus is essentially from the free-rod torsional vibration method which is expressed as:

The equation for testing shear modulus by this method can be expressed as:

$$G_D = 4.00\frac{LR}{A}mf_t^2 \quad \text{or} \quad G_D = 4.00\rho L^2 R f_t^2$$
$$R = \frac{b/a + a/b}{4a/b - 2.52a^2/b^2 + 0.21a^6/b^6},\ (b > a) \tag{15}$$

where G_D is the dynamic shear modulus (N/mm^2); L is the length of free rod (mm); R is the shape factor; b is the long side of free rod section (mm); a is the short side of free rod section (mm); f_t is the first-order torsional frequency of the free rod (Hz); m is free pole mass (kg); A is the sectional area of free rod (mm^2); ρ is air-dry density (kg/m^3).

By substituting the dimension of the free rod and the measured first-order torsional frequency (Table 2) into Eq. (21), the shear modulus can be calculated.

According to the flexural and torsional vibrations of rectangular cross section cantilever rod, the equations for calculating elastic modulus E and shear modulus G are provided, respectively [26]. The equation of shear modulus is expressed as:

$$G = \frac{\pi^2 \rho l^2 b^2 f_t^2}{3h^2} \tag{16}$$

where G is shear modulus (Pa); ρ is the material density (kg/m^3); l is the length of the plate (m); b is the width of the plate (m); f_t is the first-order torsional frequency of the cantilever plate (Hz) and h is the thickness of the plate (m).

By substituting the dimension of the cantilever plate and the measured first-order torsional frequency (Table 2) into Eq. (16), the shear modulus can be calculated.

The results of in-plane shear modulus of 0° and 90° OSB measured by the free-plate torsional mode shape method, the cantilever-plate torsional mode method, the free-rod torsional vibration method using Eq. (21) and the rectangular cross section cantilever-rod torsional vibration method using Eq. (16) are shown in Table 5.

In Table 5, the percentages in the brackets represent the relative error between the average G from dynamic test and that from the static square-plate torsional test of shear modulus.

Theoretically, the measurement of the in-plane shear modulus G_{xy} can be done using only one of the 0° and 90° OSB specimens, but in this work, it was measured by using both the 0° and 90° OSB specimens. This is to verify the correctness of the equations of free-plate torsional mode shape and cantilever-plate torsional mode methods for testing shear modulus and the corresponding mode shape coefficient. As can be seen from the second and fourth columns of data in Table 5, when the free-plate torsional mode shape and cantilever-plate torsional mode methods are used, shear modulus measured from 0° and 90° OSB specimens are almost exactly equal. The result from the free-plate torsional mode shape method is closer to the test value from the static square-plate torsional test.

Shear modulus of 0° and 90° OSB specimens obtained by Eq. (16) using the cantilever-rod torsional vibration method are not equal, with a difference of 9% which is around 12–20% smaller than the test value from static square-plate torsion test.

Comparing the above four methods with only one specimen size is not fairly enough to indicate the scope of application of the free-plate torsional mode shape and the cantilever-plate torsional mode methods in measuring in-plane shear modulus of OSB. Thus, based on the simulating calculation of shear modulus, the range of aspect ratios of the specimens that applies to measuring shear and elastic modulus of OSB by the free-plate torsional mode shape and cantilever-plate torsional mode methods is described.

4.2.5. Simulation of shear modulus and elastic modulus of OSB

By simulating calculation, the correctness of using the mode shape coefficient to calculate shear modulus depending on the specimen dimension and the validity of using the beam theory equation to check the elastic modulus of plate specimens can be verified.

In the ANSYS modal program (ANSYS Inc., ANSYS 15.0, Pittsburgh, USA), the Solid45 unit was selected for mesh by 40 × 20 × 3, in meters. Next, the elastic constants and density of the OSB plate were inputted (Table 6). The simulation procedure was as follows: enter the job name, select the calculation unit (Solid 45 unit), establish the geometric model according to the size of the specimen (select Block), grid partition, solution (including selecting the modal analysis module, calculating the order and frequency range, and adding the constraint), and solve and read the modal information (including the frequency, mode shape, and modal stress and strain).

