Construction and Building Materials 121 (2016) 285–289

Contents lists available at ScienceDirect

Construction and Building Materials

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

Determining shear modulus of thin wood composite materials using a cantilever beam vibration method

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HIGHLIGHTS

- A cantilever beam vibration method.
- In-plane shear modulus.
- Medium density fiberboard (MDF), particleboard (PB) and wood fiber plastic (WFP).
- There exists a significant linear correlation between in-plane shear modulus and bending modulus of elasticity.

ARTICLE INFO

Article history:
Received 30 January 2016
Received in revised form 6 May 2016
Accepted 1 June 2016

Keywords:
Thin wood composite materials
Cantilever beam free vibration
In-plane shear modulus
Modulus of elasticity
Logarithmic decrement

ABSTRACT

Shear modulus (*G*) of thin wood composite materials is one of several important indicators that characterizes mechanical properties. However, there is not an easy method to obtain this value. This study presents the use of a newly developed cantilever beam free vibration test apparatus to detect in-plane *G* of thin wood composite materials by measuring the first order free vibration cantilever specimens and its logarithmic decrement of vibration. Six sets of commercially purchased thin wood composite materials having three different fiber types were tested. A significant linear correlation was found between in-plane *G* and bending modulus of elasticity (MOE) from cantilever-beam free vibration test and MOE was shown to be approximately two times of in-plane *G*. This was in full agreement with previous findings by other researchers. The study demonstrated that the cantilever beam free vibration method could be widely used to obtain in-plane *G* easily for thin wood composite materials.

1. Introduction

Thin wood composite materials, 1 ~ 5 mm thickness, such as fiberboard, particleboard, wood-fiber plastic, reconstituted veneer, pulp molded products are being widely used in construction, furniture, musical instruments, vehicles, ships, medical devices and other applications that are having increasing engineering demands. Engineering analysis of the parts made from these materials requires an understanding of the fundamental mechanical properties in order to be properly specified for an application. Current testing and performance evaluation such as ASTM D1037-06a [1] uses simple bending techniques that only obtain bending modulus of elasticity (MOE) and maximum stress at failure. If shear properties are desired, a separate shear-block specimen is needed to determine shear through a particular shear-plane. Making a shear block out of thin materials would be impossible. There is a need to develop easier testing tools to quickly and accurately determine the shear modulus (*G*) for improving analyses of thin composites.

A review of the literature shows only a few detection methods and techniques related to the *G* of wood composite materials. Zhou et al. [2] presented a torsional bending vibration method, by detecting torsional mode of the vibration frequency to calculate the *G* of wood composite boards. According to surface wave propagation theory, Hu et al. [3,4] introduced one method. Stress wave was initiated in the specimen's surface when impacted on the specimen, and wave propagation time was measured to assess the dynamic *G* of wood-based panels. In ASTM D3044-94 [5], four-point bending of a rectangular plate (two diagonal supports, the other two diagonal force) is used to determine the *G*. This method is difficult and time consuming to set-up and only provides an average *G* value but does not differentiate between directions. Hearmon [6] provided a flexural vibration method for large wooden beams where *G* measurement was based on

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http://dx.doi.org/10.1016/j.conbuildmat.2016.06.007
0950-0618/

Timoshenko-Goens-Hearmon theory, the test beam was suspended by two threads at the nodal positions of the free-free vibration corresponding to its resonance mode. The specimen was impacted in the direction of the thickness at one end by a hammer. The resonance frequencies whose mode was from the first to the fourth were measured by fast frequency transform (FFT) digital signal analyzer, then G values were obtained. Divos et al. [7] demonstrated one method in which the spruce specimens were loaded in a testing machine in three-point-loading. The apparent MOEs were measured twice at two different short spans. The G of spruce specimens were calculated based on the deflection differences. In addition, torsional tests [8] and asymmetric four-point bending tests [9] were also used to determine shear properties. Most detection methods for G were mainly directed toward larger wood specimens. The study of G for thin wood composite materials has had little discussion in the literature.