In Table 6, the x-axis is the longitudinal or 0° direction of the OSB, and the y-axis is the transverse or 90° direction. For the free plates with the dimensions 1280 mm × 160 mm × 10.5 mm, 960 mm × 160 mm × 10.5 mm, 800 mm × 160 mm × 10.5 mm, 640 mm × 160 mm × 10.5 mm, 480 mm × 160 mm × 10.5 mm,

Table 5
Comparison of OSB in-plane shear modulus measured by different dynamic and static square-plate torsional methods.

Specimen type	Methods of testing shear modulus				
	Dynamic				Static
	Free-plate torsional mode shape method	Free-rod torsional vibration method	Cantilever-plate torsional mode method	Cantilever-rod torsional vibration method	Static square-plate torsion method
OSB0°	1.32GPa (0.90%)	1.34GPa (2.1%)	1.27GPa (−2.98%)	1.15 (−12.4%)	1.31GPa
OSB90°	1.31GPa (−0.15%)	1.33GPa (1.1%)	1.26GPa (−4.20%)	1.05 (−19.9%)	

Table 6
Input elastic constants and density of the OSB for the ANSYS modal calculation.

E_x (GPa)	E_y (GPa)	E_z (GPa)	μ_{xy}	μ_{yz}	μ_{xz}	G_{xy} (GPa)	G_{yz} (GPa)	G_{xz} (GPa)	Density (kg/m^3)
6.4	2.7	2.7	0.23	0.12	0.33	2.5	0.75	0.77	614

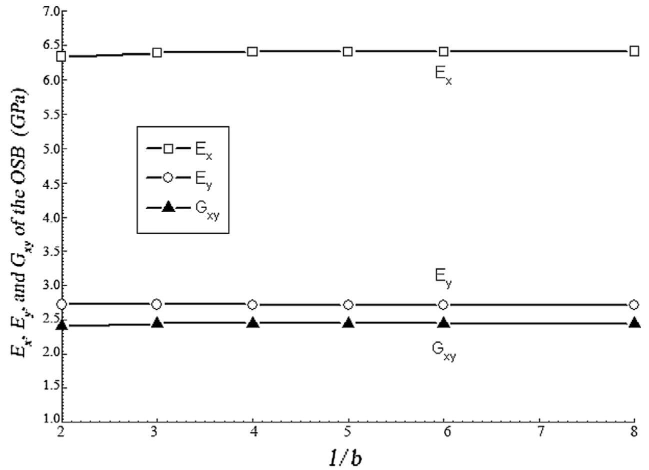

Fig. 8. Simulation values of the E_x, E_y, and G_{xy} of the OSB as the l/b of the free plate changed.

and 320 mm × 160 mm × 10.5 mm, the l/b ratios were 8, 6, 5, 4, 3, and 2, respectively. These plates were simulated with the ANSYS modal program. The obtained first-order bending and torsion frequencies of the free plates were substituted into Eqs. (1) and (3) to derive the E_x, E_y, and G_{xy}. Fig. 8 shows the simulation values of the E_x, E_y, and G_{xy} as they changed with the l/b. As the l/b ratio changed from 8 to 2, the E_x, E_y, and G_{xy} were constant and consistent with the input values. Therefore, Eqs. (1) and (3) can be used to test the elastic and shear modulus of the OSB.

For the cantilever plates with the dimensions 400 mm × 160 mm × 10.5 mm, 320 mm × 160 mm × 10.5 mm, 240 mm × 160 mm × 10.5 mm, 200 mm × 160 mm × 10.5 mm, and 160 mm × 160 mm × 10.5 mm, the l/b ratios were 2.5, 2, 1.5, 1.25, and 1, respectively. These plates were simulated with the ANSYS modal program. The obtained first-order bending and torsion frequencies of the cantilever plates were substituted into Eqs. (2) and (6) to derive the E_x, E_y, and G_{xy}. Fig. 9 shows the simulation values of the E_x, E_y, and G_{xy} as the l/b changed. As the l/b ratio changed from 2.5 to 1, the E_x, E_y, and G_{xy} were constant and consistent with the input values. Therefore, Eqs. (2) and (6) can be used to test the elastic and shear modulus of the OSB.