Some wood composite panels modelled as orthotropic materials like plywood and oriented strand board have non-uniform property values in the length, width and thickness directions. This is due to manufacturing characteristics where fibers may be preferentially aligned in the panel length direction. It is also due to hot-press conditions where high-density regions generally occur on the faces with lower-density regions toward the center. The higher-density regions generally have higher property values than lower-density regions. These factors influence material properties including G. Any G value is an average value influenced by these fiber alignments and processing factors. Further study of these factors on the value of G is beyond the scope of this study, but will be addressed later. However, some other wood composite panels can be modelled as in-plane quasi-isotropic materials, such as medium density fiberboard and particleboard, where they have nearly the same values in the length and width directions [10].

This study presents data to show the potential for a cantilever-beam free vibration test to determine an in-plane G value for thin wood composite materials. Using a newly developed cantilever beam vibration apparatus [11,12], six sets of commercially purchased thin wood composite materials were tested. The sets included three different fiber types, medium density fiberboard (MDF), particleboard (PB) and wood fiber plastic (WFP). The cantilever beams were set into their free vibration where their natural frequency and vibration logarithmic decrement were measured to calculate dynamic MOE, in-plane G, and log decrement. The goal of this research and development of the test apparatus was to provide a method that could easily provide fundamental properties for thin wood composite materials including in-plane G.

2. Theoretical basis

Wood composite materials exhibit typical polymer material characteristics having viscoelastic properties. The theoretical equation of G, using a cantilever beam vibration method, can be determined from cantilever free-vibration theory. The viscoelastic differential equations of Kelvin model, Euler -Bernoulli beam theory, kinetic theory and viscoelastic theory are used to calculate G discussed by Li et al. [13].

In-plane G and viscosity coefficient based on the differential equations in the Kelvin model are given by Eq. (1):

$$\begin{cases} \frac{2\pi}{T} = \sqrt{-\frac{In^4}{m_u^2 L^8}\left(2Gm_u l^4 c + I\eta^2 d^4 c^2\right)} \\ -\frac{\ln\lambda}{T} = \frac{I\eta n^4 c}{m_u l^4} \end{cases} \quad (1)$$

where T is the period of cantilever free vibration (s), I is the inertia moment of the beam cross-section (m^4), d is the differential steps (here, d is substituted with 10), m_u is the mass per-unit length (kg m^{-1}), l is the unclamped or "free" length of the cantilever beam (m), G is in-plane shear modulus (Pa), c is the calculated value obtained by difference method (here, c is substituted with -0.0012), η is viscosity coefficient, λ is the ratio of adjacent peaks of adjacent troughs.

Free vibration of a cantilever beam appears as a damped sine wave, as shown in Fig. 1. The ratio of two adjacent amplitudes in the same direction is called amplitude decay rate, and natural logarithms of amplitude decay rate is called logarithmic decrement (δ) [14].

According to the definition of δ, the relationship of every two adjacent amplitudes $A_1, A_2, A_3, \ldots, A_n, A_{n+1}$ is as follows:

$$\frac{A_1}{A_2} = \frac{A_2}{A_3} = \cdots = \frac{A_n}{A_{n+1}} = e^{\delta} \quad (2)$$

Because λ is the ratio of adjacent peaks of adjacent troughs, Eq. (2) can be expressed as $\ln\lambda = \delta$, and inserted into Eq. (1) and it can be rearranged and written to obtain the in-plane G as follows:

$$G = \frac{f^2(4\pi^2 + \delta^2)Ml^4}{2Lbt^3} \quad (3)$$

where f is first natural frequency of the specimen vibration without damping (Hz), δ is logarithmic decrement of vibration decay, L is compete length of the specimen (m), b is width of the specimen (m), t is thickness of the specimen (m), M is mass of the specimen (kg).

According to the damped sine wave of vibration amplitude, the logarithmic decrement δ is as follows [12]:

$$\delta = \ln\frac{A_n}{A_{n+1}} = \frac{1}{n+1}\ln\frac{A_1}{A_n} = \frac{2\pi\zeta}{\sqrt{1-\xi^2}} = 2\pi\zeta\frac{f}{f_r} \quad (4)$$

where A_1 is the first amplitude of the damped sine wave selected, A_n is the nth amplitude of the damped sine wave selected, A_{n+1} is the $(n+1)^{th}$ amplitude of the damped sine wave selected, f is first natural frequency of the specimen vibration without damping, f_r is first natural frequency of the specimen vibration tested and ζ is damping ratio.

In Eq. (4), ζ can be calculated using the logarithmic decrement δ in Eq. (5):

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \quad (5)$$

According to Eq. (4) and Eq. (5), first natural frequency of the specimen vibration f can be calculated using the measured first frequency f_r, as shown in Eq. (6).

$$f = \frac{f_r}{\sqrt{1-\zeta^2}} \quad (6)$$

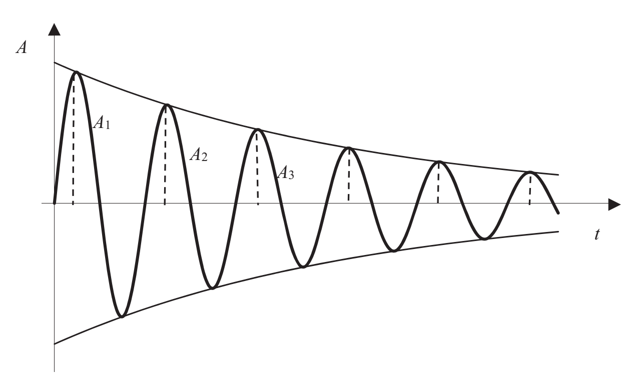

Fig. 1. Vibration signal.

From Eq. (3), an in-plane G can be calculated using the composite beams physical properties, free-vibration frequency, and logarithmic decrement. This is theoretical basis for determining in-plane shear modulus of thin wood composite materials.

3. Materials and methods

3.1. Materials

Six sets of commercial wood composite materials having three different fiber types were tested. The specimen fiber types were medium density fiberboard (MDF), particleboard (PB) and wood fiber plastic (WFP). The MDF and PB were provided by a board mill. These panels were manufactured from mixed species of both softwood and hardwood using urea-formaldehyde resin. The WEP was obtained from a local retail outlet, so the resin types or other manufacturing characteristics were not available for this test. The average moisture content of these panels was about 6%. According to each panel nominal thickness, the composite materials were cut to length. To minimize vibrational shear effects, the ratio of free length to thickness of the specimen should be greater than 14.5 [12]. All specimens were cut to the same width (50 mm). Ten specimens from each type were tested. A total of 60 specimens were prepared. Detailed dimensions are shown in Table 1. The specimens were stored in a room with a relative humidity of 30 ± 5% and a temperature of 20 ± 2 °C before and during the test.

3.2. Testing apparatus and testing procedures

Fig. 2 shows the experimental thin wood composite mechanical property analyzer which consists of the following components: base, bracket, specimen clamps, laser sensor, adjusting mechanism, initial displacement mechanism and computer. The specimen clamp can be adjusted to accommodate different specimen lengths.

Before testing, the length (L), width (b), thickness (t) and mass (M) of the specimens were measured. The specimens were clamped in position, vertically as shown in Fig. 2(b). The specimens were displaced to a known deformation and then released into free-vibration. A laser sensor detected the displacement at the beam tip as it vibrated. Displacement/time data were used to determine frequency and signal amplitude and dynamic MOE, in-plane G, and logarithmic decrement were calculated.