Table 1 indicates that there is a difference between the longitudinal and transverse elastic modulus of OSB plates. The longitudinal elastic modulus was 2.37 times (generally 2–3 times) higher than the transverse elastic modulus. The simulation results also show the same feature between the longitudinal and transverse elastic modulus of the OSB.

The results show that the elastic constant of OSB is relevant to the direction. For the dynamic elastic modulus, $E_{0°}$ was 6.84 GPa, $E_{90°}$ was 2.37 GPa, and $E_{45°}$ was 3.07 GPa. For the dynamic shear modulus, $G_{0°}$ was 1.32 GPa, $G_{90°}$ was 1.31 GPa, and $G_{45°}$ was 1.16 GPa. Due to the small difference between the measured $G_{0°}$ and $G_{90°}$ values, they can be regarded as the estimated values of the in-plane shear modulus G_{xy}.

The simulation of the shear modulus was conducted as follows. First, the elastic constant and density of the material were input into the ANSYS program to obtain the first-order torsional frequency. Next, the first-order torsional frequency was substituted into the mode shape coefficient of OSB given in this work to derive the shear modulus. When the l/b ratio is 2–8 for free plate and 1–2.5 for cantilever plate, the calculated shear modulus was independent of the aspect. In addition, the simulation result of shear modulus was equal to the in-plane shear modulus G_{xy} that was inputted into the ANSYS program. This indicates that the mode shape coefficients C_1, C_2, or γ given in the work can be used to calculate the in-plane shear modulus of OSB from the measured first-order torsional frequency.

To prove the method of testing shear modulus of OSB proposed in this work does not depend on the size of the specimen from the view of experiment, the truncation test of the 0° OSB specimens was conducted. Longitudinal specimens No. 2 and No. 3 (with length of 600 mm, width of 120 mm and thickness of 10.5 mm) shown in Table 1 were taken and cut into four specimens with length of 298 mm. After testing the first-order torsional frequency under the state of free constraint, the specimens were cut short into 240 mm and 180 mm successively and the first-order torsional frequency was tested under the state of free constraint. Then using the free-plate torsional mode shape method, that is, Eq. (3) and the longitudinal mode shape coefficient γ, the in-plane shear modulus G_{xy} was calculated. The scatter plot of the in-plane shear modulus G_{xy} depending on the aspect ratio l/b is shown in Fig. 10.

It can be seen from Fig. 10 that the in-plane shear modulus of OSB tested by the free-plate torsional mode shape method is independent of the specimen size. Therefore, it is concluded from both the simulation calculation and the experiment of shear modulus of OSB that when using the equation and the corresponding mode shape coefficient proposed in this work for dynamic test of shear modulus of OSB, there does not exist different shear modulus tested by specimens with different aspect ratios.

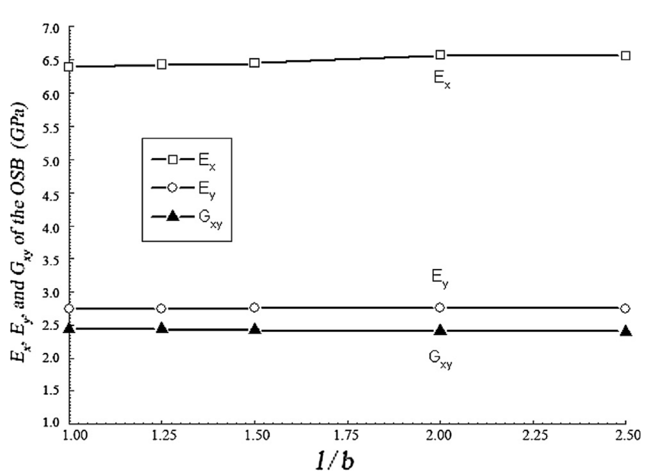

Fig. 9. Simulation values of the E_x, E_y, and G_{xy} of the OSB as the l/b of the cantilever plate changed.