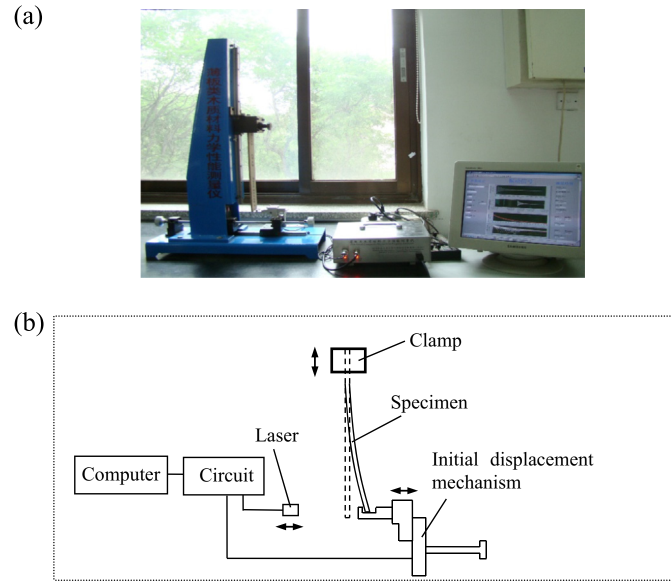

Fig. 2. Thin wood composite mechanical property analyzer. (a) Laboratory vibration testing of a specimen. (b) Structure schematic of apparatus.

Table 2
Shear modulus (G) of the thin wood composites tested.

Specimen series	Number	Shear modulus (GPa)			Standard deviation
		Average	Minimum	Maximum	
MDF 4.6 × 340	10	2.31	2.00	2.75	0.24
MDF 3.7 × 340	10	1.79	1.55	2.08	0.15
MDF 2.6 × 230	10	2.09	1.70	2.44	0.32
PB 5 × 340	10	1.49	1.30	1.63	0.09
PB 3 × 230	10	1.24	1.04	1.59	0.18
WFP 2 × 230	10	1.19	1.06	1.30	0.07

4. Results and discussion

4.1. Testing results of in-plane shear modulus (G)

The in-plane G values calculated for the six commercial thin wood composite materials are shown in Table 2. The average G values are highest for MDF panels, followed by PB, and then WFP are the lowest. Also, the average G values for the three kinds of MDF are different, and the average G for two kinds of PB is also different. Since these panels are from different commercial lines, the differences are most likely due to variations in manufacturing techniques and components. The standard deviation within each series of 10 specimens is accounted for by differences within the large panel from which they are cut.

4.2. Comparison of in-plane shear modulus (G) with density

The in-plane G plotted as a function of density is shown in Fig. 3 for the different materials and panels. It clearly shows that the commercial boards used for this study are significantly different. It also shows that within each material type as density increases

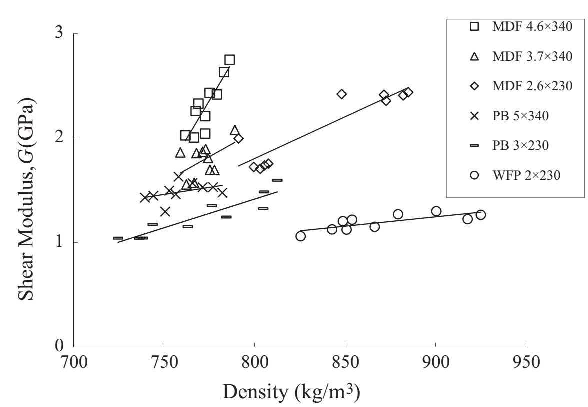

Fig. 3. Shear Modulus as a function of panel density for different panel types.

G also increases. An increase in G would be expected in wood composite panels since increasing density is generally associated with increasing properties.

Table 1
Dimensions and number of the specimens tested.

Specimen series	Dimensions ($t \times b \times L$, mm)	Number	Average density (kg/m^3)
MDF 4.6 × 340	4.5 × 50 × 340	10	773
MDF 3.7 × 340	3.7 × 50 × 340	10	771
MDF 2.6 × 230	2.6 × 50 × 230	10	836
PB 5 × 340	5 × 50 × 340	10	759
PB 3 × 230	3 × 50 × 230	10	768
WFP 2 × 230	2 × 50 × 230	10	871

4.3. Logarithmic decrement

Logarithmic decrement is the measure of mechanical damping or lost energy during vibration. For wood composites, less damping is generally associated with higher density (higher bonding). Fig. 4 shows a general trend of damping decreases with increasing

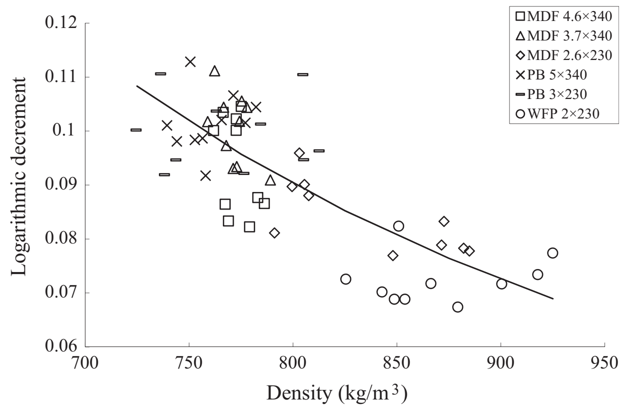

Fig. 4. Logarithmic decrement as a function of board density.

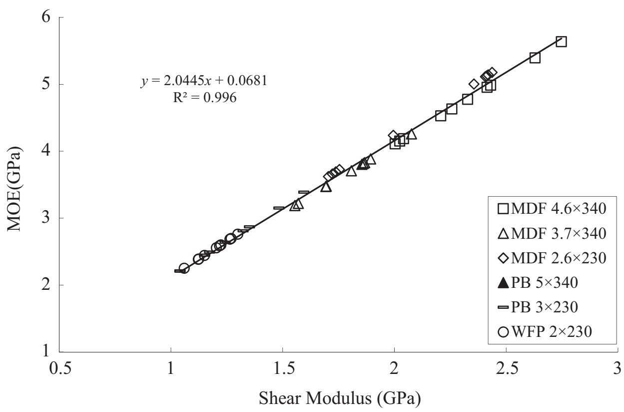

Fig. 5. Relationship between shear modulus and modulus of elasticity.

density. This would be expected since higher density is associated with improved bonding and thus improved energy (stress) transfer within the board. Improved energy transfer within the panel should result in lower damping.

4.4. Comparison of in-plane shear modulus (G) with dynamic modulus of elasticity (MOE)

The cantilever beam vibration apparatus is also able to calculate dynamic MOE for thin wood composite materials [11,12]. Comparing dynamic MOE with in-plane *G* (Fig. 5) shows there is a clear linear correlation of $E = 2.0445G + 0.0681$ with R^2 value of 0.996.

In terms of in-plane quasi-isotropic material properties, the relationship between the MOE and in-plane *G* is a linear relationship, given by Eq. (7) [15].

$$2G = \frac{E}{u + 1} \tag{7}$$

In this study, even though the panel materials used were significantly different as shown in Figs. 3 and 4, the basic relationship between MOE and in-plane *G* is still very linear where *E* is shown to be approximately two times that of in-plane *G*.

We know that the results from the proposed cantilever beam vibration method to estimate in-plane *G* may need additional verification. The verification should be done by using another test method that determines *G* using a different configuration than the method presented. This could be a difficult task, especially for thin wood composite materials. Static test methods are generally accepted as good reference methods. Some comparable values for MDF properties have also been found in the literature. Zhou et al. [16] presented the mean values MOE = 3.098 GPa and *G* = 1.522 GPa for MDF panels in the shear tests according to ASTM D3044-94. Yoshihara et al. [17,18] determined MOE and in-plane *G* of MDF by flexural vibration and used the values MOE = 3 GPa and G = 1.5 GPa for the finite element calculations. These values represent similar values as those obtained using the cantilever-beam method presented in this study.

5. Conclusions

This study introduced a cantilever-beam free vibration test apparatus that could be used to determine in-plane shear modulus for thin wood composite materials. The newly developed thin wood composite mechanical property analyzer tested six sets of commercially purchased thin wood composite materials having three different fiber types, medium density fiberboard (MDF), particleboard (PB) and wood fiber plastic (WFP). Even though the physical properties and material properties of all the panels were significantly different, the relationship between MOE and in-plane *G* shown to have significant linear correlation and MOE was shown to be approximately two times that of in-plane *G*. This was in full agreement with previous findings by other researchers. These results indicated the cantilever beam free vibration test method could be widely used to obtain in-plane *G* values easily for different thin wood composite materials.

Acknowledgements

This project was funded by the State Forest Administration of China through the Special Research Funds for Public Welfare (Grant No. 201304512).

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