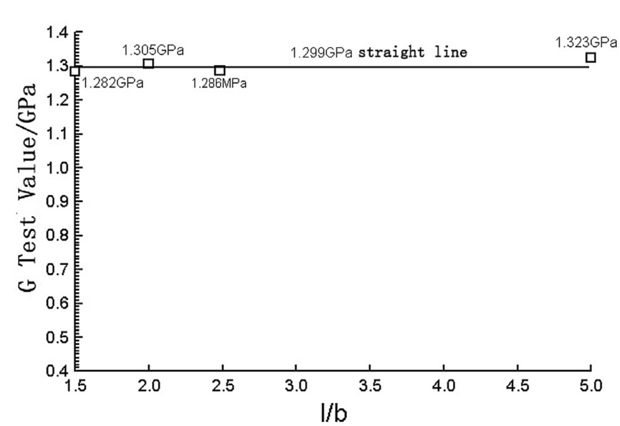

Fig. 10. Shear modulus of OSB longitudinal specimen varying with the aspect ratio.

There is a lower bound required for the aspect ratio of specimen used in the dynamic test of shear modulus proposed in this work. Whether the method is applicable to the test of shear modulus by the free square plate method remains to be discussed. The requirement of the lower bound of the aspect ratio of the specimen is currently the limitation of the method.

In addition, the shear modulus tested by the transverse and longitudinal OSB specimens are almost equal. Whether this result applies to other wood-based structural panels and wood remains to be further studied.

In the aspect of longitudinal and transverse elastic modulus, OSB shows the characteristics of anisotropy. In the OSB square-plate torsional test, it was found that there is a large difference of the shear modulus calculated by Eq. (13) which applies to isotropic material when the strain gauge is pasted along a diagonal. Considering OSB is anisotropic, according to the plane strain analysis and the Hooke's law for shear, Eq. (14) was derived which applies to anisotropic materials to measure shear modulus by the square-plate torsional test. The Eq. (14) has adequate theoretical evidence. In the equation, the linear strains in the ±45° directions which are perpendicular to each other are measured. The effect of the linear strain components ε_x and ε_y on the linear strain in the ±45° directions is eliminated. This treatment conformed to the principle, which makes the measured shear modulus reliable and reduces the dispersion of the measured data of shear modulus. Table 5 shows the measured shear modulus from the square-plate torsional and dynamic tests. The result shows that the measured shear modulus from dynamic and static tests were consistent. Therefore, the dynamic measurement of shear modulus of OSB by using the mode shape coefficient developed in this work is feasible and robust.

In general, for unidirectional materials, shear modulus reaches its maximum in the 45° direction. However, different from these unidirectional materials, shear modulus of OSB is $G_{45^\circ} < G_{0^\circ} < G_{90^\circ}$.

5. Conclusions

1. Dynamically measured shear modulus of 0° and 90° OSB board specimens are almost equal. Thus, measured shear modulus of either 0° or 90° can be used as the estimated value of in-plane shear modulus G_{xy} of OSB.
2. The free-plate torsional mode shape method and the cantilever-plate torsional mode method apply to testing the in-plane shear modulus of OSB dynamically. The correctness is verified by the static square-plate torsional test.
3. OSB should be treated as an orthotropic material rather than a unidirectional composite in the theoretical analysis. For OSB, $G_{45^\circ} < G_{xy}$.
4. In the measurement of static shear modulus by the square-plate torsional test, ±45° strain gauges should be pasted at the center of both upper and lower surfaces of the square plate along the diagonals. To ensure the measurement accuracy and reduce the dispersion, shear modulus of OSB should be calculated from the difference between the measured values in the ±45° directions.

Declaration of Competing Interest

None.

Acknowledgements

This study was funded by the 2016 Platform of Significant Innovation in Strategic Emerging Industries and Public Service (SCJ [2016]221), the 2018 Self-made Experimental Teaching Instrument Project of Nanjing Forestry University (NLZZYQ201804), and the 2017 Jiangsu Province Forestry Science and Technology Innovation and Extension Fund (LYKJ[2017]41).

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